



A COMPREHENSIVE METHODOLOGY FOR PERFORMING PROSPECTIVE LIFE CYCLE ASSESSMENTS OF FUTURE AIR TRANSPORT SCENARIOS

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Abstract

In the context of the climate crisis, the aviation industry is undergoing a major transformation to reduce its environmental impact. Such a transformation requires a comprehensive, multi-criteria assessment of the environmental impacts associated with a range of technical solutions. Limiting the scope to climate change could lead to an undesirable "burden shifting" of the environmental impacts. This paper aims to develop and implement a prospective life cycle assessment module in the open-source framework AeroMAPS, which enables the simulation and evaluation of prospective scenarios for the aviation sector. The relevance of the proposed methodology is illustrated through an application. Different scenarios for the adoption of alternative fuels by the aviation sector are modelled and evaluated. The results show the importance of considering the electricity mix used in the production of electrofuels. It also highlights other important environmental impacts, such as the formation of particulate matter, which ultimately affects human health. The comprehensive exploration of scenarios made possible by the prospective LCA methodology is a promising approach that will help develop more effective strategies to mitigate the environmental impacts of aviation.

Keywords: Sustainable Aviation; Life Cycle Assessment; Prospective Scenarios; Technology Assessment

1. Introduction

Faced with the urgent need to address environmental challenges such as climate change and resource consumption, the aviation industry is undergoing a major transformation. Promising strategies such as Sustainable Aviation Fuels (SAFs) [1, 2, 3], more efficient aircraft [4] and advanced air traffic management [5] have the potential to reduce emissions and improve efficiency [6].

Evaluating such strategies to guide the transition of air transportation to a more sustainable future requires a modelling effort of the air transport system and its evolution. To this end, overall aircraft design tools, such as FAST-OAD [7] and SUAVE [8, 9, 10], can be used to estimate the performance of future architectures. Similarly, for energy carriers, detailed approaches provide information on specific processes [11, 12], while more global approaches enable the comparison of different production pathways [13]. The results obtained from the technical models must then be aggregated to create scenarios that describe the evolution of air transport in the future and the associated environmental impacts. Initiatives in this direction include the academic tools AIM2015 [14], FLEET [15] and AeroMAPS [16], and industrial initiatives such as the Cascade tool from Boeing [17]. These software tools make it possible to conduct prospective analyses to estimate the impacts of transition strategies. However, these assessments often focus primarily on climate change and occasionally on energy resource consumption. Additional environmental impacts such as air pollution and resource depletion (e.g. land use and water use for SAFs) need to be carefully assessed to avoid "burden shifting". To this end, the Life Cycle Assessment (LCA) methodology provides a standardised framework for evaluating all relevant environmental impacts that occur throughout the life cycle of a system, from raw material extraction, through manufacturing and use, to recycling and disposal [18, 19]. As highlighted by Rupcic *et al.* [20], existing LCA applications in the aviation sector are often too narrow in scope

to provide a global perspective on the industry (e.g. ignoring several energy carriers) and/or are limited to climate change impacts when addressing environmental issues. Another major challenge in performing prospective environmental analyses is to adapt the environmental datasets supporting the LCA to align with the scenario projections. For example, the evolution of the electricity mix for producing liquid hydrogen in 2035 and 2050 will generate different environmental impacts. Recently, Thonemann *et al.* [21] provided life cycle inventory (LCI) datasets for the prospective assessment of conventional and hybrid-electric aircraft technologies. Lai *et al.* [22] proposed an approach for the prospective LCA of SAF production in Sweden. Sacchi *et al.* [23] relied on the premise library [24] to generate prospective datasets for evaluating the sustainability of a European climate-neutral aviation. However, no research has yet proposed the integration of prospective LCA methods with software tools for the systematic assessment of transition scenarios for the aviation sector.

In this context, the aim of this paper is to develop a methodology for integrating prospective LCA methods into an existing framework, AeroMAPS [16], to perform a comprehensive environmental assessment of air transport transition scenarios. The implementation of the methodology will facilitate the rapid evaluation of a range of prospective scenarios to support decision-making and avoid burden-shifting.

To this end, the paper is structured as follows. Section 2 describes the various methods and tools that support the analyses. Section 3 presents the overall methodology developed in this paper, i.e. the integration of prospective LCA methods into AeroMAPS, including some details on data collection. Section 4 illustrates the relevance of the approach through several applications. Finally, Section 5 offers concluding remarks and perspectives.

2. Methods and Tools

This section presents the different methods and tools that support the sustainability assessment of prospective scenarios. First, the open-source software AeroMAPS, which is used to simulate and evaluate future scenarios for air transport, is described. Then, the resources for conducting life cycle assessments to extend the environmental evaluations conducted by AeroMAPS are presented.

2.1 AeroMAPS

AeroMAPS is an open-source framework for performing a multidisciplinary assessment of prospective scenarios for air transport [16]. A simplified architecture of the current version of AeroMAPS is shown in Figure 1.

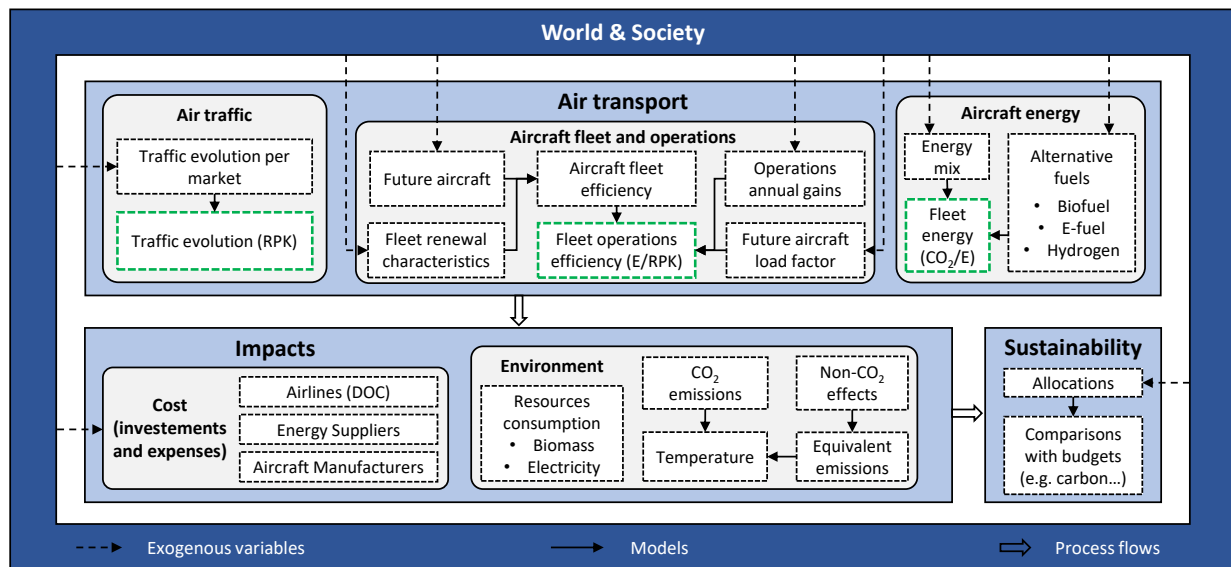


Figure 1 – Simplified architecture of AeroMAPS.

The framework relies on a set of exogenous inputs such as air traffic growth, improvements in aircraft technology and potential gains in operational efficiency. The input values defined by the user are

fed into the main *air transport* module, which simulates the temporal evolution of the air transport system, including the air traffic, aircraft fleet and energy required to operate the aircraft fleet. The evolution of air traffic is modelled by simple exponential growths, the value of which can be specified per period and per category (short/medium/long-haul passengers and freight). This demand is then satisfied by an aircraft fleet whose composition and performance can be defined by using fleet renewal models [25], and introducing new aircraft into the fleet as discrete-time events. In particular, the user should provide the performance of each aircraft architecture (e.g. using results from overall aircraft design tools), its year of entry into service, its final market share and its rate of penetration into the fleet. Finally, the energy implications associated with the defined aircraft fleet are assessed. The fleet uses a mix of energy sources, including drop-in fuels (fossil kerosene, electrofuel, biofuel) and non-drop-in fuel (hydrogen), the proportion of which must be specified by the user. An electricity mix (e.g., high/low-carbon grid or dedicated renewable) can also be specified for the production of electricity-based fuels.

In a second step, two other modules are used to estimate the economic and environmental impacts of the user-defined scenario and to assess its sustainability. The economic assessment involves the use of cost models to estimate, among other things, the Direct Operating Costs (DOC), taking into account energy costs, maintenance costs and carbon taxes. The environmental assessment includes climate models to estimate both CO₂ and non-CO₂ effects on climate change. The estimation of the induced temperature change can for instance rely on the use of the climate metric GWP* which is relevant for Short-Lived Climate Pollutants (SLCP) such as aviation non-CO₂ effects [26, 27]. The environmental module also estimates the consumption of biomass and electricity resources. Finally, a comparison of these impacts with *sustainability* targets (e.g. a carbon budget allocated to aviation) completes the scenario assessment.

The initial version of AeroMAPS described above focuses on a limited number of environmental impacts, namely climate change and depletion of biomass and electricity resources. In addition, the impacts associated with the user-defined scenario do not take into account socio-techno-economic developments such as changes in the global electricity mix and improvements in fuel production processes, or only in a very basic way through user specifications. Therefore, the present work aims to refine the environmental assessment to include additional impact categories and considerations, based on a comprehensive and prospective LCA approach.

2.2 Tools for Performing Prospective Life Cycle Assessments

The life cycle assessment methodology is a standardised framework for evaluating the environmental impacts of a system over its full life cycle [18, 19]. In particular, this approach quantifies the emissions and resource consumption associated with the production of capital goods supporting the supply chain. The life cycle perspective enables, for example, a rigorous environmental assessment of an energy carrier accounting for the industrial processes (e.g. electricity mix for hydrogen electrolysis) rather than narrowing the scope to the combustion phase.

The life cycle model calculates the material and energy flows required along the different life cycle stages of the air transport system, as well as the related emissions occurring during the industrial processes and operations. The construction of such a model relies on a thorough collection of data which can be partitioned into primary data, which relates to the foreground system, and secondary data representing the background system [28]. The foreground system is the system under study, namely the air transport. It describes technically a number of processes on which the decision-maker has a degree of control, such as the blending mandates of alternative fuels in a fleet of aircraft. In this paper, the technical modelling of the foreground system is provided by the dedicated models of the AeroMAPS framework. On the other hand, the background system consists of processes on which no or only indirect influence may be exercised, for example the industrial processes for producing energy carriers. In the methodology presented in this paper, the ecoinvent database [29] is used to build the life cycle inventory of the background system. Specifically, it provides datasets representing the flows from and to the environment occurring during the extraction, transportation and treatment of materials used in the aircraft manufacturing processes, for the production of capital goods in the fuel supply chain (e.g. petroleum refinery), and for the construction and maintenance of generic airport infrastructures.

Prospective LCA aims to model the system "at a future point in time relative to the time at which the study is conducted" [30]. As such, prospective LCA requires a modelling effort of the incumbent technologies and their market share in the future [31]. For this purpose, the Python library premise [24] uses future projections from Integrated Assessment Models (IAMs) such as REMIND [32, 33] or IMAGE [34] to update the background databases consistently over time. The scenarios upon which the IAMs operate reflect socio-economic and technical changes on a global scale in line with climate change scenarios [35, 36]. For example, the approach proposed by premise enables to model the energy mix evolution in different regions of the world. Because the influence of the assumptions underlying the IAMs may be difficult to highlight, some authors have proposed to introduce parameters to model specific evolutions of the background system [37]. These two approaches are complementary, as IAMs ensure a consistent modelling across sectors, while parameterised background datasets allow to capture specific aspects that more closely influence the environmental impacts of the foreground system.

Once the life cycle modelling of the system is completed, the emissions and resource extractions are characterised using environmental models that describe the cause-effect chain, or environmental mechanisms, that ultimately lead to impacts across a range of categories. This includes the well-known ReCiPe [38] and CML [39] Life Cycle Impact Assessment (LCIA) methods, among others. The creation of a life cycle model and the quantification of its potential impacts is facilitated by the development of LCA software tools including the open-source framework Brightway [40], which seamlessly integrates background databases, LCIA methods, and helper functions to conduct full LCA studies. More recently, the Python library lca-algebraic [41] has been developed as a layer on top of Brightway to facilitate the definition of parameterised models at both background and foreground levels.

3. Workflow and Data Collection

This section presents the integration of the aviation and environmental modelling tools into a unified framework for systematically evaluating the environmental impacts of future air transport scenarios.

3.1 Workflow

As illustrated in the workflow diagram in Figure 2, the proposed methodology consists of a three-step process.

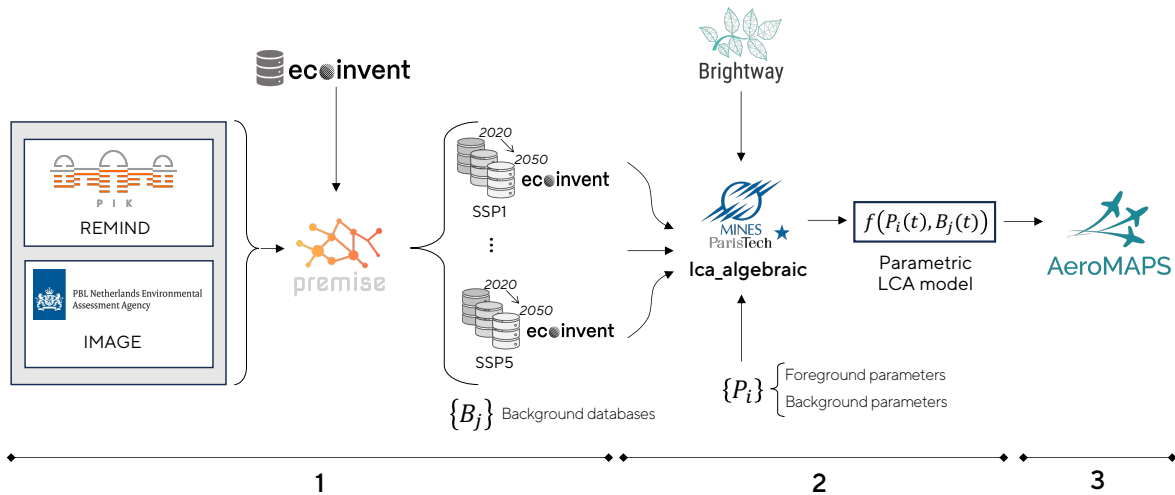


Figure 2 – Schematic view of the workflow for impacts evaluation in AeroMAPS.

1. First, the ecoinvent database containing the background data for the capital goods involved in the air transport life cycle is duplicated and transformed to enable prospective analyses. For this purpose, the premise library is used to match process performance and technology market shares to scenarios modelled by IAMs and defined by Shared Socio-economic Pathways (SSPs) and climate trajectories (Representative Concentration Pathway — RCP). A new set of

background databases is generated for a given scenario, with a time step of five or ten years. In addition, premise proposes new inventories not originally present in ecoinvent, such as the production of electrofuels and biofuels via Fischer-Tropsch. Finally, user-provided datasets are imported specifically to represent the fuel combustion process based on literature values.

2. In a second step, the background databases are combined with parameters to build an LCA model representative of the air transport system life cycle. The LCA model involves two types of parameters: background parameters and foreground parameters. Background parameters enable to select the appropriate prospective database according to the socio-economic scenario and the year. In particular, for a given IAM scenario, the LCA model interpolates the background databases on an annual basis to fill the gap for missing years. That is, the emissions, material, and energy flows associated with an activity for a specific year are expressed as a linear combination of the two databases closest in time. Additional parameters are defined to fine-tune the background systems, for example to adjust the electricity mix used in the production process of electrofuels. Foreground parameters are then introduced which represent the amount of each background element involved in the foreground system (air transport), for example the amount of kerosene consumed and the number of aircraft to be produced per year. By introducing parameters, the LCA model is ultimately expressed as a combination of time- and scenario-specific datasets. The creation of the parametric LCA model is achieved using lca-algebraic and brightway. In addition, lca-algebraic generates expressions of the characterised impacts for each of the LCIA methods chosen by the user, allowing for a rapid computation of the environmental impacts whenever the values of the parameters are updated. The impacts are expressed per functional unit, defined here as the total revenue passenger kilometres transported annually.
3. Finally, the characterised LCA model is effectively evaluated using the time-dependent parameter values provided by the air transport module of AeroMAPS. The impacts on the different environmental categories are returned and displayed in the AeroMAPS user interface.

3.2 Data Collection

This section provides a description of the data supporting the LCA of air transport scenarios. The datasets used in the life cycle inventory originate from different sources. Datasets for the production of aircraft and the construction, maintenance and decommissioning of airport infrastructures are from the ecoinvent v3.9.1 "cut-off by classification" database [29]. Similarly, datasets for the production of kerosene are obtained from the ecoinvent database. Two types of SAFs are considered here: biofuels from forestry residues and electrofuels from hydrogen electrolysis and Direct Air Capture (DAC), both produced via the Fischer-Tropsch synthesis process. For the production of SAFs, the datasets from premise are used, with an allocation of the synthesis burdens based on the respective energy content of the co-products (diesel, kerosene, naphtha and lubricating oils and waxes). The original dataset for the production of electrofuels has been modified to adjust the share of grid electricity and dedicated photovoltaic electricity in the industrial processes. For this purpose, a parameter was introduced into the LCA model to set the electricity mix. Due to the load factor of the photovoltaic power plant, the electrolyzers and direct air capture systems involved in the production of electrofuel are oversized to handle the power peaks. It is assumed that the oversizing is inversely proportional to the load factor. Finally, the emissions resulting from the combustion of fuels during aircraft operation are obtained from literature values. A direct emission factor of 74.0 gCO₂ per MJ of fuel is used [42]. Emission indices, in kilogram of pollutants produced by the combustion of one kilogram of fuel, are provided by AeroMAPS based on [43] for nitrogen oxides (NO_x), sulfur oxides (SO_x) and soot. In particular, the emission index of soot is assumed 80% lower for biofuel and electrofuel compared to fossil kerosene, and no emission of sulfur oxides is considered for alternative fuels. Emission indices for non-methane volatile organic compounds (NMVOC) and dinitrogen oxides (N₂O) are obtained from [44, 45]. For fossil kerosene, heavy metals emissions are also considered [44, 46]. Finally, the combustion processes of biofuels and electrofuels are adjusted for CO₂, CH₄ and CO to reflect their biogenic nature, which is justified by the short rotation period of the feedstocks [47]. All emissions

are assumed to occur during flight, in the upper troposphere and lower stratosphere (below 9000 m of altitude), although future work may distinguish ground emissions that occur near airports and propose new LCIA methods for emissions in flight.

The background datasets are scaled to the foreground system with time-dependent parameters representing the number of aircraft produced, energy consumption and total number of revenue passenger kilometres (RPKs) travelled between airports. The parameters of the LCA model considered in this paper are described in Table 1.

Table 1 – Parameters involved in the LCA model.

	Parameter	Type	Unit	Description
Background	iam_model	string	-	IAM model to use
	iam_scenario	string	-	IAM scenario (SSP and RCP)
	year	integer	-	Year of projection
	elec_photovoltaic_share	percentage	-	Share of photovoltaic vs. grid electricity for electrofuel production
Foreground	elec_photovoltaic_load_factor	percentage	-	Load factor of photovoltaic power station
	aircraft_production_long_range	float	-	Number of long-range aircraft produced
	aircraft_production_medium_range	float	-	Number of medium-range aircraft produced
	aircraft_production_short_range	float	-	Number of short-range aircraft produced
	emission_index_nox_biofuel	float	kg_{NO_x}/kg_{fuel}	NO_x emission index for biofuel
	emission_index_nox_electrofuel	float	kg_{NO_x}/kg_{fuel}	NO_x emission index for electrofuel
	emission_index_nox_kerosene	float	kg_{NO_x}/kg_{fuel}	NO_x emission index for kerosene
	emission_index_soot_biofuel	float	kg_{BC}/kg_{fuel}	Soot emission index for biofuel
	emission_index_soot_electrofuel	float	kg_{BC}/kg_{fuel}	Soot emission index for electrofuel
	emission_index_soot_kerosene	float	kg_{BC}/kg_{fuel}	Soot emission index for kerosene
	emission_index_sulfur_biofuel	float	kg_{SO_x}/kg_{fuel}	Sulfur emission index for biofuel
	emission_index_sulfur_electrofuel	float	kg_{SO_x}/kg_{fuel}	Sulfur emission index for electrofuel
	emission_index_sulfur_kerosene	float	kg_{SO_x}/kg_{fuel}	Sulfur emission index for kerosene
	energy_consumption_biofuel	float	MJ	Biofuel consumption
	energy_consumption_electrofuel	float	MJ	Electrofuel consumption
	energy_consumption_kerosene	float	MJ	Kerosene consumption
	rpk_long_range	float	RPK	Long-range Revenue Passenger Kilometre
	rpk_medium_range	float	RPK	Medium-range Revenue Passenger Kilometre
	rpk_short_range	float	RPK	Short-range Revenue Passenger Kilometre

The data presented here serve as a preliminary basis to support the prospective LCA of air transport. Future work should focus on improving the collection and quality of this data to ensure the completeness, consistency and accuracy of the assessment.

4. Applications

This section illustrates the relevance of the methodology by assessing and comparing three scenarios for the future development of the aviation sector. The assumptions and choices underlying the case study are presented below. The results obtained for the three scenarios are then presented. An analysis is also carried out to explore the sensitivity of the environmental impacts to the electricity mix used for the production of electrofuels and the underlying IAM scenarios. Finally, the main findings and limitations of the study are discussed.

4.1 Assumptions and Choices

All three scenarios share a common evolution of air traffic, aircraft fleet and operations. Specifically, the air traffic follows an annual growth of +3% for both passenger and freight markets. The average load factor is improved to reach 85% in 2050. It is assumed that new aircraft architectures for short-medium range (SMR) and long range (LR) will enter into service in 2035, enabling a 20% reduction in energy consumption per seat per kilometre. Operational improvements are also included, allowing a reduction in energy consumption per seat-kilometre of around 6% between 2020 and 2050.

The energy mix consumed by the aircraft fleet varies from one scenario to the other. In the first scenario, only kerosene derived from fossil petroleum is considered. Scenarios 2 and 3 explore the implementation of blending mandates for SAFs from 2025 to 2050 at the global scale, inspired by

the ReFuelEU Aviation initiative [48]. For instance, it is assumed that 35% of biofuels and 35% of electrofuels are used in 2050. The third scenario differs from the second in that only photovoltaic electricity is used to produce synthetic kerosene instead of the grid electricity mix for the second scenario. A load factor of 14% is taken for the photovoltaic power production.

In all three scenarios, the shared socio-economic pathway SSP2, also called middle of the road (i.e. where the world trends follow their historical patterns), is assumed with a baseline no-climate-policy at a global level [35, 36]. The pathway is modelled using the IAM REMIND v3.0 [33], with a 10-year time step. Finally, the environmental impacts are evaluated with the ReCiPe 2016 v1.03 LCIA methods [38], both at the midpoint (18 indicators) and endpoint (3 indicators) levels, with a "hierarchist" approach. The assumptions underlying the three scenarios and their evaluation are summarised in Table 2.

Table 2 – Scenarios evaluated in the case study.

	Scenario 1	Scenario 2	Scenario 3
Air traffic	3% annual air traffic growth		
Fleet & operations	Trend fleet renewal introducing new SMR and LR architectures in 2035 with a 20% reduction in energy consumption per seat-kilometre Operational gains of 6.1% between 2020 and 2050 at the fleet level Average load factor increase from 82.4 to 85% until 2050		
Energy mix	100% fossil kerosene	ReFuelEU mandate with biofuels from forestry residues and electrofuels with H ₂ from electrolysis with grid electricity mix	electrofuels with H ₂ from electrolysis with photovoltaic electricity
Socio-economic scenario and global climate policy	SSP2 "middle of the road" without global climate policy (modelled with REMIND v3.0)		
LCIA methods	ReCiPe 2016 v1.03 (18 midpoint indicators, 3 endpoints indicators)		

4.2 Results

The environmental impacts for the three scenarios are presented in Figures 3 to 8, and in Appendices A to C. Specifically, this section only provides the results for a selection of three midpoint indicators and for the endpoints. The remaining midpoint indicators are detailed in the Appendices. A direct comparison of the scenarios through a coupled midpoint-endpoint analysis is also provided.

Scenario 1

In Scenario 1, environmental pressure increases across all categories in 2050 compared to 2020. In line with the academic literature [20, 23, 49, 50], climate change is mainly driven by the production and combustion of fossil kerosene. This result holds for most of the environmental impacts, with varying rankings of importance. Airport facilities also play an important role in some categories, such as land use.

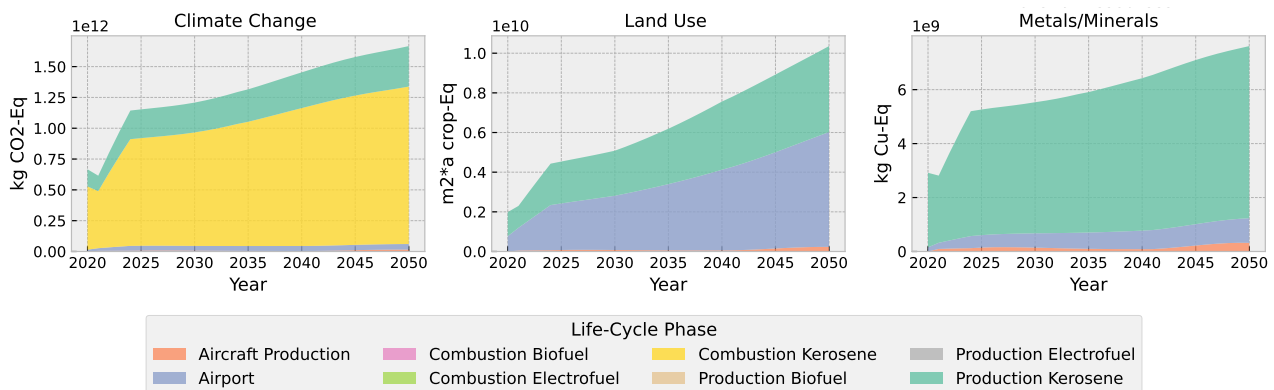


Figure 3 – Environmental impacts for Scenario 1 across three midpoint categories: climate change, land use, and material resource use.

At the endpoint level, similar to climate change, kerosene combustion is the main contributor to the degradation of ecosystem quality and human health. Finally, raw material extraction and manufacturing processes for aircraft production play a minor role in most environmental categories. However, improving the representativeness of the data, e.g. by characterising more precisely certain aircraft grade materials, could lead to an increase in the importance of this life cycle phase.

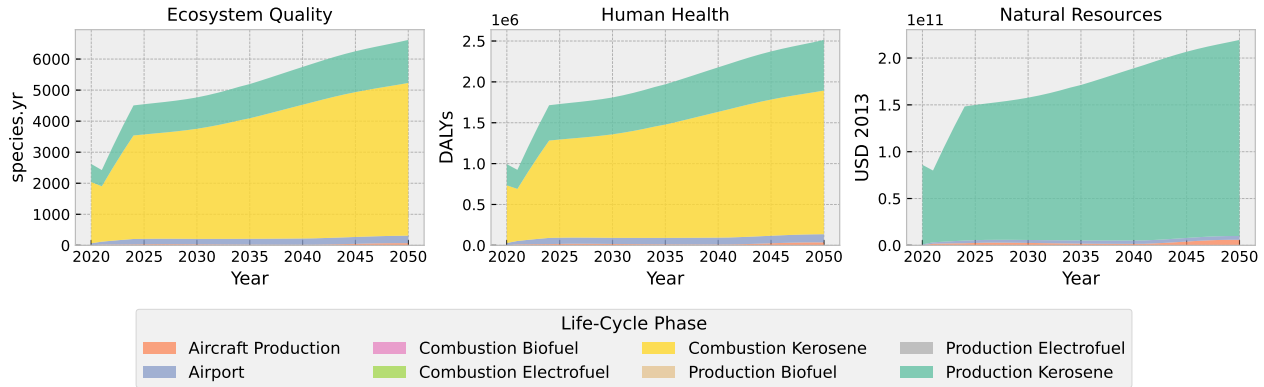


Figure 4 – Environmental impacts for Scenario 1 at endpoint level: ecosystem quality, human health, and natural resources.

Scenario 2

Compared to Scenario 1, the results for Scenario 2 indicate that replacing fossil kerosene with the considered alternative fuels does not lead to a reduction in all environmental impacts over the next decades. Indeed, the replacement of fossil kerosene with alternative fuels shifts the impacts to the upstream phases, i.e. their production. Specifically, whereas biofuels from forestry residues allow for a substantial reduction in climate change impacts, they increase the pressure on land use. The same phenomena can be observed for electrofuels produced using global grid electricity, but the benefits in terms of climate change impacts are limited due to the use of relatively carbon-intensive electricity. Overall, at the endpoint level, replacing fossil kerosene with electrofuels does not allow for a significant reduction of the burdens, except for the depletion of natural resources.

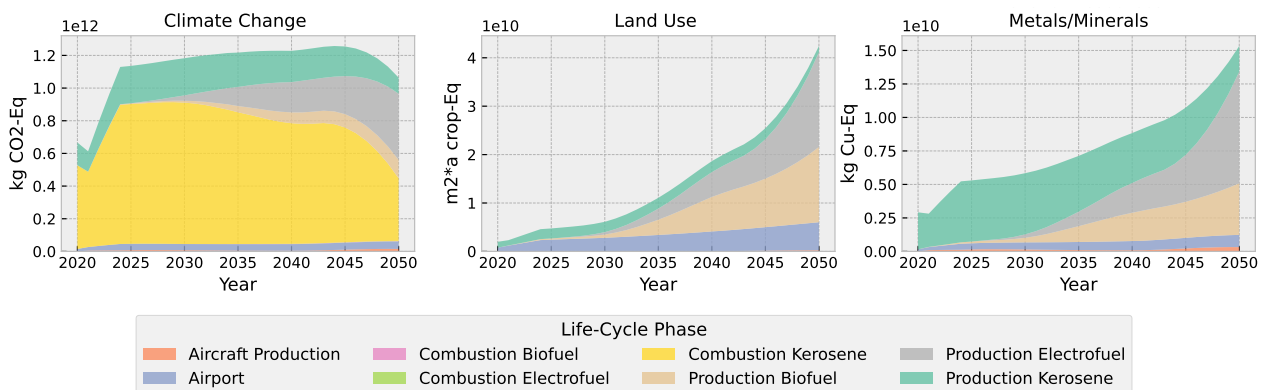


Figure 5 – Environmental impacts for Scenario 2 across three midpoint categories: climate change, land use, and material resource use.

Scenario 3

The use of electrofuels produced by means of photovoltaic electricity limits the environmental impacts in Scenario 3 as compared to Scenario 2. At the midpoint level, impacts on climate change are fairly stable up to 2045, and the massive deployment of electrofuels thereafter allows for a non-negligible reduction. However, some indicators such as land use and material resources remain higher than with fossil kerosene. Scenario 3 achieves the greatest reduction in endpoint damages when com-

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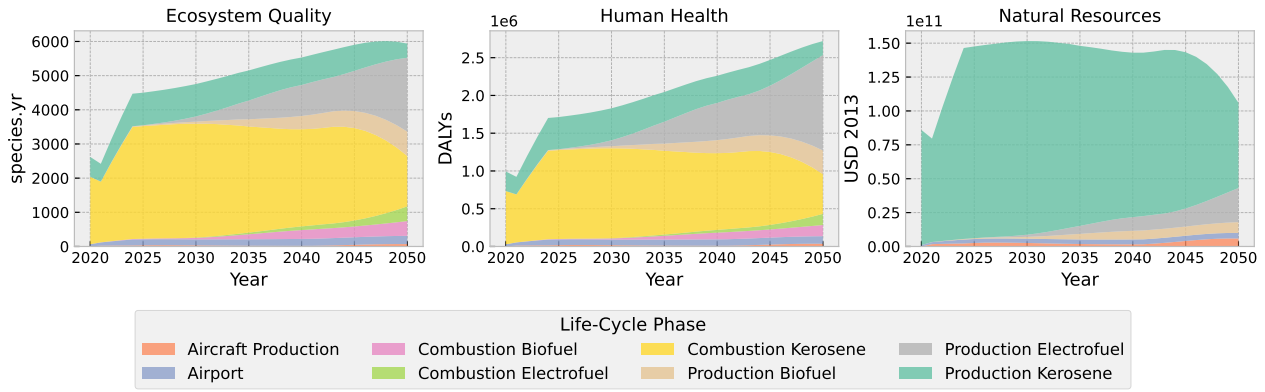


Figure 6 – Environmental impacts for Scenario 2 at endpoint level: ecosystem quality, human health, and natural resources.

pared to Scenarios 1 and 2. Nevertheless, as in the other scenarios, ecosystem quality and human health are more severely affected in 2050 than in 2025.

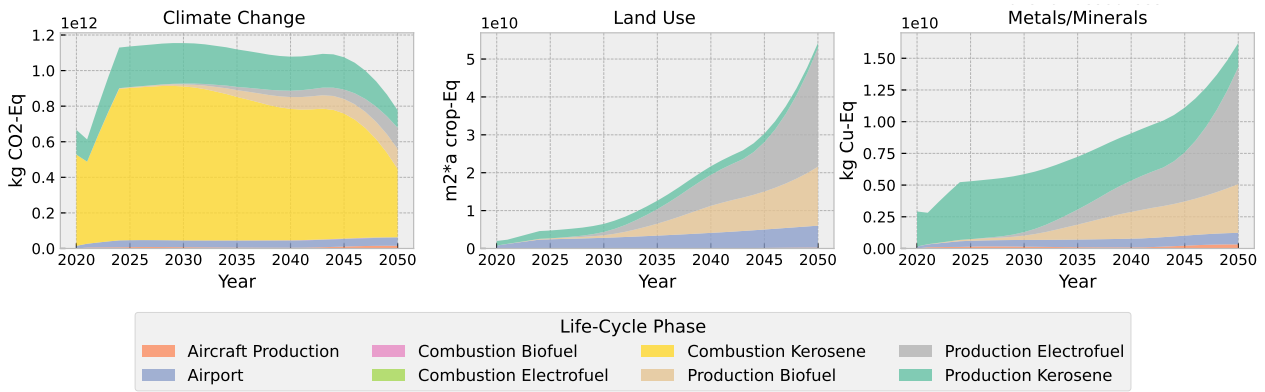


Figure 7 – Environmental impacts for Scenario 3 across three midpoint categories: climate change, land use, and material resource use.

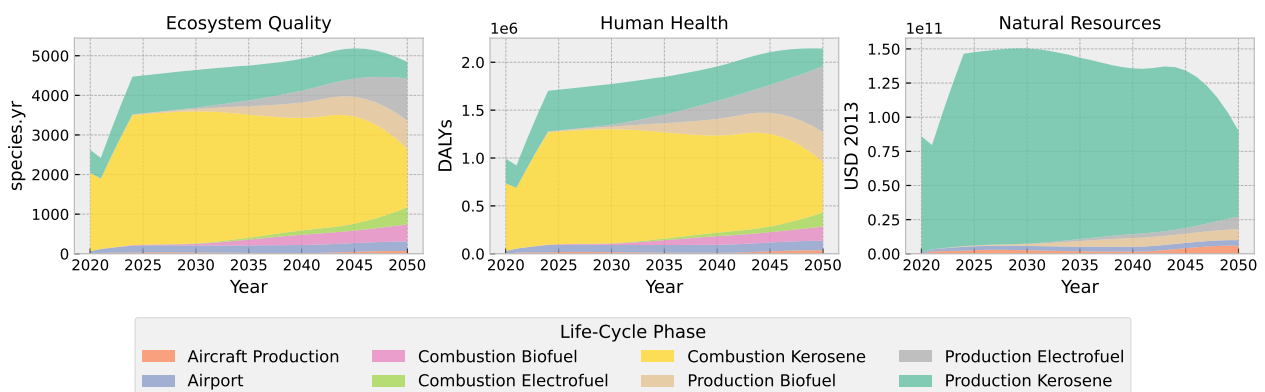


Figure 8 – Environmental impacts for Scenario 3 at endpoint level: ecosystem quality, human health, and natural resources.

Comparison

To facilitate comparison of the three scenarios, the results at the endpoint level for the year 2050 are presented in Figure 9. For each endpoint indicator, the results are normalised to those of Scenario 1. As mentioned previously, Scenario 3 results in the lowest environmental impact. Paradoxically, Scenario 2 generates more impacts on human health than Scenario 1. Regarding the contribution of

midpoint impacts to the endpoints, climate change is the main contributor to ecosystem quality. Interestingly, the contribution of land use increases in Scenarios 2 and 3, because of the electricity production facilities. For human health, climate change is also the main contributor in Scenario 1, followed by the formation of particulate matter. The latter becomes the first contributor to the damage on human health in the two other scenarios because of electricity production. However, the share of particulate matter formation due to the combustion of alternative fuels could be refined in future work to improve the reliability of the results. Finally, natural resources are largely impacted by non-renewable, fossil energy resources, whereas the contribution of material resources remains marginal.

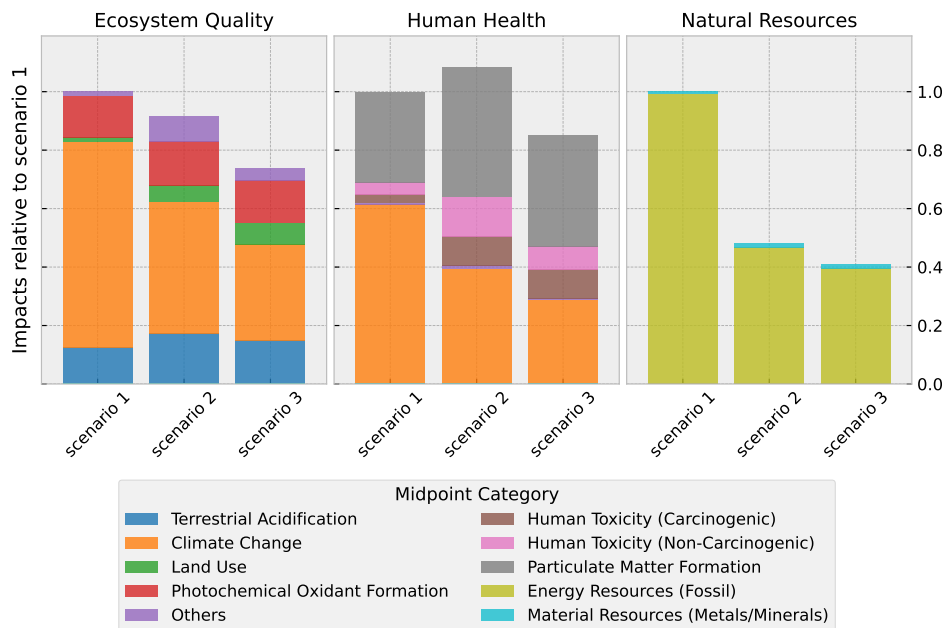


Figure 9 – Endpoint damages for the three scenarios in 2050 (normalised on Scenario 1), with the contribution of midpoint impacts.

4.3 Sensitivity Analyses

To investigate the influence of the background parameters, two sensitivity analyses are proposed. First, the sensitivity of the environmental impacts to the electricity mix used for the production of electrofuels is explored. Results are given in Figures 10 and 11. Scenario 2 corresponds to the case with a 0% share of photovoltaic (i.e. electricity from the grid only), while Scenario 3 corresponds to the case with a 100% share of photovoltaic. Values for Scenario 1, independent of the electricity mix in this study, are also provided for comparison. As mentioned previously, a 100% dedicated photovoltaic for producing electrofuels results in less impacts at the endpoint level, but increases pressure in some midpoint categories such as land use. Interestingly, an optimal share of dedicated photovoltaic is observed on some midpoint or endpoint indicators (e.g. material resources and human health). This is due to the oversizing of the electrofuel production plants, which is inversely proportional to the share of photovoltaic. Note that this does not take into account the possible interaction between the electricity grid and photovoltaic power to smooth out power peaks and therefore minimise the need to oversize the electrofuel facilities. Finally, while Scenario 2 shows a higher impact on human health in 2050 compared to Scenario 1, the substitution of one fifth of grid electricity with photovoltaic power for the production of electrofuels balances the impacts between the two scenarios.

Secondly, the sensitivity to the Shared Socio-economic Pathways (SSPs) and climate trajectories (RCPs) modelled by REMIND is examined. In addition to the baseline scenario – SSP2 without global climate policy, two other scenarios are considered: SSP1-RCP2.6 and SSP2-RCP2.6. The narrative for SSP1 reflects a world of sustainability-focused growth and equality [35]. For both SSP1-RCP2.6 and SSP2-RCP2.6, the socio-economic pathway is combined with climate mitigation policies

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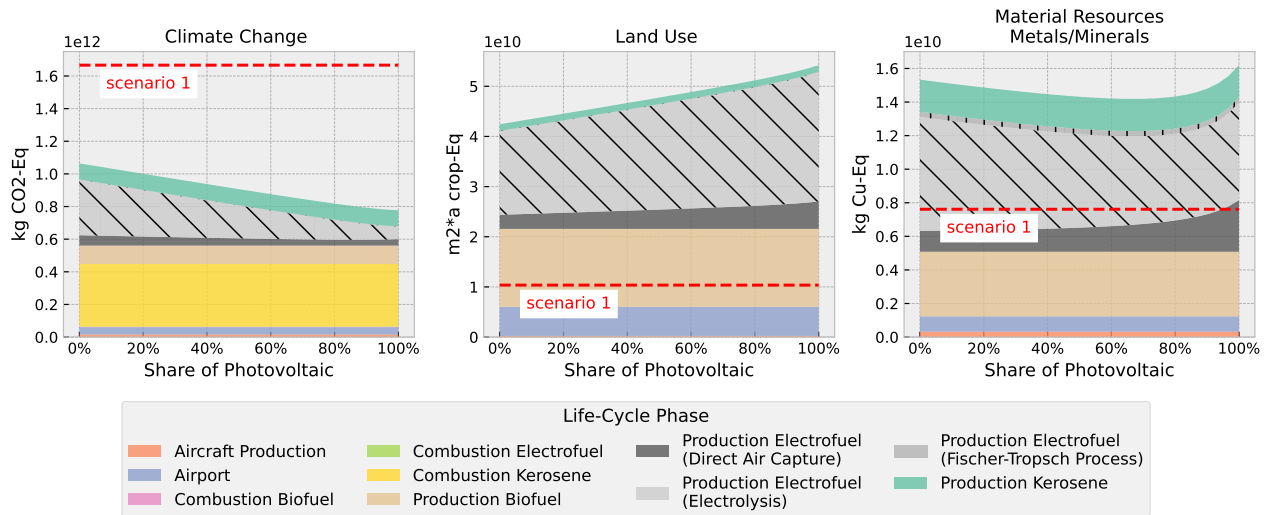


Figure 10 – Sensitivity of climate change, land use, and material resource use to the share of photovoltaic in the electricity mix, with the ReFuelEU mandate, in 2050.

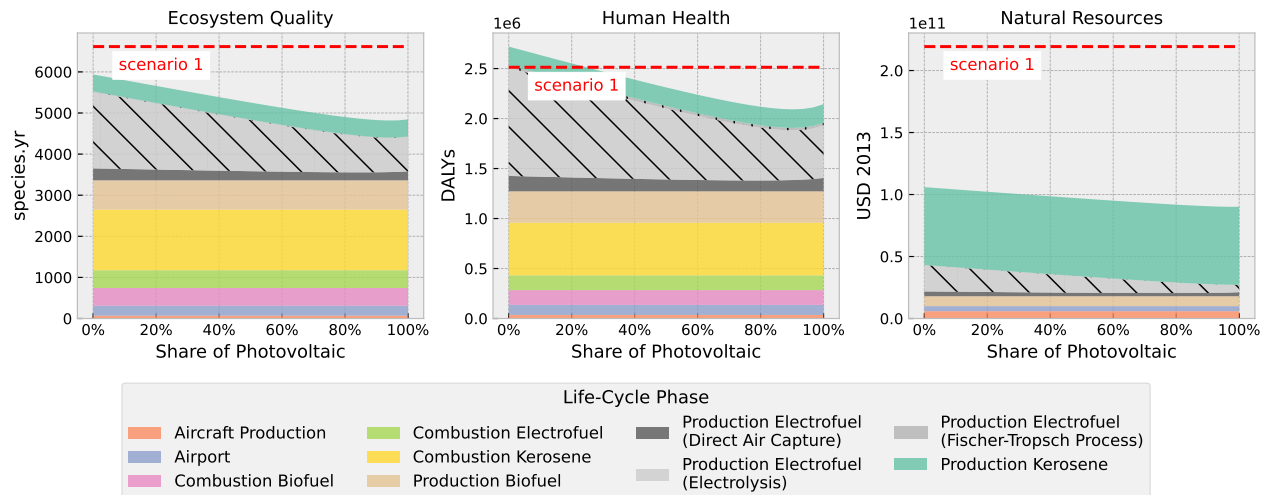


Figure 11 – Sensitivity of endpoint impacts to the share of photovoltaic in the electricity mix, with the ReFuelEU mandate, in 2050.

in line with the Paris Agreement (RCP forcing levels of 2.6 W/m^2). For the purpose of the analysis, Scenario 2 is considered in the following to model the transition at the level of the aviation sector. Figures 12 and 13 provide the results at the midpoint and endpoint level respectively. As expected, the effect of climate mitigation measures is clearly visible on climate change. Similar observations were found in several other midpoint indicators, such as particulate matter formation and terrestrial acidification. This is mainly due to the development of low-carbon electricity in RCP2.6 scenarios. Overall, the three endpoint damages are significantly reduced when implementing ambitious climate policies. The results are less sensitive to the socio-economic pathway. Although it might have been expected that the impacts would be lower in a world driven by SSP1 than by SSP2, the projected impacts are quite similar. This has to be put into perspective with the developments underlying the different SSPs. In SSP1, climate targets are largely met by lowering consumption growth in a number of human activities. However, in the present study, the assumptions underlying the development of the aviation sector are decoupled from the SSPs, e.g. regarding the growth of air traffic. Future work should therefore take into account the consistency between the development of the aviation sector and the world evolution.

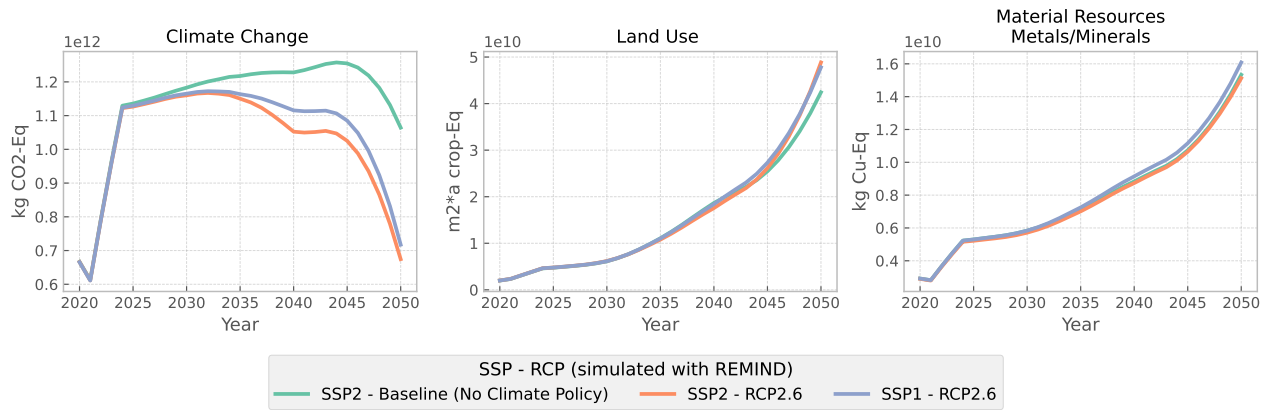


Figure 12 – Environmental impacts for Scenario 2 for different SSPs and climate mitigation targets across three midpoint categories: climate change, land use, and material resource use.

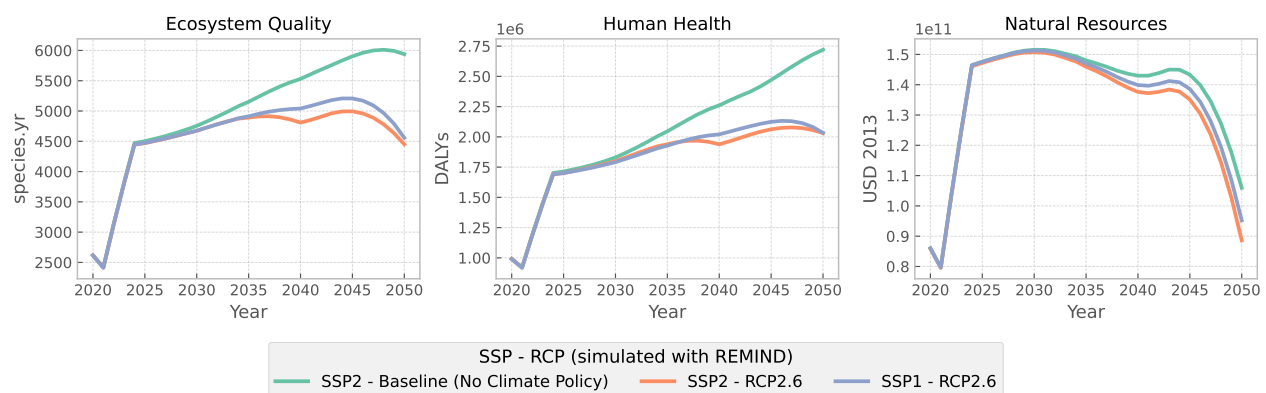


Figure 13 – Environmental impacts for Scenario 2 for different SSPs and climate mitigation targets at endpoint level: ecosystem quality, human health, and natural resources.

4.4 Discussions

The replacement of fossil kerosene by SAFs is an option being considered by many stakeholders in the aviation sector. However, such a decision must take into account the necessary interaction between air transport and the other sectors that support the transition. The case study presented above shows that despite the introduction of biofuels and electrofuels, the impact of air transport on several environmental indicators is hard to abate. Without delving into the specifics of biofuels production, the case study presented above shows that careful consideration must be given to the production pathway of electrofuels. The evolution of the electricity mix used in hydrogen electrolysis and DAC is of significant importance. An electricity mix supported by coal, oil and gas sources is not able to substantially reduce the impacts on ecosystem quality and human health. Specifically, the so-called "burden shifting" is illustrated by increases in particulate matter formation, land use and human toxicity as climate change is mitigated. This results in a trade-off that may adversely affect the areas of protection (human health, ecosystem quality, and natural resources), as observed for the increase in human health impacts in Scenario 2. It is therefore necessary to assess the extent to which some key variables can be adjusted to steer the air transport system towards a more sustainable trajectory. An example of a sensitivity analysis on the electricity mix is presented here to quantify how the use of dedicated photovoltaic plants could enable a reduction in environmental damages. This analysis could be generalised to identify the main parameters driving the evolution of the aviation sector and its environmental impacts, including additional energy carriers, improvements in aircraft technology and efficiency, and air traffic demand, among others. Finally, although global changes in the world over the next few decades may appear to be beyond the scope of the aviation industry decisions, it is important to assess the extent to which changes in society and climate policy could affect the

sector's environmental impact, all other things being equal. Such an analysis enables anticipation of strategies that should be adopted in connection with other human activities, particularly since the transformation of the aviation sector is heavily dependent on the transformation of the energy industry.

5. Conclusions and Perspectives

This paper presents a comprehensive methodology for integrating prospective LCA methods into the AeroMAPS framework to assess future air transport scenarios. In addition to the current AeroMAPS modules, this methodology is based on various frameworks such as Brightway, lca-algebraic and premise. The results highlight the significant environmental impacts associated with current and future air transport practices, particularly concerning the adoption of SAFs. Despite their potential benefits, the analysis underscores the importance of considering the entire energy production pathway to avoid burden-shifting and unintended environmental trade-offs. Key findings from the case study suggest that the transition to more sustainable aviation requires careful planning and significant adjustments in the energy sector, particularly in the adoption of renewable energy sources for electrofuel production. Additionally, the study reveals that current aircraft production practices are not significant contributors to the environmental impacts. However, future studies should include recycling, specific aircraft-grade material quality, and new hybrid-electric architectures to better assess this phase.

By combining multiple frameworks for modelling the aviation sector and its interaction with other industries and the environment, the proposed methodology enables the exploration and evaluation of a range of scenarios. Such a scenario exploration plays a pivotal role in understanding the potential variability in environmental impacts. Overall, this research provides valuable insights for policymakers and industry stakeholders to develop more effective strategies for reducing the environmental impact of aviation.

Future research work in this direction should address the following limitations and opportunities. First, improving the completeness and accuracy of the inventory, for instance by enhancing data collection and covering all the aviation mitigation levers of action (e.g. other alternative fuels, new aircraft architectures, offsetting mechanisms) is a challenge for carrying out exhaustive life cycle assessments. Then, advanced sensitivity and uncertainty analyses would enable the identification of the key parameters influencing the environmental impacts of aviation. Similarly, comparing multiple LCIA methods could be beneficial for capturing a wide range of environmental effects and ensuring the robustness of the results. These methods could also be improved to include the non-CO₂ effects of aviation, which are not covered in this paper, in particular regarding climate change impact. Lastly, it would be of great interest to combine these environmental approaches with socio-economical ones to enable holistic analyses of transition scenarios for air transport.

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Appendix

A Environmental Impacts at Midpoint Level for Scenario 1

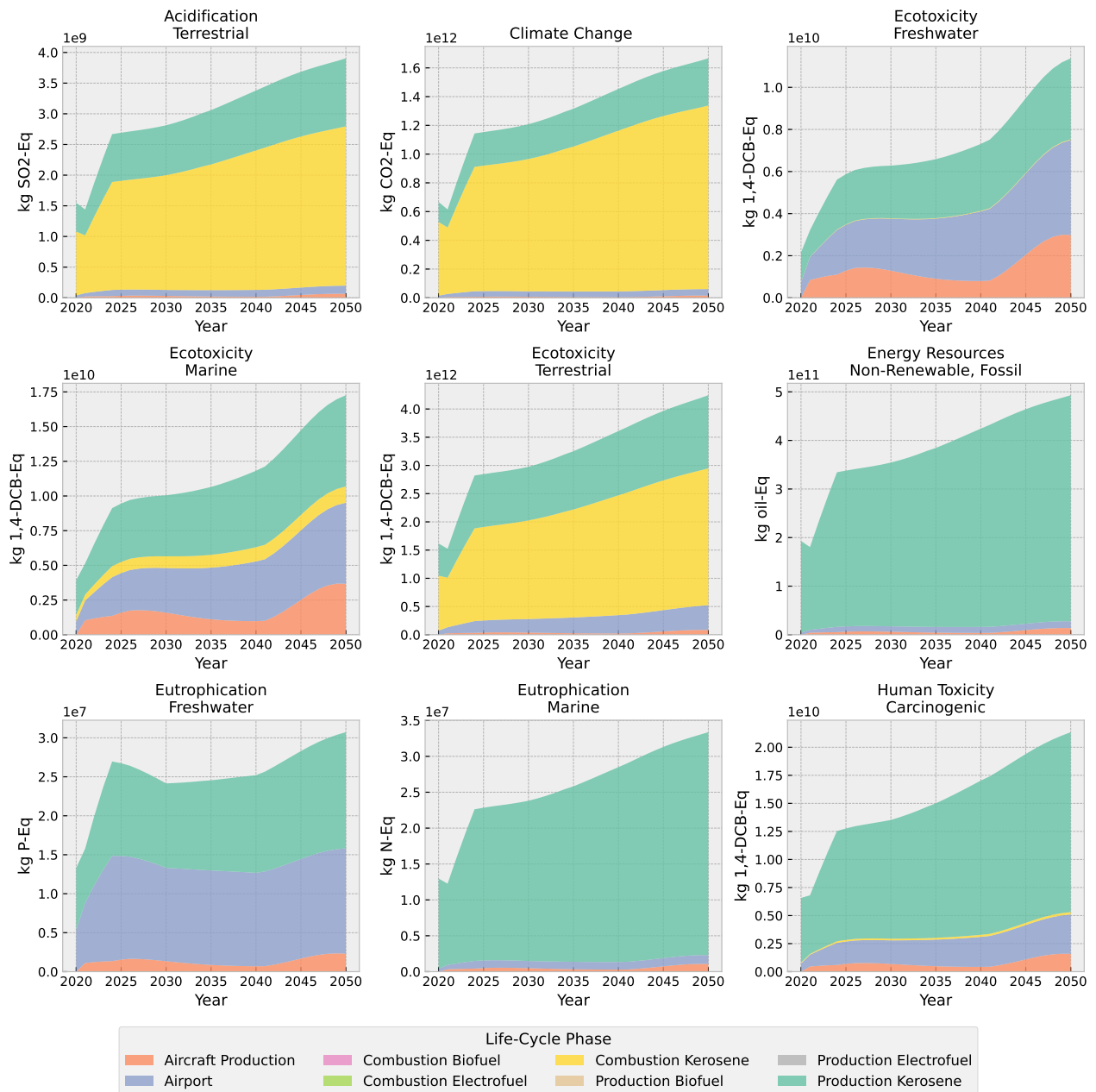


Figure 14 – Environmental impacts for Scenario 1 at midpoint level.

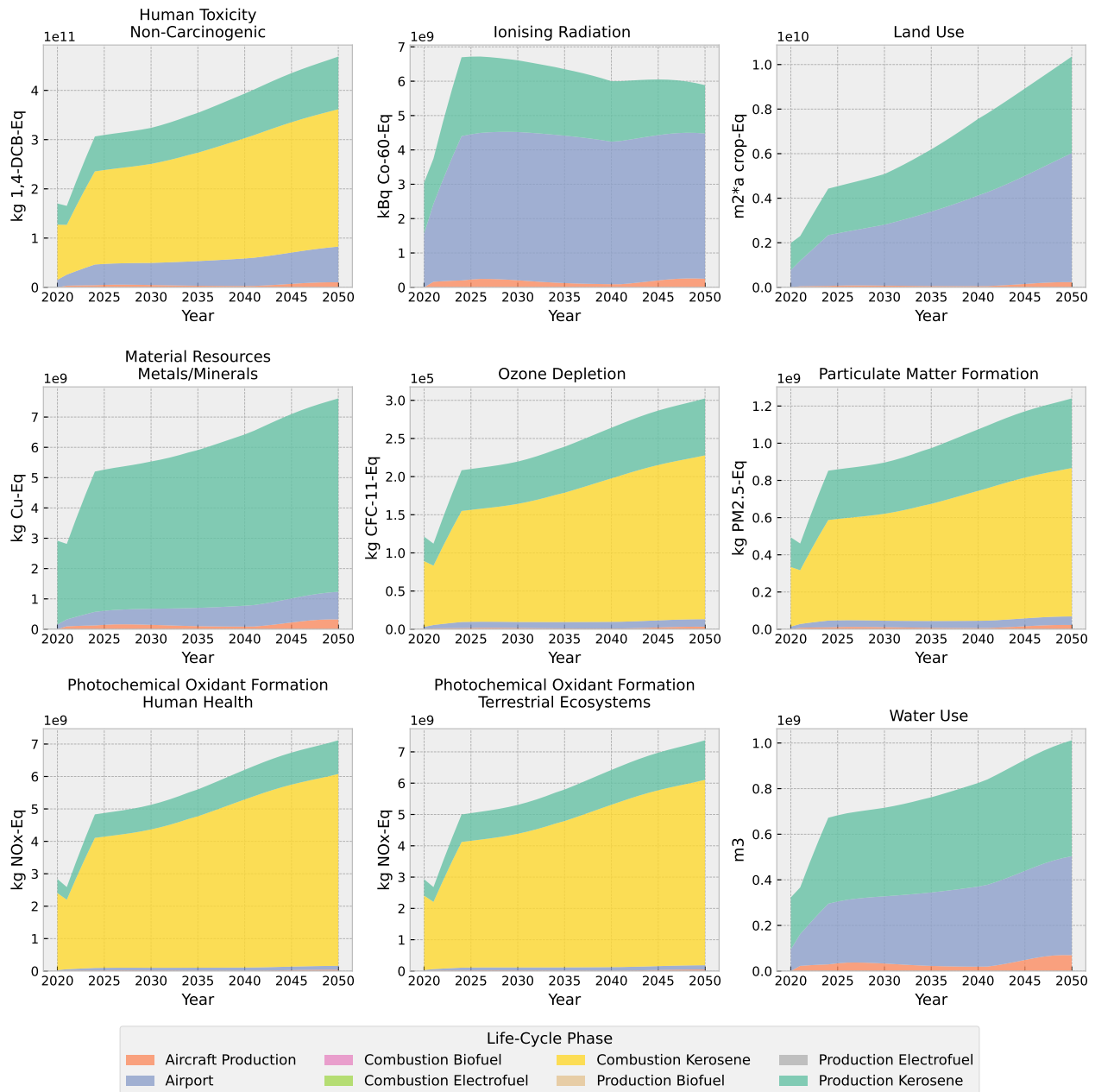


Figure 15 – Environmental impacts for Scenario 1 at midpoint level (continued).

B Environmental Impacts at Midpoint Level for Scenario 2

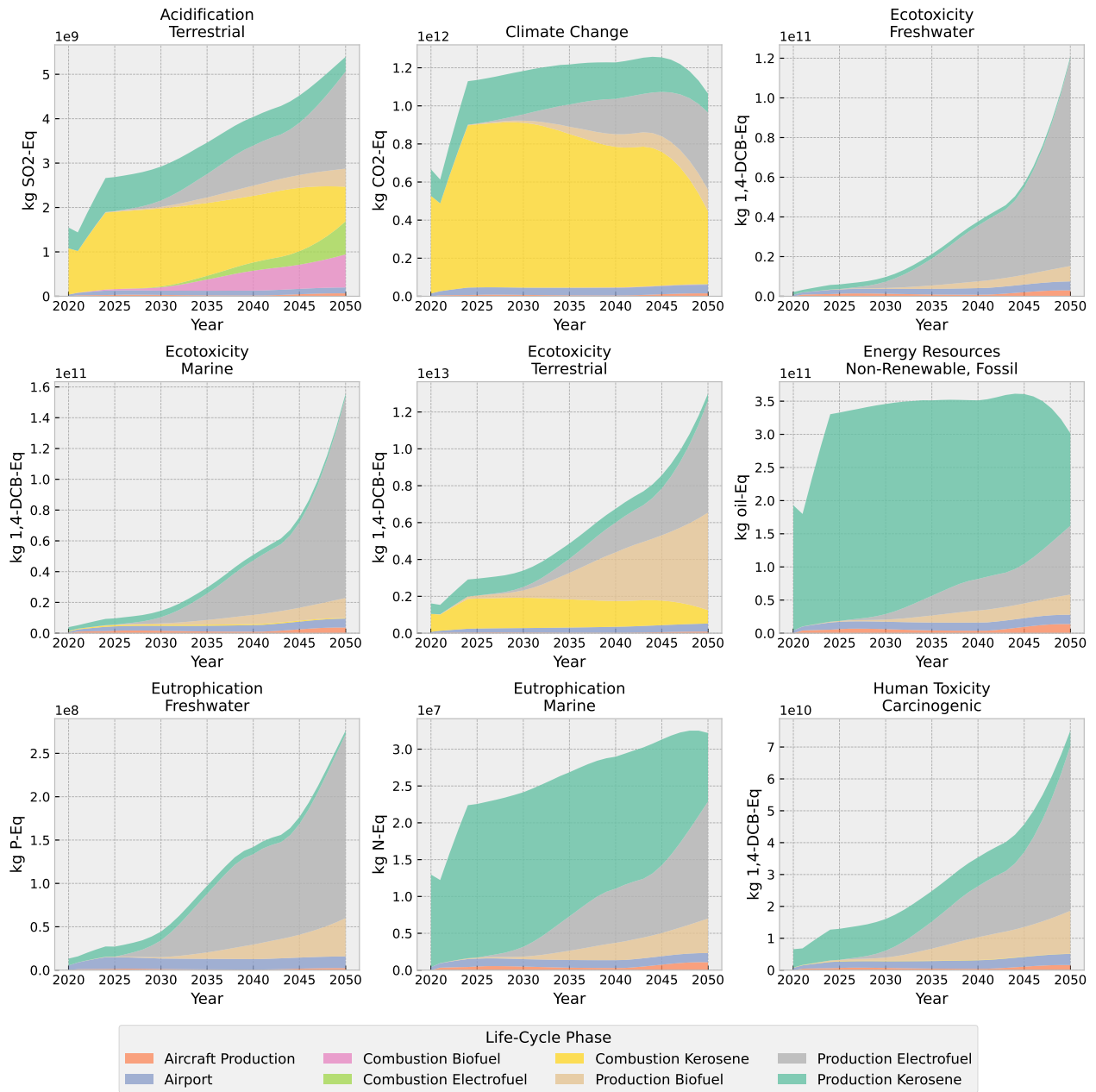


Figure 16 – Environmental impacts for Scenario 2 at midpoint level.

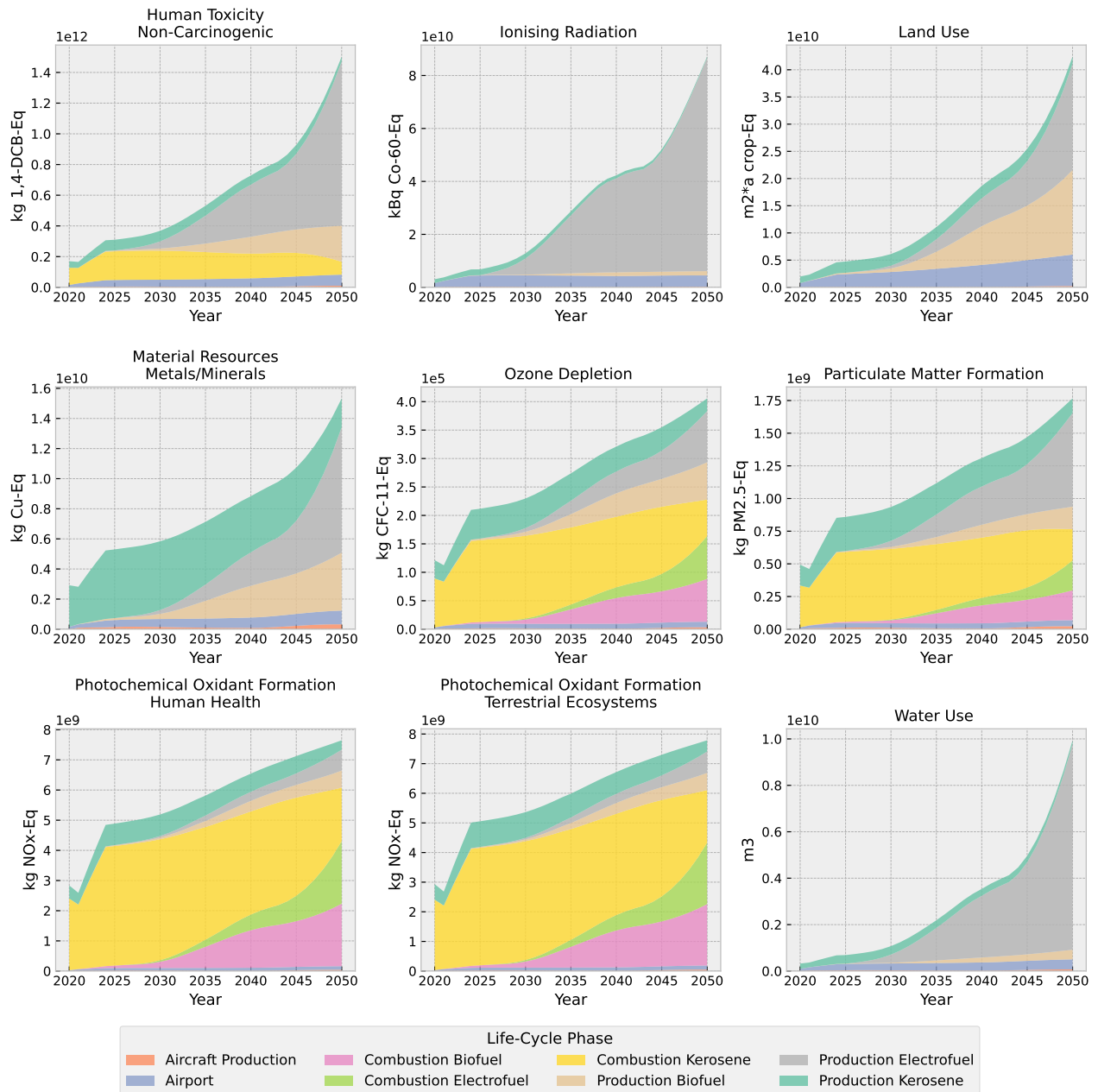


Figure 17 – Environmental impacts for Scenario 2 at midpoint level (continued).

C Environmental Impacts at Midpoint Level for Scenario 3

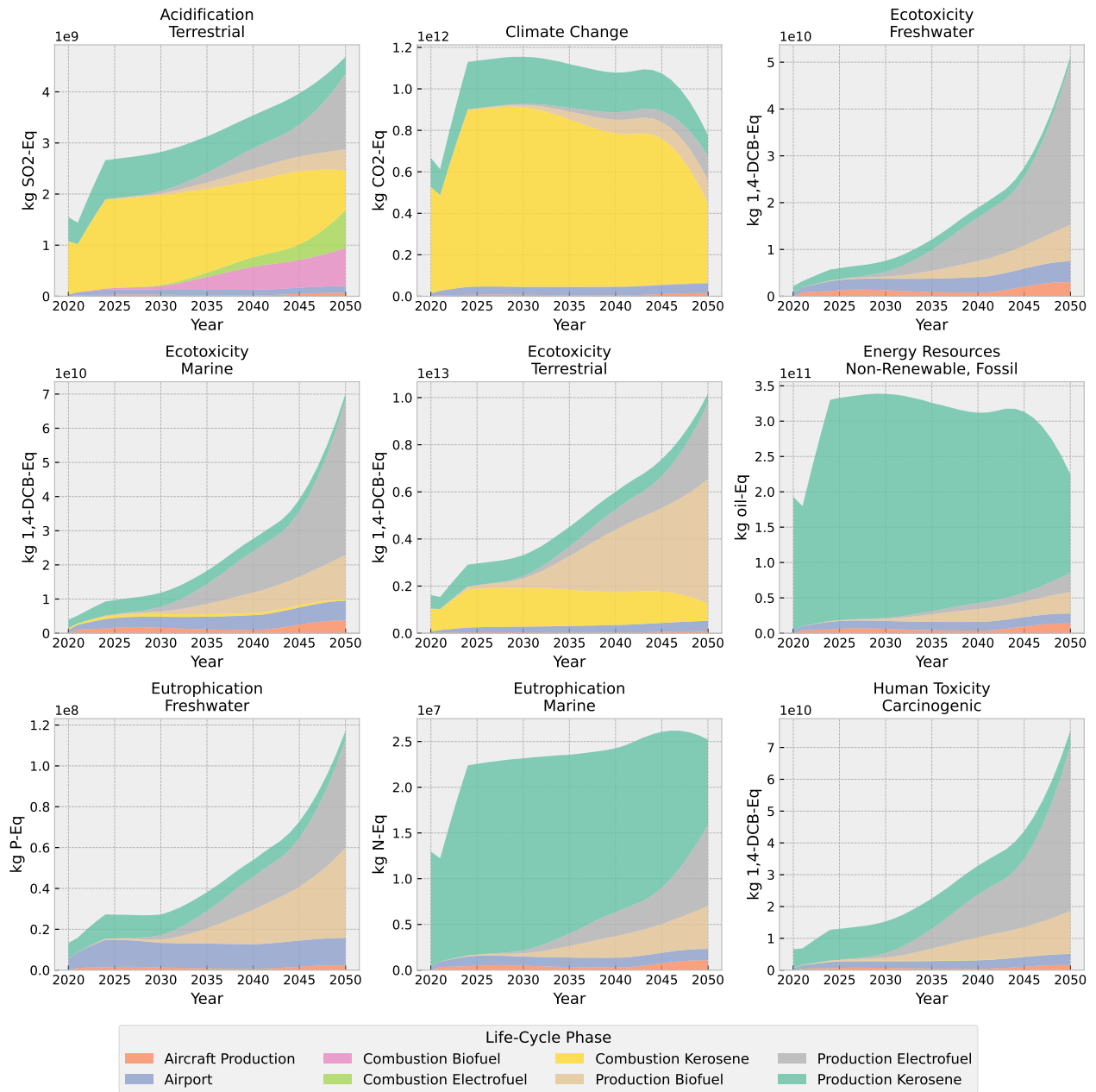


Figure 18 – Environmental impacts for Scenario 3 at midpoint level.

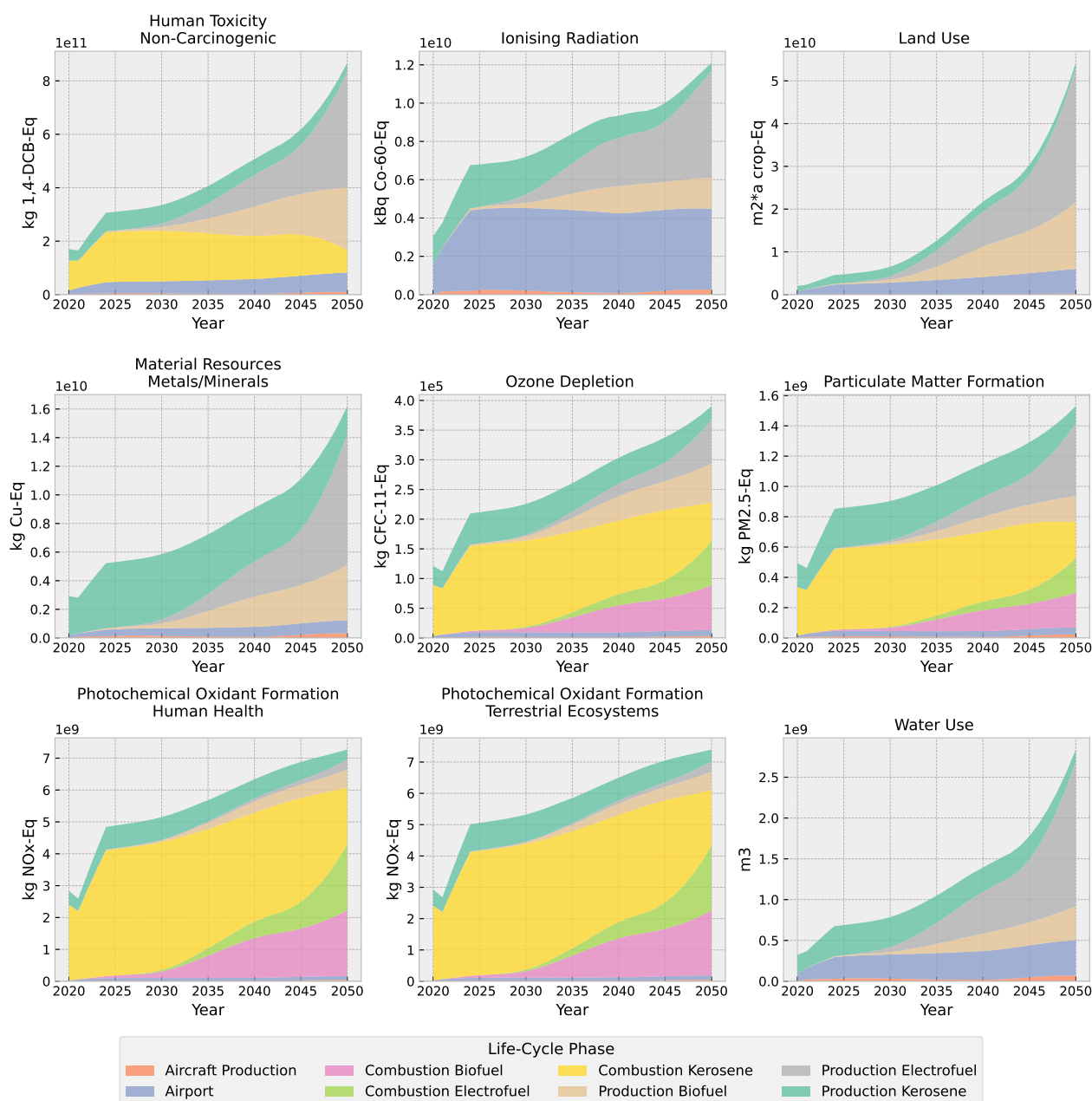


Figure 19 – Environmental impacts for Scenario 3 at midpoint level (continued).

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