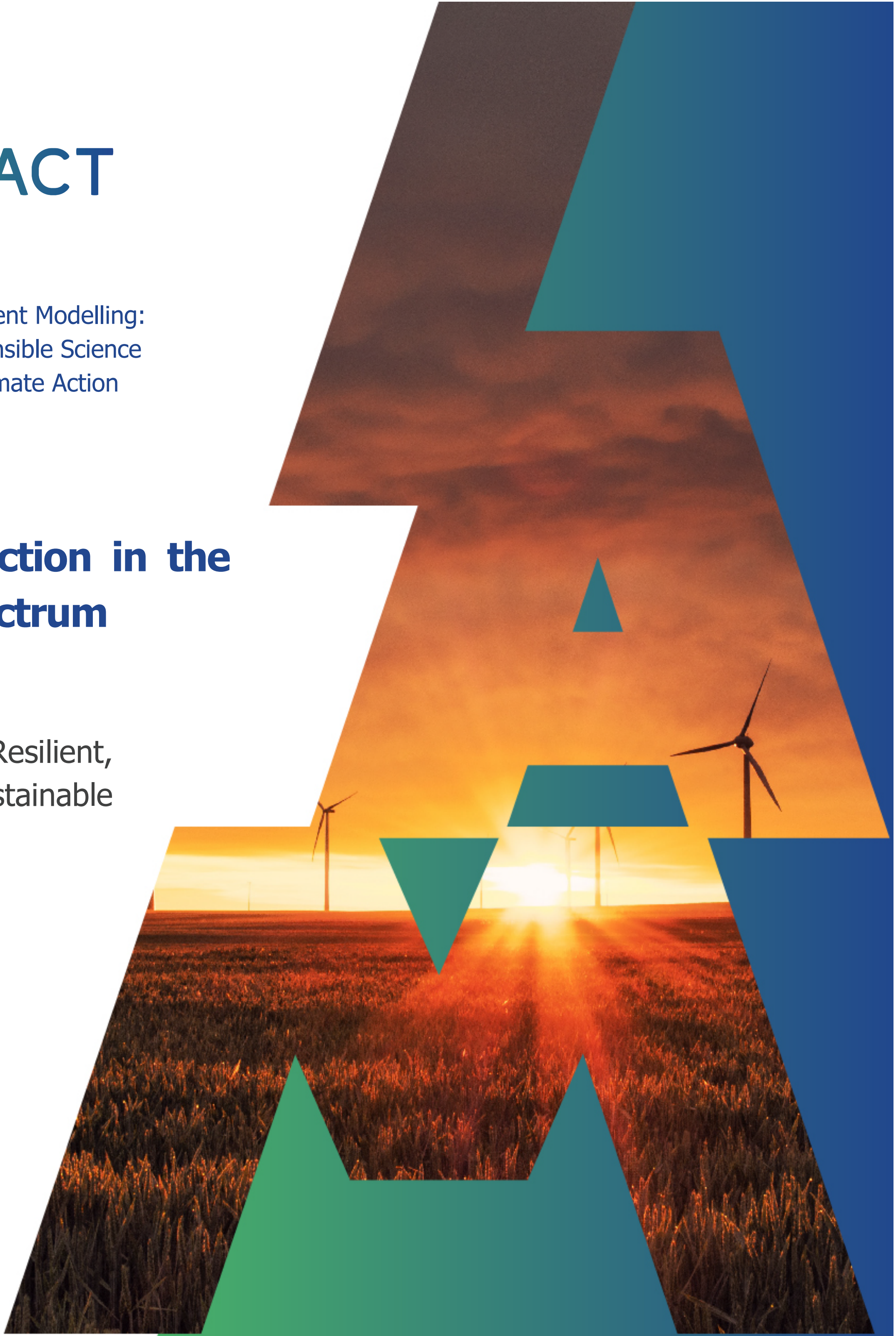
IAM COMPACT

Expanding Integrated Assessment Modelling:
Comprehensive and Comprehensible Science
for Sustainable, Co-Created Climate Action



D5.8 - Climate action in the sustainability spectrum

WP5 Expanding – Resilient, inclusive, and sustainable recovery and development

31/05/2024

Funded by
the European Union

www.iam-compact.eu

Disclaimer

Copyright Message

Grant Agreement Number	101056306		**Acronym**	IAM COMPACT
Full Title	Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action			
Topic	HORIZON-CL5-2021-D1-01-04			
Funding scheme	HORIZON EUROPE, RIA – Research and Innovation Action			
Start Date	September 2022		**Duration**	36 Months
Project URL	https://www.iam-compact.eu			
EU Project Advisor	Andreas Palialexis			
Project Coordinator	National Technical University of Athens – NTUA			
Deliverable	D5.8 - Climate action in the sustainability spectrum			
Work Package	WP5 - Expanding – Resilient, inclusive, and sustainable recovery and development			
Date of Delivery	**Contractual**	31/05/2024	**Actual**	31/05/2024
Nature	Report		**Dissemination Level**	Public
Lead Beneficiary	National Technical University of Athens (NTUA)			
Responsible Author	Natasha Frilingou		**Email**	nfrilingou@epu.ntua.gr
	NTUA		**Phone**	+30 210 7723612
Contributors	Ilkka Keppo, Behzad Zamanipour [Aalto]; Adrián Mateo, Noelia Ferreras [CARTIF], Gonzalo Parrado Hernando, Luis Javier Miguel [UVa]; Alexandros Nikas, Konstantinos Koasidis [NTUA]; Russel Horowitz, Clàudia Rodés, Theo Rouhette, Iñaki Arto [BC3]			
Reviewer(s)	Conall Heussaff [Bruegel]; Dirk-Jan Van de Ven [BC3]; Adam Hawkes [Imperial]			
Keywords	climate policies; sustainability policies; integrated assessment models; clustering; policy types; policy modelling			

EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

The report will be used to guide consortium partners on how to assess the progress of Sustainable Development Goals (SDGs) in the IAM COMPACT modelling suite and reinforce modelling capacity to include biodiversity dimensions and uncertainty analysis of investments towards SDGs. It can also be beneficial to modelling teams and other researchers beyond the consortium, illustrating how decarbonisation can be achieved in conjunction with sustainability.

3. Short summary of results (<250 words)

The task associated with this report aims to provide sustainable decarbonisation pathways, including biodiversity, materials, and biophysical limits, as well as place climate action as a cross-cutting theme across the sustainability spectrum. It aligns climate action and sustainable development by assessing integrated co-benefits of climate-neutral pathways and policies targeting different SDGs. IAM-driven pathways have limited coverage of SDGs and are mostly focused on climate action, energy efficiency, industry, and infrastructure, while other environmental and social dimensions are rarely assessed. Thus, we analyse the capabilities of each IAM COMPACT model to represent SDGs, creating a suitable quantitative framework that facilitates their evaluation. We emphasise synergistic effects among SDGs, by detecting barriers to and co-benefits of specific goals, assessing model weaknesses and potential improvements to fill gaps and reinforce modelling capacity, and providing feedback on measures targeting multiple SDGs.

We then focus on models' capacity to analyse energy, land, and material resources, biophysical limits, aspects of global biodiversity conservation, and nature restoration. By developing a set of biodiversity indicators, a policy package is created to affect the indicators and produce scenarios that are simulated with the goal of gaining a deeper understanding of biodiversity, material resources, and biophysical limits.

Finally, we synthesise the previous sections and develop a multi-level integration of IAMs and uncertainty analysis with quantified implications for multiple SDGs. We draw from relevant SDG indicators extracted from IAMs, a novel multi-objective optimisation process, and stochastic multicriteria acceptability analysis.

4. Evidence of accomplishment

This report.

Funded by
the European Union

Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

NTUA – National Technical University of Athens	EL
Aalto – Aalto Korkeakoulusaatio SR	FI
AAU – Aalborg Universitet	DK
BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES
Bruegel – Bruegel AISBL	BE
CARTIF – Fundacion CARTIF	ES
CICERO – Cicero Senter for Klimaforskning Stiftelse	NO
E3M – E3-Modelling AE	EL
KTH – Kungliga Tekniska Hoegskolan	SE
POLIMI – Politecnico di Milano	IT
UPRC – University of Piraeus Research Center	EL
UVa – Universidad De Valladolid	ES
WI – Wuppertal Institut fur Klima, Umwelt, Energie GGMBH	DE
IIMA – Indian Institute of Management	IN
THU – Tsinghua University	CN
USMF – University System of Maryland	US
AAıT – Addis Ababa University	ET
KEI – International Civic Organisation Kyiv Economics Institute	UA
RUSL – Raja Rata University of Sri Lanka	LK
TUM – Technical University of Mombasa	KE
UNIGE – Université de Genève	CH
Imperial– Imperial College of Science, Technology and Medicine	UK

Funded by
the European Union

Executive Summary

The IAM COMPACT task associated with this report aims to provide sustainable decarbonisation pathways, including biodiversity, materials, biophysical limits, and place climate action as a cross-cutting theme across the sustainability spectrum. It aligns climate action and sustainable development by assessing integrated co-benefits of climate-neutral pathways and policies targeting different SDGs. IAM-driven pathways have limited coverage of SDGs and are mostly focused on climate action, energy efficiency, industry, and infrastructure, while other environmental and social dimensions are rarely assessed.

Thus, this report starts by analysing the capabilities of each IAM COMPACT model to represent SDGs, creating a suitable quantitative framework that facilitates their evaluation. It places emphasis on synergistic effects between SDGs, detecting barriers to and co-benefits of specific SDGs, assessing model weaknesses and potential improvements to fill gaps and reinforce modelling capacity, providing feedback on measures targeting multiple SDGs (Section 1).

In then focuses on models' capacity to analyse energy, land, and material resources, biophysical limits, aspects of global biodiversity conservation and nature restoration. Through developing a set of biodiversity indicators, a policy package is created to affect the indicators and produce scenarios which are simulated with the goal of gaining a deeper understanding of biodiversity, material resources, and biophysical limits (Section 2).

Finally, we synthesise the previous sections and develop a multi-level integration of IAMs and portfolio analysis of investments with quantified implications for multiple SDGs, across socioeconomic futures and considering different uncertainties. We draw from relevant SDG indicators extracted from IAMs, a novel multi-objective optimisation process, and stochastic multicriteria acceptability analysis (Section 3).

Contents

Funded by the European Union

Table of Figures

Funded by the European Union

Table of Tables

Funded by
the European Union

Abbreviations

Acronyms	Meaning
AFOLU	Agriculture, Forestry and Other Land Use
B3W	Build Back Better World
CAF	Cancun Adaptation Framework
CAP	Common agricultural policy
CEAP	Circular Economy Action Plan
CCLW	Climate Change Laws of the World
CEDI	Clean Energy Demand Initiative
COP	Conference of the Parties
CPD	Climate Policy Database
DSDG	Division for Sustainable Development Goals
EAP	Circular Economy Action Plan
EC	European Commission
EEA	European Environment Agency
EU	European Union
FMC	First Movers Coalition
IAMs	Integrated Assessment Models
I^2 AM PARIS	Integrating Integrated Assessment Modelling in Support of the Paris Agreement
IEA	International Energy Agency
IEAD	International Energy Agency Database
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change and Forestry
NAPs	National Action Plans
NCCAS	National Climate Change Adaptation Strategy
NCDs	Nationally Determined Contributions
NECPs	National Energy and Climate Plan
OECD	The Organization for Economic Cooperation and Development
REDD	Reducing Emissions from Deforestation and Forest Degradation
R&D	Research & Development
SDGs	Sustainable Development Goals
UN	United Nations
UNFCCC	The United Nations Framework Convention on Climate Change
UN-REDD Programme	The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
WCS	World Conservation Strategy

Introduction

IAM COMPACT seeks to comprehensively quantify sustainable futures from a cross-sectoral perspective, by exploring SDGs alongside climate neutrality and their interactions with the pillars of human development, resource use, earth system, governance, and infrastructure. Seemingly two separate agendas, sustainable development and climate action are highly intertwined (von Stechow et al., 2016; Moreno et al., 2024): the former is an explicit part of the Paris Agreement while the latter constitutes one of the SDGs, which inter alia further include poverty and hunger elimination, social and gender equalities, quality education and decent work, strong institutions, responsible production, environmental and biodiversity protection, and good health. Despite having been designed and/or adapted to support climate policy, integrated assessment modelling frameworks have been found well-equipped to analyse many goals of sustainable development (van Soest et al., 2019). Nonetheless, the need to assess climate action in conjunction with the other 16 SDGs has hitherto been addressed mostly by means of treating SDGs as interactions of low-carbon mitigation pathways, explicitly (e.g., van de Ven et al., 2019) or implicitly (e.g., Doelman et al., 2020), as also reflected in IPCC AR6.

Although climate policies are usually applied to a sector or system, they are directly/indirectly connected to other sectors/dimensions, from energy, to industry, transport, water, and to land uses, biodiversity, society, economy. The design of climate policies in the context of sustainable development, demonstrating their impacts beyond mitigation can foster acceptability and promote successful implementation, reframing the climate challenge as transformation opportunities from a 'whole systems' view (Pye et al., 2021). Sustainability cannot be achieved in isolation, as human and Earth/natural systems are inevitably interconnected; cross-sectoral modelling (from IAMs to sectoral models) is thus fundamental to effective evaluation of policies, allowing the simulation of feedbacks and links among sectors and thus providing insights to policymakers on how climate and sustainable development policies interact with one another as well as on sustainability overall. It is therefore important to define a common, consistent evaluating framework on a comparable modelling basis through a list of indicators capable of quantifying progress toward SDGs. The "Global indicator framework for SDGs" and its related repository with the latest references, and the emerging target space for SDG progress in IAMs (Sörgel et al., 2021), has served as a basis (Section 1).

Mainstream IAM activities tend to rely on a one-way relationship between environment and economy, usually integrating negative side-effects or economic costs marginally reducing economic output. Biodiversity loss and ecosystem restoration costs are addressed through land use changes driven by transitional mining, construction, maintenance needs. Demand for critical materials will dramatically increase in the next decades driven by a shift to renewables, and fossil fuel use is expected to persist throughout the transition despite progressive phase-out. In measuring progress toward truly sustainable development, we develop a framework that examines the impact of human activities and policies on society, nature, and environment. Based on a 'planetary boundaries' perspective (Rockström et al., 2009), we quantitatively assess the biophysical limits of the biosphere, the effects of the management of material resources and the human pressure on the biosphere (Section 2).

The world stands at a critical crossroads, where big investments are needed in industry and energy supply-side technologies, energy efficiency, low-emission transport, and demand management. Business and policy are increasingly aware of the potential for synergies between decarbonisation and other SDGs towards climate neutral and development pathways. We thus develop a multi-level integration of IAMs and uncertainty analysis with quantified implications for multiple SDGs, in an effort to provide a holistic framework of sustainable development and uncertainty analysis, away from climate isolationism (Section 3).

Funded by
the European Union

1. Capacity to assess SDGs in the IAM COMPACT models

The Sustainable Development Goals (SDGs) are the tools set by the United Nations (UN) to assess the successful evolution of the different sectors or areas across the world. They attempt to cover a wide spectrum of life dimensions, from environment to world hunger or life of aquatic species, rendering it extremely challenging to construct a model able to address them all at the same time. The same task seeks to analyse the capabilities of each IAM COMPACT model to represent SDGs by creating a suitable quantitative framework that facilitates what may be a complex study due to the huge and abstract list of SDG indicators established by the UN.

This proposed research does not only aim at an isolated analysis but focuses on the synergies among the SDGs and the current gaps in the field of sustainable goals modelling of the IAMs of this project in order to find combinations and exploit some input-output relationships to examine those measures that targets multiple SDGs.

1.1 Introduction

The United Nations agreed to adopt the 2030 Agenda for Sustainable Development in 2015. The 2030 Agenda is centred around the 17 Sustainable Development Goals (SDGs), and highlights that development must balance social, economic, and environmental sustainability. However, this set of goals was preceded by decades of work, starting from the 1992's Earth Summit in Rio de Janeiro and going through the Millennium Summit in 2000 or the Johannesburg Declaration in 2002. Thus, in 2013, a 30-member Working Group was charged with creating the 2030 Agenda for Sustainable Development with 17 SDGs clearly aligned with other international agreements such as the Paris Agreement on Climate Change (2015) (UN, 2015).

SDGs are a collection of 17 interlinked global targets which aim to "achieve peace and prosperity for and the planet, now and in the future", having the sustainability as its core both in social, economic, political, and environmental aspects. The review, updating and reviewing progress of SDGs are carried out annually under the High-level Political Forum on Sustainable Development platform, led by the Division for Sustainable Development Goals (DSDG) (van Soest et al., 2019), while an annual report is published each year to track their progress. This progress is measurable thanks to a set of targets and indicators for each goal that was released in 2017 to ensure the feasibility and measurability of them (Biermann et al., 2017).

The hierarchical distribution of SDGs, targets and indicators consists of 8-12 targets per goal and 1-4 indicators per target for a total of 17 SDGs, 169 targets and 232 indicators. Two different types of targets can be identified: on the one hand the "outcome targets" whose function is to clarify the desired objectives of the goal and, on the other hand, the "means of implementation targets" which try to explain how the SDGs must be reached (Allen et al., 2018).

Although indicators were exhaustively reviewed in 2020, which resulted in several changes (some of them were replaced while others were removed), the impact of SDGs in today's society is still limited and their measurement is fraught with difficulties (UN, 2020).

In the subsection below, the 17 Sustainable Development Goals are listed and explained (UN, 2015).

List and content of SDGs

- **SDG1:** No poverty → This goal aims to end poverty in all its forms everywhere. It has 7 targets and 13 indicators.
- **SDG2:** Zero hunger → Achieving food security, ending hunger, improving nutrition and enhancing sustainable agriculture are the expected outcomes of this goal. It consists of 8 targets and 14 indicators to track progress.
- **SDG3**: Good health and well-being → To ensure healthy lives and well-being for everybody. To do so, 13 targets and 28 indicators are taken into account.
- **SDG4:** Quality education → An inclusive and equitable education is expected to be reached, promoting

lifelong learning opportunities. Goal 4 has 10 targets with a sum of 11 indicators.

- **SDG5:** Gender equality → Equality between genres and women empowerment are pursued with this goal through 9 targets and 14 to measure them.
- **SDG6:** Clean water and sanitation → Clean water has to be available for all with sustainable management and sanitation. This SDG consists of 8 targets and 11 indicators.
- **SDG7:** Affordable and clean energy → SDG 7 aims to ensure access to affordable, clean and reliable energy for all. It uses 5 targets and 6 indicators.
- **SDG8:** Decent work and economic growth → This goal targets promoting sustainable economic growth, full employment and decent work for everyone. It has 12 targets and 17 indicators.
- **SDG9:** Industry, innovation and infrastructure → This goal aims to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. It consists of 8 targets and 11 indicators.
- **SDG10:** Reduced inequalities → The objective is to reduce inequalities within and among countries, addressing issues of discrimination, income inequality, and social inclusion. This goal has 10 targets with a sum of 14 indicators.
- **SDG11:** Sustainable cities and communities → Creating sustainable, inclusive, and resilient cities and human settlements is the focus of this goal. It uses 10 targets and 15 indicators to measure progress.
- **SDG12:** Responsible consumption and production → This goal encourages sustainable consumption and production patterns, including reducing waste and promoting resource efficiency. It consists of 11 targets and 13 indicators.
- **SDG13:** Climate action → The aim is to take urgent action to combat climate change and its impacts. SDG 13 has 5 targets and 15 indicators to track progress.
- **SDG14:** Life below water → This goal focuses on conserving and sustainably using the oceans, seas, and marine resources. It consists of 10 targets and 12 indicators.
- **SDG15:** Life on land → Protecting, restoring, and promoting sustainable use of terrestrial ecosystems is the objective of this goal. SDG 15 has 12 targets and 14 indicators.
- **SDG16:** Peace, justice and strong institutions → Promoting peaceful and inclusive societies for sustainable development, ensuring access to justice, and building effective, accountable, and inclusive institutions are the key aims. It uses 12 targets and 24 indicators.
- **SDG17:** Partnership for the goals → This goal focuses on strengthening the means of implementation and revitalizing the global partnership for sustainable development. SDG 17 has 19 targets and 25 indicators to monitor progress.

Design of policies oriented to SDGs

Several studies have concluded that a potential solution for enhancing the positive effects of SDG-related policies is to analyse the interactions between them, i.e. to consider the SDGs as an interconnected network with positive (**synergy**) and negative (**trade-off**) interlinkages in order to foster those policy measures that boost as many SDGs as possible at the same time (de Miguel & Laurenti, 2020).

Although this topic may be considered as emerging, there are various studies conducted which can be used as a solid basis to build-up an analysis of SDG interactions and IAM representations. Griggs et al. (2017) reported the first SDG interaction guide (widely used in these short of studies) while Pradhan et al. (2017) created a ranking of global synergies and trade-offs with the Goals. More recently, different studies have put their focus on more specific topics, analysing interactions among certain SDGs (e.g. environment-poverty-energy (Scharlemann, et al., 2020)) and locating the research in a precise country or region (Mainali et al., 2018; de Miguel & Laurenti, 2020).

Regardless the study scope and scale, all the undertaken studies have come to the same conclusion: the mere pursuit of improving a single sustainable objective often leads to unintended effects on other SDGs, making the final gain-loss balance clearly skewed to the negative side (Nilsson, et al., 2018), with the isolating or silos perspective being the strongest problem that policy implementation must face.. This way, it is essential to work as an integrated way to ensure an efficient and feasible Sustainable Path (Coopman et al., 2016). Interactions among SDGs will be further studied in Section 2.3.1 SDG interactions: synergies and trade-offs.

Most of studies based their knowledge on historical data and how these SDG-related policy decisions have affected to the rest of targets. However, it is more than necessary to assess these interlinkages in the long-term, with IAMs (Integrated Assessment Models) being the best alternative for informing policymakers about it (van Soest et al., 2019).

Since some IAM inputs are representations of policies, it is necessary to understand how these SDG policies affect each other (Weits et al., 2018). The capability of IAMs and other sectoral models that are part of this project to implement distinct policies was mapped for the Deliverable 4.1, showing that some models are narrowly focused on a certain sector while others may broad a larger range of policies less comprehensively.

Therefore, the main goal of this section is to map how the models represent SDGs (indicators, policies, etc.) so that both modelling weaknesses and future improvements can be detected and addressed by coupling and connecting several synergetic IAMs or sectoral models. The mapping process will be covered in Section 1.2 whereas the potential synergies between models will be undertaken in Section 1.3.2.

Despite the existing knowledge gap in this field, various frameworks have been developed by different research, aiming at identifying and analysing synergies and negative effects of SDGs with IAMs. The major inconvenience to face is that this type of evaluation is a complex process due to the large quantity of indicators for each target and goal and they can even be slightly adapted to be integrated in a model. Thus, it is important to settle an evaluation framework which is discussed and described in the following Section 1.1.3.

SDG Evaluation Framework

As it has been previously commented on Section 1.1, the huge number of targets and indicators involved in tracking the progress of SDGs complicates a holistic view of how SDGs are interlinked, and the potential benefits and trade-offs created between them. Moreover, when applying SDGs to simulation models and future scenarios, several indicators from different goals may overlap while others (mainly means of implementation targets) are cumbersome or impossible to measure (Hák et al., 2016).

In recent years, various studies have emerged aiming to face this issue, dealing with the relationship between SDGs and IAMs, and how an optimal quantification of their evolution can be achieved through simulations. (Hák et al., 2016; Allen et al., 2017). Although it is a topic still under development, most of them have proposed a same potential solution based on the establishment of a "target space". This concept refers to the choice of a reduced set of targets (specific variables that can be quantified with relative simplicity) according to certain principles (explained later in this section) with the objective of evaluating the achievement of all SDGs in future scenarios, thus helping to identify potential synergies and trade-offs between them (van Vuuren, et al., 2022).

Target spaces are really useful tools that allow IAMs to assess the evolution of the SDGs and ease intercomparability between models (mainly coupled models to meet all the range of targets). However, the design of target spaces requires a rigorous methodology and the involvement of different field experts to define the selection principles, choose the targets and indicators and validate the definitive outcomes.

The methodology to define a target space often consists of three consecutive steps in which the participation of stakeholders and experts is essential (van Vuuren et al., 2022; Soergel et al., 2021):

(a) Determination of the key principles and selection criteria: stakeholders and scientists define a set of postulates that will be the basis of the indicator selection.

(b) Exploration and review of literature: All of the targets and indicators proposed by the UN as well as other

International Agreements, papers and studies are analysed to pre-select the potential indicators that meet the stipulated principles. Some of these choices may be not included in the "official" indicators such as novel indexes. The output of this step has to be further assessed.

(c) Validation of the target space: The capacity of some models to represent SDGs is evaluated with the target space and the results are assessed and refined by experts.

Regarding the selection principles, although they can differ among authors, it is widely accepted that an effective target value or indicator has to meet the following characteristics:

- To be relevant for society
- To be science-based
- To be robustly quantifiable
- To have long-term perspective
- To be simple, transparent and usable

At the same time, for target values to be suitable, they must:

- To be actionable
- To be achievable
- To have comparable and available data

Once the selection principles are identified, the available literature related to the SDGs is reviewed to select a relatively short list of indicators, with their corresponding target values, trying to achieve a holistic SDG representation. The characteristics of target spaces are not fixed e.g. the length of the list of indicators depends on the authors' considerations and they can contain only UN-proposed indicators or include diverse indexes and metrics from other references.

Soergel et al. (2021) include within their target space two kind of indicators: "key indicators" which are the most relevant ones and could be sufficient to evaluate the SDG modelling capacity of IAMs; and "other indicators" which can be omitted in some circumstances, but whose inclusion provides a more thorough analysis. Thus, the overall list of proposed indicators amounts to 56, but can be summarised into just 20 (only key indicators), which constitutes a large reduction compared to the 232 UN's indicators.

On the other hand, van Vuuren et al. (2022), which is one of the main reference papers for SDG target spaces, introduces a condensed target space composed of 36 indicators with a long-term reference point of 2050.

The target space indicators for both van Vuuren et al. (2022) and Soergel et al. (2021) are listed in Annex I.

After selecting the indicators, the next step consists of grouping them into broader categories to facilitate the SDG assessment. It is widely accepted to use the key elements identified during the preamble of the 2030 Agenda to monitor SDG progress, also known as the "5 Ps": **People, Peace, Prosperity, Planet** and **Partnerships.** Yet, in this context "**Partnerships**" is excluded due to the complexity of being modelled by IAMs and "**Planet**" is split into **Planetary Integrity** and **Sustainable Resource** (Management), resulting in five categories.[1]

Table 1 shows the different SDGs collected by each category according to several references.

Table 1. SDGs covered by each target space category. Source: Own elaboration

[1] https://unfoundation.org/blog/post/the-sustainable-development-goals-in-2019-people-planet-prosperity-in-focus/

Category	SDGs covered	Description
People	SDG1, SDG3, SDG4 & SDG5	The goals related to topics which goes beyond economic development such as health or education are part of this group.
Peace	SDG16 & SDG17	Both SDGs aim to achieve fair and peaceful societies and institutions as well as to meet the rest of the goals.
Prosperity	SDG8, SDG9, SDG10 & SDG 11	Goals closely related to socioeconomic topics.
Planetary Integrity	SDG13, SDG14 & SDG15	Climate action, biodiversity and planetary boundaries are clustered here.
Sustainable Resources	SDG2, SDG6, SDG7 & SDG 12	It encompasses the access and maintenance of the basic resources (food-water-energy).

Finally, once the target space is well defined and established, it is necessary to validate the target values for each indicator. This process is often conducted by experts on each field, i.e. scientists, researchers, policy makers, etc.

The main use of target spaces consists of comparing the target values of each indicator (reference point of 2050) with those projected by IAMs using a given scenario, either a current one (such as the Shared Socioeconomic Pathways (SSPs)) or a novel scenario. This comparison allows to determine future gaps, synergies and trade-offs as well as to highlight to policy makers the lack of strict guidelines to achieve the targets (Tosun & Leininger, 2018).

1.2 IAM COMPACT target space and SDG mapping

The major objective of Subtask 5.6.1 is to map the capacity of the IAM COMPACT models to represent the SDGs, so as to build up a fully integrated modelling environment capable of projecting and tracking the progress of these goals, their synergies and trade-offs. With this target defined, the mapping has been undertaken by consulting the modelling teams, i.e. requesting the modellers to provide information on the capabilities of their IAMS and sectoral models, as in the Deliverable 4.1 (From policy needs to scenario frameworks), but in this case, focused on SDGs analysis.

Since this process could become a bit cumbersome and difficult, based on the references analysed for this report, a target space has been created by combining van Vuuren et al. (2022) and Soergel et al, (2021) indicators to shorten the list of indicators. Therefore, the modelling teams have received a template with a list with different indicators as well as the possibility to indicate other indicators not addressed in the target space but officially proposed by the UN, trying to establish as broad a template as possible.

The completed template is not only an output of this Subtask 5.6.1 but also an essential input for the Subtask 5.6.3 (Uncertainty analysis of investments against multiple SDG indicators), so in order to ease the data transfer, besides requesting whether the model can represent a certain indicator or not, the modelling teams have been asked to note if it is done through a direct variable (directly the indicator is modelled) or a proxy. The proxies are variables that have a close relation with the indicator of interest, so that they can be used in place to measure the progress of specific SDGs, in case they are calculated in the models. This way, the capabilities of our modelling ensemble of IAM COMPACT can be expanded.

Part of this template can be found in the following Table 2 (the entire template is included in Annex I).

Funded by
the European Union

Table 2. Template used to assess the capacity of IAM COMPACT models to simulate the SDGs. Source: Own elaboration

Clusters	SDGs	Proposed indicators	Included in the model? Yes (X) No ( )	Directly included in the model? If NO fill the next column	Proxy variable in the model	Units
People	SDG1	1.2.1. Number of people living under extreme poverty conditions				%
		Food expenditure share				%
		Other indicator? (please fill)				
	SDG3	Healthy life expectancy				yr
		3.2.1. Under-5 mortality rate				%
		3.9.1. Disability adjusted life years (DALYs) lost from particulate matter (PM 2.5)				DALYs/yr
		Other indicator? (please fill)				
	SDG4	4.6.1. Share of people >15 w/o education				%
		4.1.2 Completion rate (primary education, lower secondary education, upper secondary education)				%
		Other indicator? (please fill)				
	SDG5	Education gender gap in (a) secondary education (age 20-24 w at least lower secondary education); and (b) primary education (age 15-19 with at least primary education)				%

		Female estimated earned income over male				%
		Other indicator? (please fill)				
Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita				%
		8.1.1: Annual growth rate of real GDP per capita				%
		8.5.2. Unemployment rate				%
		Other indicator? (please fill)				
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)				%
		Direct CO_2 emissions from industry				Gt CO_2/yr
		9.4.1. Private and government-financed gross domestic R&D expenditure (GERD) in per cent GDP				%
		Proportion of people using the internet				%
		Proportion of adult people with access to financial services				%
		Travel time to the nearest city				h
		Other indicator? (please fill)				
	SDG10	10.2.1. Share of population with <50% of national median income				%

		Average income of bottom 40% relative to national average				%
		Other indicator? (please fill)				
	SDG11	11.6.2. Share of people exposed to annual average PM2.5>25 μg/m3				%
		11.1.1. Number of people living in slums				%
		Other indicator? (please fill)				
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)				Gt CO_2 eq/yr
		Global Mean Temperature (GMT) increase according to Paris Goals				ºC
		Cumulative CO_2 emissions, counted from 2011				Gt CO_2/yr
		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage				Gt CO_2/yr
		Cumulative land-use change emissions				Gt CO_2 eq/yr
		Other indicator? (please fill)				
	SDG14	Aragonite saturation state				dmnl
		Saturation state of calcite				dmnl
		Phosphorous flow from freshwater systems into the ocean				Mt P/yr

Funded by
the European Union

		14.2.1. Proportion of fish stocks within biologically sustainable levels				%
		14.3.1: Average marine acidity (pH) measured at the surface				dmnl
		Net primary production of biomass in oceans				GtC/yr
		New (export) production of biomass in oceans				GtC/yr
		Other indicator? (please fill)				
	SDG15	Industrial and intentional biological fixation of N				Mt N/yr
		Biodiversity Intactness Index				dmnl
		15.1.1: Forest area as a proportion of total land area				%
		Primary forests as share of total terrestrial land area (excluding surface water)				%
		Land area afforested				km^2
		Global area of forested land as % of original forest cover				%
		Area of forested land as % of potential forest per biome				%
		Other natural land as share of total land area				%
		Percentage of land that is non-agricultural				%
		Other indicator? (please fill)				

1.3 Analysis of the results

Table 3 shows a summary of the inputs collected from the modelling teams, indicating which SDGs can be represented by each model. This table does not specify the indicator used in each case nor whether it is directly modelled or using a proxy, but all this information is available in Tables A3-A21 in the Annex I.

Table 3. SDG representation in IAM COMPACT models. Source: Own elaboration

	People				Prosperity				Planet Integrity			Sustainable Resources				Peace, Inst. & Imple.		TOTAL
	SDG1	SDG3	SDG4	SDG5	SDG8	**SDG9**	SDG 10	SDG 11	**SDG 13**	SDG 14	SDG 15	SDG2	SDG6	**SDG7**	SDG 12	SDG 16	SDG 17	
ATOM									X					X				2
Calliope									X					X				2
CHANCE	X			X			X							X				4
China-MAPLE					X	X			X			X	X	X				6
CICERO									X									1
CLEWs						X			X		X	X	X	X	X			7
DREEM	X	X						X	X					X				5
DyNERIO					X	X					X	X	X	X	X			7
EnergyPLAN						X			X					X				3
EXPANSE		X			X			X	X		X			X		X		7
GCAM	**X**	**X**				**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**			**12**
IMACLIM-China	X				X	X			X					X				5
MENA-EDS					X	X			X				X	X				5
MUSE				X		X								X				3
OSeMOSYS									X					X	X			3
PROMETHEUS					X	X	X		X				X	X				6
TIAM						X			X					X				3
WILIAM		**X**	**X**		**X**	**X**			**X**	**X**	**X**	**X**	**X**	**X**			**X**	**11**
WISEE Global St.						X												1
WISEE-EDM						X												1
WTMBT					X	X					X	X	X	X				6
Total	5	5	2	3	9	**15**	4	4	**16**	3	7	7	9	**19**	5	2	2	

Funded by
the European Union

The three most represented SDGs are SDG7 (Affordable & Clean Energy), SDG13 (Climate Action) and SDG9 (Industry, Innovation & Infrastructure), as one would expect, since these three topics are often addressed widely by IAMs and sectoral models (mostly are energy models in this project) and lots of data is easy to find and compare.

The opposite is true for several SDGs that are barely represented in the analysed IAMs and sectoral models such as SDG4 (Quality Education), SDG16 (Peace, Justice and Strong Institutions) and SDG17 (Partnership for the Goals), although the latter might not be taken into account as it is a Goal on Goals themselves. At first glance, it is striking that the Goals related to social and behavioural topics tend to be the least considered among models, which is probably due to the difficulties of modelling and quantifying these abstract variables, and this is a clear area for improvement.

The information gathered through the surveys is largely in line with the results provided by van Soest et al. (2019) which will be further commented in Section 2.3.1 on SDG interactions.

To check the particular indicators represented by each model, see Annex I.

SDG interactions: synergies and trade-offs

This specific analysis has the objective of support one of the activities of the tasks, that it is to assess model weaknesses and potential improvements of the models in relation to measuring progress towards SDGs, also putting emphasis on synergistic effects between SDGs, detecting barrier as well as drivers. The scope of the recent studies conducted on this topic varies from global approaches to the interlinkages among all SDGs to national analysis of, for example, how an environmental or energy mitigation policy affects life on land. Therefore, the first step in this subsection is to define the scale and the approach of this analysis:

- Scale: The IAM COMPACT project includes both global and national models and some of them can be disaggregated into several regions. In order to analyse the interlinkages from a broader and more complete approach the analysis pursued is global.
- Approach: As previously mentioned, the objective of this task is to evaluate model weaknesses and potential improvements, with an emphasis on synergistic effects, barriers, and drivers between SDGs. This implies analysing every SDG and its links with the rest of the list, in order to also assess the capacity we have in our ensemble of models to track the most relevant synergies and trade-offs.

According to these two requirements, a literature review has been carried out aiming at identifying the global interconnections of SDGs. Pradhan et al. (2017) followed a method which consisted of a statistical process called "the nonparametric Spearman's rank correlation (p) analysis" in which the strength of association of a pair of variables (in this case, two indicators) was measured and quantified (Spearman, 1904). When the obtained p-value was greater than 0.6, the relationship was classified as a synergy, while if the value was less than -0.6, it was catalogued as a trade-off. For those pairs with values in the middle range, a new category with the name of "non-classified" was included to avoid over-interpretation (Hauke & Kossowski, 2011).

Pradhan et al. (2017) analysed interactions among indicators for distinct SDGs as well as indicators within the same Goal (only those with more than 100 data pairs). The scale of the research was national and global since they initially performed an individual study for every country and then synthesized the results by averaging a global value. The main conclusion of this publication was that almost each SDG synergies exceed trade-offs as can be seen in Figure 1.

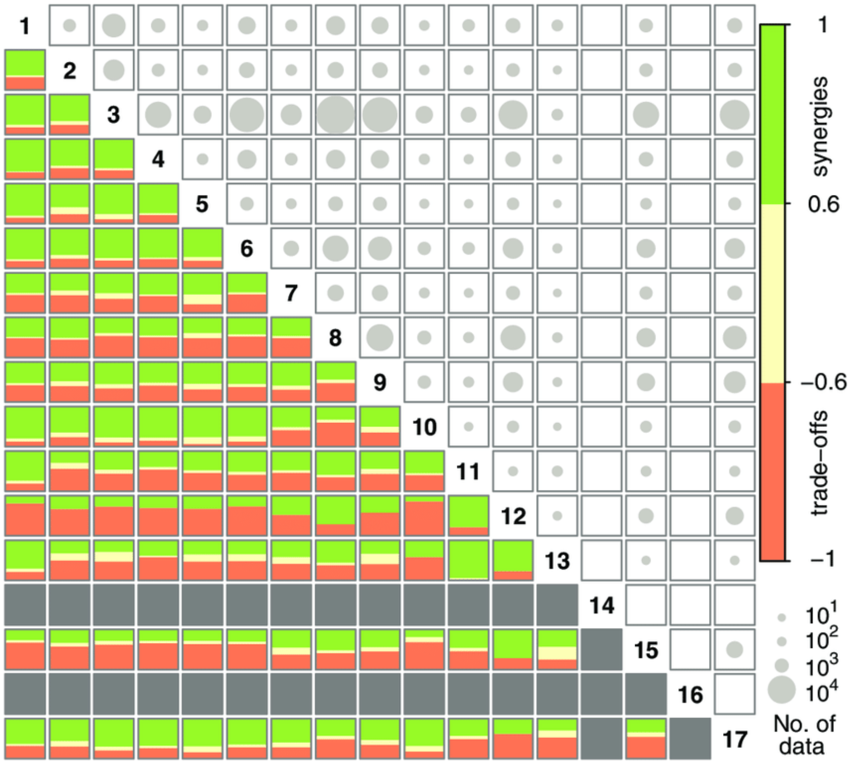


Figure 1. Intra and inter relationships between SDG indicators. Source: (Pradhan, Costa, Rybski, & Lucht, 2017)

Although there was lack of information for the analysis of two Goals (14 & 16, grey boxes), it was thorough research which allowed to observe some noticeable correlations. SDG1 (No Poverty) is the most synergistic Goal with positive p-values with almost all the others, as is SDG3 (Good Health). The major reason for this situation is that some indicators are similar in several SDGs, facing a same issue from different points of views (e.g. reducing the number of deaths due to disasters, SDG1, vs. improving disaster risk reduction strategies, SDGs 11 & 13) (Mathy & Blanchard, 2016).

On the contrary, SDG8 (Economic Growth), SDG9 (Industry), SDG12 (Consumption) and SDG15 (Life on Land) present the majority of trade-offs across the list since they are closely related to the economic development which could be linked to a non-sustainable environmental situation (Sen, 1983). Thus, these are the interactions which should be more carefully addressed by worldwide governments targeting to break this traditionally established bond between economic growth and pollution & biodiversity damages.

To summarize the analysed interactions, Pradhan et al. (2017) elaborated the following Figure 2, which shows the global ranking of the 10 strongest SDG pairs, for both synergies and trade-offs. As above discussed, SDGs 1 & 3 top the synergy ranking, while SDGs 12 & 15 provide the most negative interconnections.

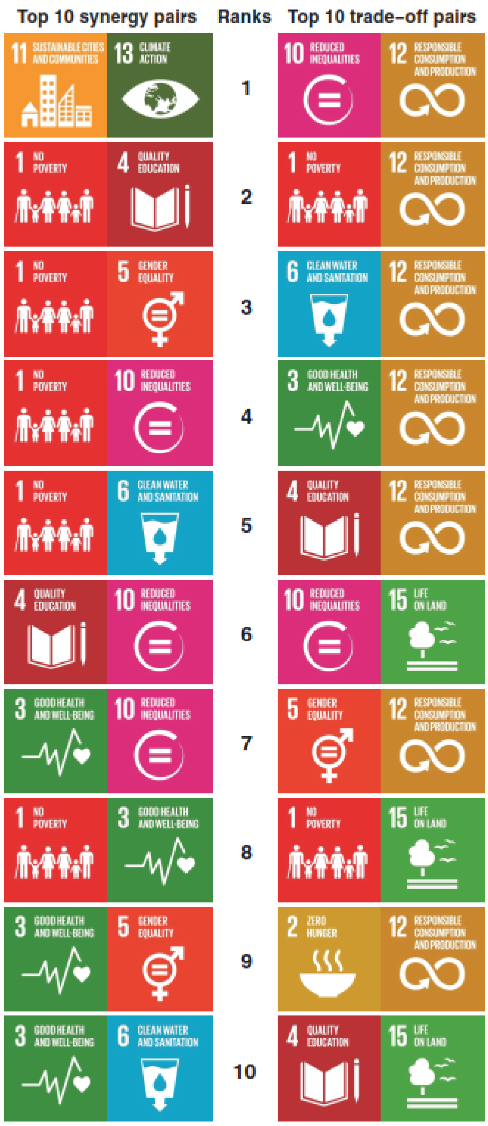


Figure 2. Strongest synergies and trade-offs between SDGs. Source: (Pradhan, Costa, Rybski, & Lucht, 2017)

On the other hand, a different approach to SDG interactions was conducted by van Soest et al. (2019). As in this deliverable, they studied the interlinkages using IAMs and analysing how these tools track SDGs and integrate policies. This complex process was carried out by combining and comparing information coming from three sources: an expert survey on SDG linkages; current and future representations of SDG target status and their interconnections in IAMs; and a synthesis of the SDGs-IAMs literature.

The models used for this purpose were: AIM-CGE, China TIMES, DNE21+, GCAM (also included in IAM COMPACT), GEM-E3, IMAGE, IPAC, PRIMES, REMIND-MAgPIE, MESSAGE-Brazil, MESSAGE-GLOBIOM, and WITCH.

The outcomes provided by van Soest et al. (2019) allows to have a holistic perspective of the SDG representation in IAMs (something similar to what is expected in this task but with a different list of proposed indicators) as well as their interconnected effects. Nevertheless, they did not make a differentiation between synergies and trade-offs but gathered all of them as interactions.

In Figure 3 it is possible to observe that SDGs 7 (Energy), 13 (Climate Action) & 9 (Industry) are the most represented Goals (quantifiable targets), while SDGs 5 (Gender Equality) & 16 (Peace) have a minimum representation. As mentioned below, these outcomes are very similar to what has been provided by the modellers for the IAMs and sectoral models of this project.

Funded by
the European Union

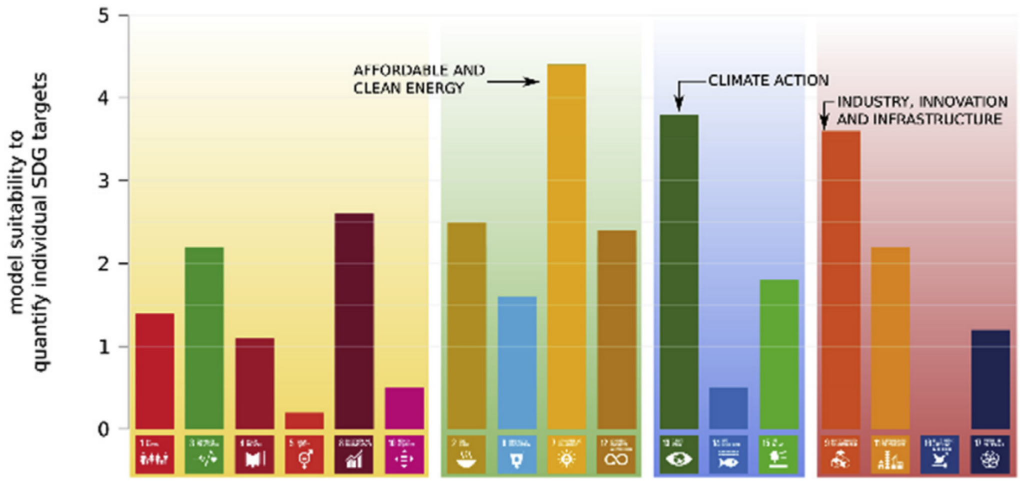


Figure 3. Model suitability to represent SDGs quantitatively. Source: (van Soest et al., 2019)

In Figure 4, although complexly, the interactions between SDGs are shown, also indicating their representation in IAMs (through a star scale), their strength dimension (through a grey scale) and an agreement between interaction importance and representation in IAMs (orange and blue coloured cells). It can be inferred that, as Pradhan et al. (2017) also concluded, SDG1 has strong connections with many Goals. However, the SDGs 7 & 8 were also identified in Soest et al. (2019), which does not match with the previous research.

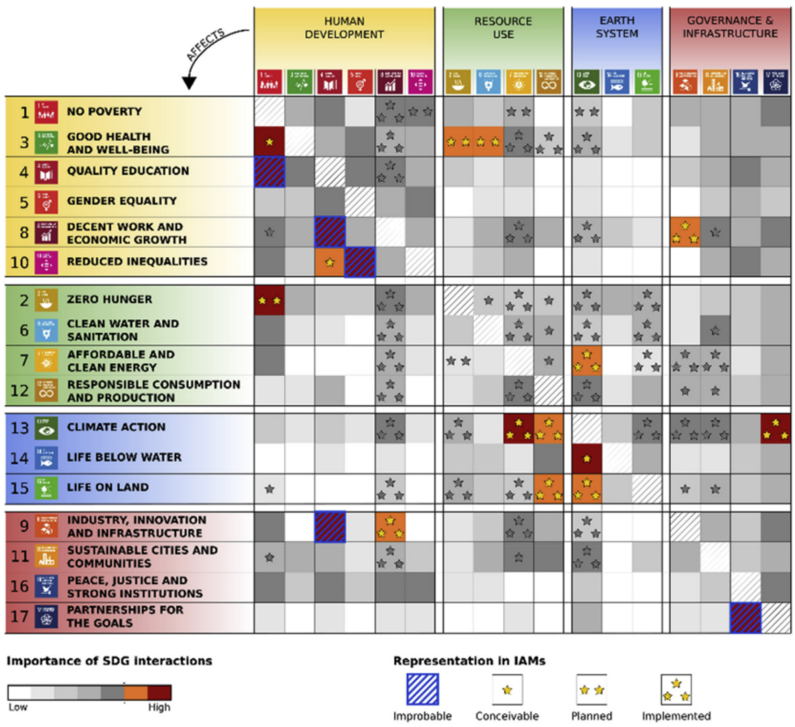


Figure 4. SDG interaction & representation in IAMs matrix. Source: (van Soest et al., 2019)

Modelling Capacity Improvement

After conducting a cross-check between SDG interactions and the capabilities of IAMs to represent the SDGs, it is possible to state that two models clearly outperform the rest when it comes to including the Goals. These two models are GCAM and WILIAM, which integrate 12 and 11 SDGs, respectively.

GCAM assesses indicators for the strongest synergy between Goals identified by Pradhan et al. (2017) (SDGs

11↔13), a relationship that is not part of WILIAM. Nevertheless, WILIAM could be really useful for the negative interactions as it contains indicators related to both SDGs 12 and 15, the Goals with the most trade-offs associated (7 out of 10 of those detected by Pradhan et al. (2017)).

By combining the capabilities of these two models, it is possible to represent 15 of the 20 strongest interactions, with 17 of them being represented by adding the CHANCE model since it includes the SDG5 (not represented by other IAMs).

Regarding the additional relevant interactions spotted by van Soest et al. (2019), those related to both SDGs 14-16 (not analysed in the other research) and SDGs 7-9 can also be addressed with WILIAM, GCAM and EXPANSE.

Therefore, all the strong interactions noted by the two studies can be analysed by making use of the four models mentioned above.

References

Allen, C., Metternicht, G., & Wiedmann, T. (2018). Initial progress in implementing the Sustainable Development Goals (SDGs): A review of evidence from countries. *Sustainability Science, 13*, 1453-1467. doi:https://doi.org/10.1007/s11625-018-0572-3

Allen, C., Nejdawi, R., El-Baba, J., Hamati, K., Metternicht, G., & Wiedmann, T. (2017). Indicator-based assessments of progress towards the Sustainable Development Goals (SDGs): a case study from the Arab region. *Sustainable Science, 12*, 975-989. doi:https://doi.org/10.1007/s11625-017-0437-1

Biermann, F., Kanie, N., & Kim, R. (2017). Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. *Current Opinion in Environmental Sustainability, 26*, 26-31. doi:https://doi.org/10.1016/j.cosust.2017.01.010

Coopman, A., Osborn, D., Ullah, F., Auckland, E., & Long, G. (2016). *Seeing the Whole: Implementing the SDGs in an Integrated and Coherent Way.* London: Stakeholder Forum.

Doelman et al. (2020). Afforestation for climate change mitigation: Potentials, risks and trade-offs. Global Change

Biology, 26(3), 1576-1591.

de Miguel, C., & Laurenti, R. (2020). Synergies and Trade-offs among Sustainable Development Goals: The Case of Spain. *Sustainability*. doi:https://doi.org/10.3390/su122410506

Griggs, D. J., Nilsson, M., Stevance, A., & McCollum, D. (2017). *A Guide to SDG Interactions: From Science to Implementation.* Paris: International Council for Science (ICSU).

Hák, T., Janousková, S., & and Moldan, B. (2016). Sustainable development goals: a need for relevant indicators. *Ecological Indicators, 60*, 565-573. doi:https://doi.org/10.1016/j.ecolind.2015.08.003.

Hauke, J., & Kossowski, T. (2011). Comparison of values of Pearson's and Spearman's correlation coefficients on the same sets of data. *Quaestiones Geographicae, 30*, 87-93. doi:https://doi.org/10.2478/v10117-011-0021-1

Mathy, S., & Blanchard, O. (2016). Proposal for a poverty-adaptation-mitigation window within the green climate fund. *Climate Policy, 16*, 752-767. doi:https://doi.org/10.1080/14693062.2015.1050348

Moreno, J., Campagnolo, L., Boitier, B., Nikas, A., Koasidis, K., Gambhir, A., Gonzalez-Eguino, M., Perdana, S., van de Ven, D. J., Chiodi, A., Delpiazzo, E., Doukas, H., Gargiulo, M., Herbst, A., Al-Dabbas, K., Alibaş, Ş., Neuner, F., le Mouël, P., & Vielle, M. (2024). The impacts of decarbonization pathways on Sustainable Development Goals in the European Union. Communications Earth & Environment 2024 5:1, 5(1), 1–14. https://doi.org/10.1038/s43247-024-01309-7

Nilsson, M., Chisholm, E., Griggs, D., Howden-Chapman, P., McCollum, D., Messerli, P., . . . Stafford-Smith, M. (2018). Mapping interactions between the sustainable development goals: Lessons learned and ways forward. Sustainable Science, 13, 1489-1503. doi:https://doi.org/10.1007/s11625-018-0604-z

Pradhan, P., Costa, L., Rybski, D., & Lucht, W. (2017). A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earth's Future, 5. doi:https://doi.org/10.1002/2017EF000632

Scharlemann, J., Brock, R., Balfour, N., Brown, C., Burgess, N., Guth, M., . . . Wicander, S. (2020). Towards understanding interactions between Sustainable Development Goals: The role of environment—Human linkages. Sustainable Science, 15, 1573-1584. doi:https://doi.org/10.1007/s11625-020-00799-6

Sen, A. (1983). Development: Which way now? The Econometrics Journal, 93, 745-762. doi:https://doi.org/10.2307/2232744

Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., . . . Bertram, C. (2021). A sustainable development pathway for climate action within the UN 2030 Agenda. Nature Climate Change, 11, 656-

664. doi:https://doi.org/10.1038/s41558-021-01098-3

Spearman, C. (1904). The proof and measurement of association between two things. The American Journal of Psychology, 15, 72-101. doi:https://doi.org/10.2307/1412159

Tosun, J., & Leininger, J. (2018). Governing the interlinkages between the Sustainable Development Goals: approaches to attain policy integratio. Global Challenges, 13. doi:https://doi.org/10.1002/gch1002.201700036

UN. (2015). Transforming our World: the 2030 Agenda for Sustainable Development. United Nations.

UN. (2020). The Sustainable Development Goals Report 2020. New Yorks: United Nations.

Van de Ven et al. (2019). Integrated policy assessment and optimisation over multiple sustainable development goals in Eastern Africa. Envir. Res. Letters, 14(9), 094001.

van Vuuren, D. P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D., . . . Soergel, B. (2022). Defining a sustainable development target space for 2030 and 2050. One Earth, 5, 142-156. doi:https://doi.org/10.1016/j.oneear.2022.01.003

von Stechow, C., Minx, J. C., Riahi, K., Jewell, J., McCollum, D. L., Callaghan, M. W., Bertram, C., Luderer, G., & Baiocchi, G. (2016). 2 °C and SDGs: united they stand, divided they fall? Environmental Research Letters, 11(3), 034022. https://doi.org/10.1088/1748-9326/11/3/034022

2. Biodiversity, material resources, and biophysical limits

2.1 Introduction

Integrated assessment models (IAMs) claim to represent the complex links between variables that play a significant role in local, regional, and global systems (Van Beek et al., 2020). Moreover, these models are complex computer simulations that are specifically designed to represent the interactions and feedback loops between the socioeconomic and natural systems over an extended period. Consequently, they serve as a representation of reality, with the primary objective of providing data-driven insights to inform climate policymaking and to enhance understanding of the interconnections included (Parsons & Fisher-Vanden, 1997).

The conservation of global biodiversity, which is currently undergoing a decline, is a significant global objective that has been extensively addressed in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019). Although the main drivers of biodiversity have been identified and ranked, all of them synergistically operate and result from other indirect economic, social, and cultural activities (Díaz & Malhi, 2022). As illustrated in Figure 5, the drivers of biodiversity loss exhibit a consistent pattern of impact across all regions. Regarding Europe, the principal driving force is land use, closely followed by the direct exploitation of ecosystems. For instance, the intensive management of grasslands has been observed to result in a reduction in species richness, carbon sequestration capacity and nitrogen losses to water (Schils et al., 2022). In contrast, good forestry management practices, such as silvicultural management, has been shown to enhance biodiversity in European forests (Oettel & Lapin, 2021).

Conservation, restoration, and prediction of the biodiversity state requires a holistic perspective that can be provided by IAMs (Leclère et al., 2020). It is of great importance to develop a framework that examines the impact of human activities and policies on society, nature, and environment. This will enable us to comprehend the consequences of these activities and policies and anticipate their future effects (Veerkamp et al., 2020). To estimate the extent of habitat degradation, which is a significant contributing factor to species loss (Banks-Leite et al., 2020), it is essential that IAMs are able to quantify the dynamic changes in land use. Furthermore, the relationship between land use and economic activities is crucial for understanding the drivers of biodiversity loss. (Harfoot et al., 2014).

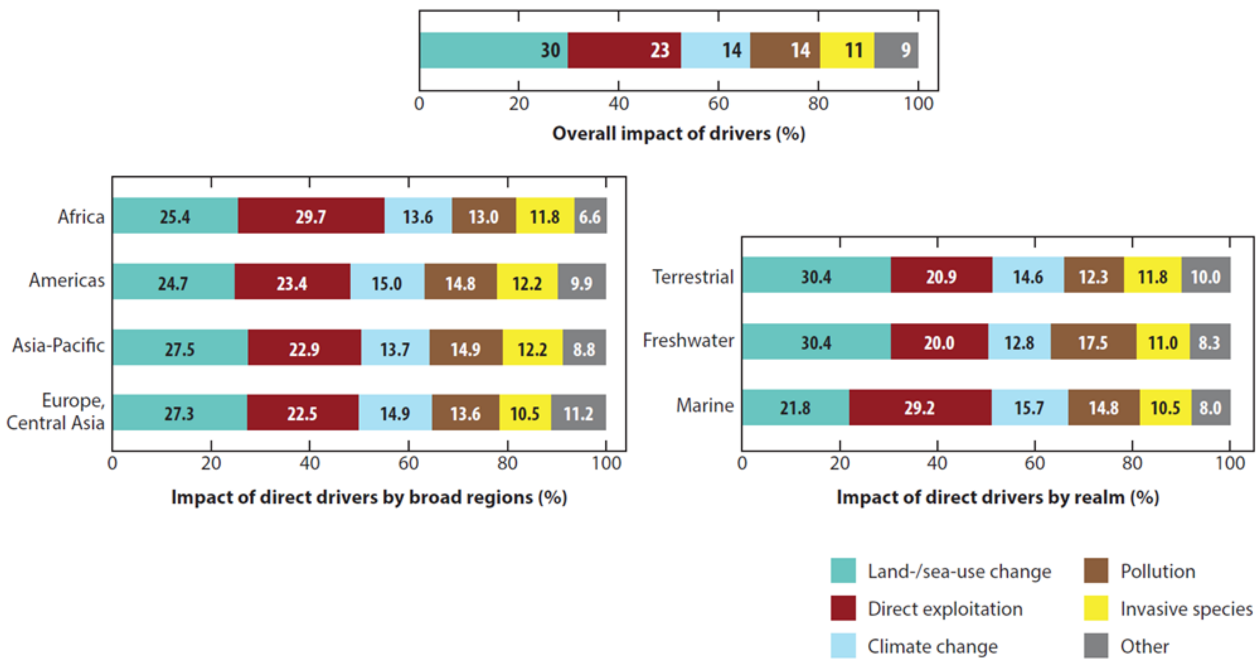


Figure 5. Drivers of loss of biodiversity. Extracted from (Díaz & Malhi, 2022)

Funded by
the European Union

It is of great importance to consider the impact of human societies on the natural world, and to recognise the reciprocal influence between the two. The state of nature has a significant influence on the well-being of humans, and vice versa (Díaz et al., 2018). There are different methods to estimate the benefits and damages that societies can receive from nature. Among them, the most relevant framework in literature is the Natural Contribution to People (NCP), explored on IPBES (2019). This indicator is based on the "Ecosystem services" framework conceptualized for the Millenium Ecosystem Assessment (2003) (Figure 6). This report collects and classify the benefits provided by nature in terms of security, culture, and health. (Díaz et al., 2018).

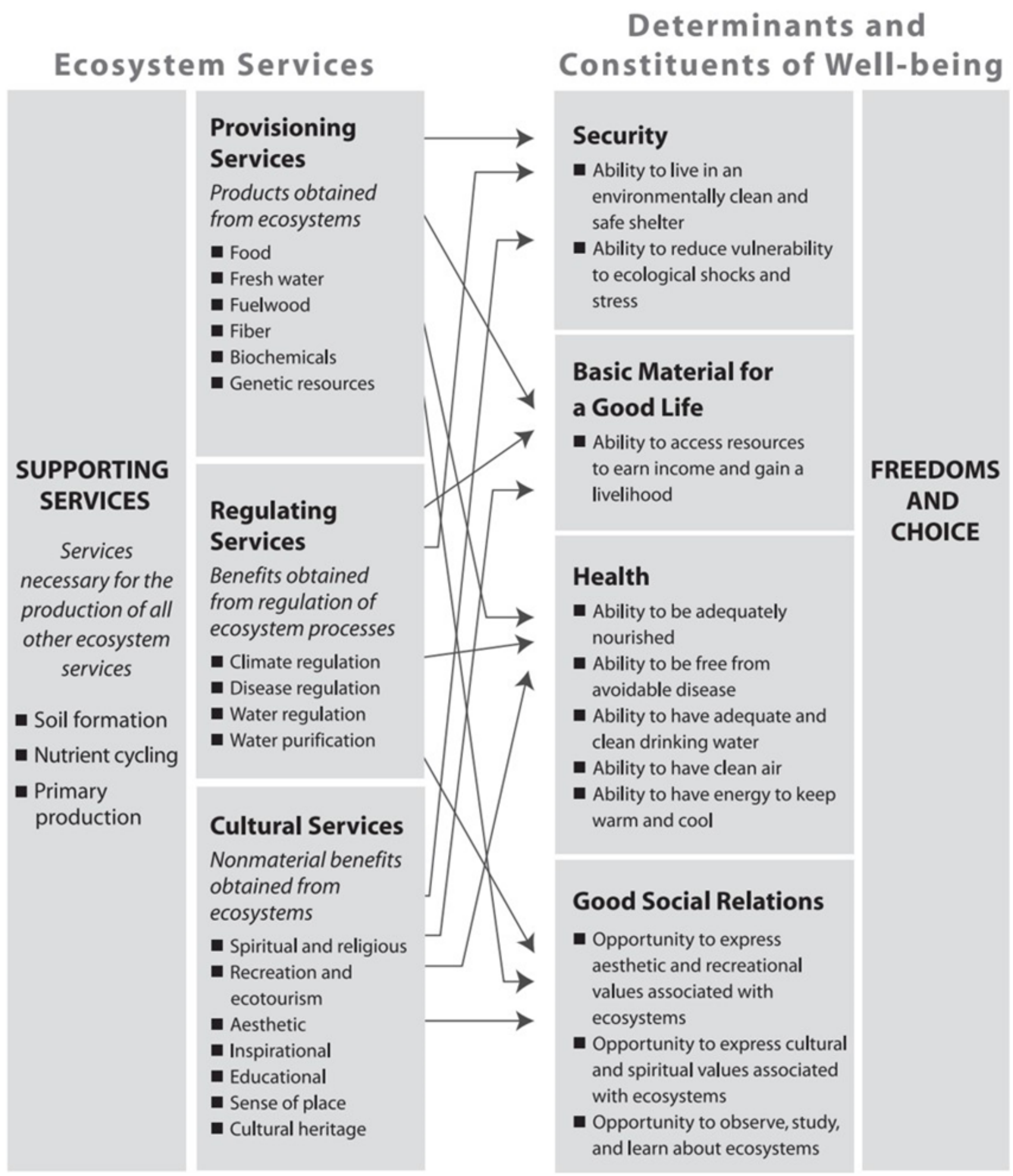


Figure 6. Relationship between ecosystem services and human well-being (taken from the Millenium Ecosystem Assessment 2003).

In particular, the NCP could be employed to illustrate the effects of biodiversity loss on the economy system. Some examples of the consequences of biodiversity loss include a decline in food security due to the loss of pollinator species, disruption of the water cycle at regional and global scales due to changes in ecosystem structure caused by habitat loss, soil degradation and a reduction in crop productivity over time, and the loss of natural pest controls and an increase in net farm income loss due to the destruction of natural habitats (IPBES, 2019). In essence, the greater the number of loops between nature and human systems that are identified, the more crucial it becomes to comprehend the nature of this relationship.

2.1.1 Biodiversity indicators selected

This section defines the indicators that are going to be considered to assess biodiversity in WILIAM model. The *Essential Biodiversity Variables* (EBV) consists in a set of measurements for monitoring biodiversity worldwide (Pereira et al., 2013). WILIAM is the only IAM addressing these variables in IAM-COMPACT. EBV variables are grouped into different classes such as genetic composition, species population, species traits, community composition, ecosystem structure and ecosystem function (GEO BON, 2014). We focus on two of this EVB classes: ecosystem structure and ecosystem function. IPBES (2019) provides a great range of indicators for each class, but we choose one per EBV class. The following indicators have been selected for their inclusion feasibility in WILIAM.

The exchanges among ecosystems components determine the internal flows of energy and materials constituting the biogeochemical cycles (Rotmans, 1999). These cycles (i.e. the carbon cycle) allow the system to be self-sufficient, maintain a balance between losses and gains, and support the ecosystem well-functioning. *Net primary production* (NPP) is the main source of carbon in ecosystems and therefore sustains the biosphere functioning (Richardson et al., 2023). It is calculated as the net result of two metabolic processes occurring in plants, the photosynthesis (carbon uptake from CO_2), and the respiration (carbon emissions of CO_2) (IPBES, 2019). Photosynthesis is the main CO_2 sink (the most efficient mechanism of carbon sequestration known by humanity) (Minasny et al., 2022). However, human activities take possession of NPP to produce goods, what disrupts the balance of both mechanisms (respiration and photosynthesis). The appropriation of NPP by humans is called *Human appropriation of NPP* or (HANPP) (Liang et al., 2023). HANPP is a quantitative estimation of the potential NPP reduced by human activities such as row cropping, logging, grazing and land use change (Haberl et al., 2014). Consequently, this indicator covers the actual vegetation removal caused by agriculture, forestry, etc., and the productive area removal caused by land use changes (Richardson et al., 2023) (Figure 7).

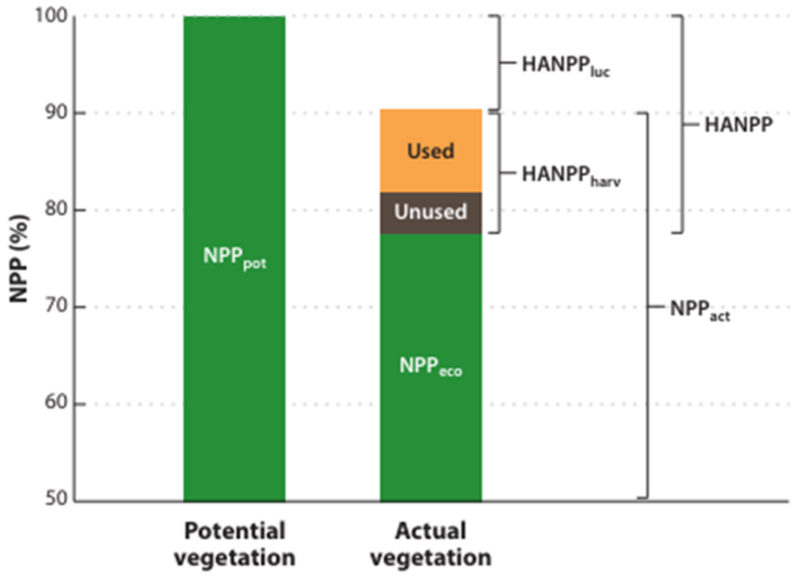


Figure 7. Definition of human appropriation of net primary production (HANPP). HANPP by land use changes ($HANNP_{luc}$) ; HANPP harvested ($HANPP_{hav}$); NPP actual (NPP_{act}); NPP for ecosystems (NPP_{eco}); NPP potencial (NPP_{pot}) (Extracted from (Haberl et al., 2014)

Changes on the ecosystem structure are related to perturbations in the habitat of species. Fragmentation, deforestation, or homogenisation of the forest land profiles are factors explaining this phenomenon. These factors are driven by land use changes, which reflect the land demands of human economic and cultural activities (*Global Forest Resources Assessment 2020*, 2020). Taking this into account, the selected indicator is the biodiversity habitat index (BHI), which estimate impacts of habitat loss, degradation and fragmentation on retention of terrestrial biodiversity in a region, from forest change and land-cover change data (Hoskins et al., 2018) (Figure 8).

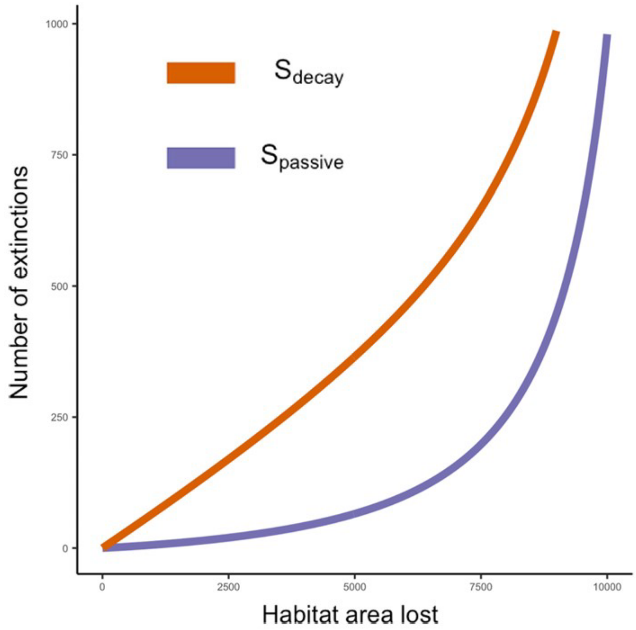


Figure 8. The relationship between habitat loss and species loss. Specially, here is represented the endemics–area relationships according to two possible approaches to the evolution of the loss of biodiversity: passive (purple) suggests that species are lost in proportion to their abundance and distribution in the natural habitat; and decay of the ecosystem (orange) suggests that ecological processes change in smaller and more-isolated habitats. Source: (Chase et al., 2020).

2.1.2 Biodiversity indicators in WILIAM

The modelling of land-use changes is the core of the representation of the relationship between ecosystem's services and economical and cultural activities. WILIAM (Samsó et al 2023) 1.3 version was used for the introduction of biodiversity indicators. Table 4 lists the variables selected in WILIAM to integrate the dimension of biodiversity. So, policies and endogenous causal loops influence to these indicators.

Table 4. Biodiversity sub-module inputs from WILIAM.

Indicators	Description	Units
Land use area by region	Area of each land use included in WILIAM by nine regions.	km^2
Matrix of land use changes	Matrix of land use changes by nine regions from a donor land to a receiving land.	km^2/ year
Roundwood extracted	All the roundwood extracted by nine regions.	t /Year
Land products available from croplands	Land products produced by nine regions from all croplands	t /Year
Average share of regenerative agriculture	Average percentage of regenerative agriculture by nine regions.	%
Average share of traditional agriculture	Average percentage of traditional agriculture by nine regions.	%
Share of grasslands under regenerative management	Average percentage of grasslands under regenerative management by nine regions.	%

Funded by
the European Union

2.1.2.1 NPP-HANPP on WILIAM

To achieve a deeper understanding of the human appropriation, this pair of indicators have been modelled at three levels: global, regional, and regional forest. The three levels share the same methodology as shown in Figure 9:

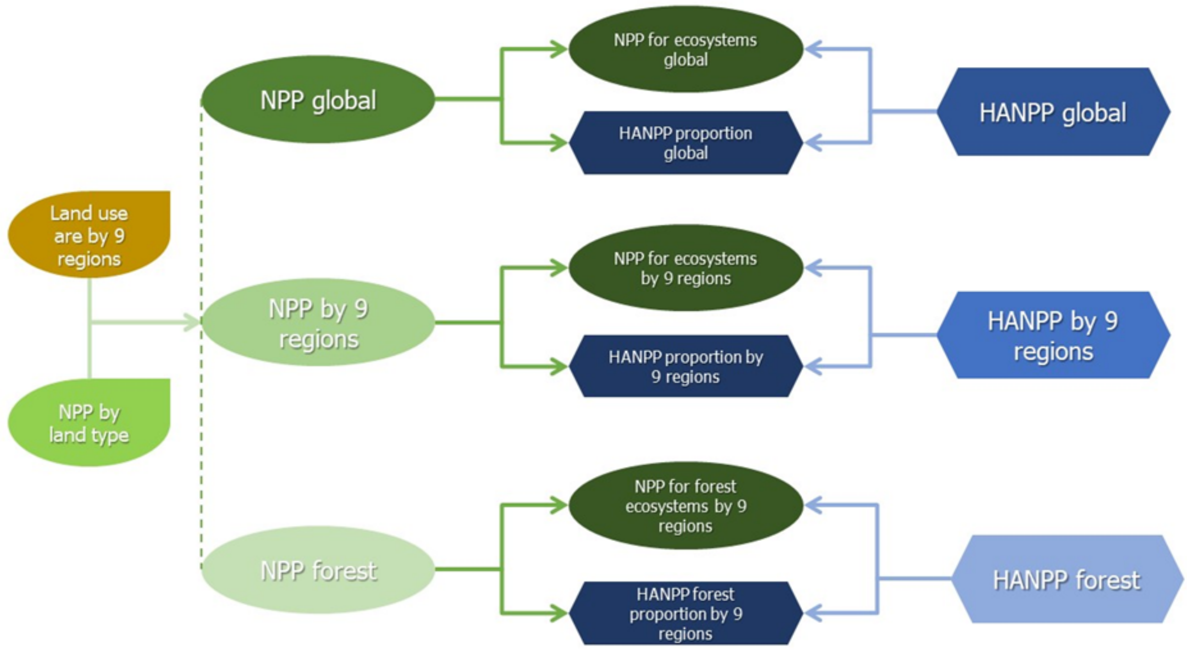


Figure 9. NPP-HANPP framework of WILIAM

Net primary production has been calculated by confronting year by year production factors of the different land uses and the area of each land use. Land uses vary in the type and complexity of vegetation, resulting in different levels of NPP production (i.e. forest primary produces the highest and most stable NPP of all the land use types collected on WILIAM). In the case of forest lands, production also logically varies according to forest type and bioclimatic area (Li et al., 2018; Huston & Wolverton, 2009), but these variations could not be considered due to the type of aggregation of the model and have been adjusted and weighted. Another highlight is the integration of the effects of the different types of agro-pastoral management. Human appropriation of NPP has been estimated following the formula descripted on (Haberl et al., 2014):

$$HANPP = HANPP_{luc} + HANPP_{harv}$$

Where $HANNP_{luc}$ is the NPP change due to human-induced land alteration, while $HANPP_{harv}$ is the NPP appropriation due to harvests (Marull et al., 2018). $HANNP_{luc}$ is calculated by the result of the balance between losses and gains of each land type, allowing the model to estimate the annual changes in NPP due to the different production values of each land type. In summary, losses in NPP due to land use changes. The other component, $HANPP_{hav}$, is the sum of every activity related to the recollection of land products, i.e., all products (including residues) obtained from cropland for different uses, roundwood extracted (the measurement of solid wood content and bark volume, which plays a key role in the wood supply chain (Berendt et al., 2021)), and the effect of grazing on grasslands (Figure 10). Specifically, NPP forest is only harvested by roundwood extraction in WILIAM model.

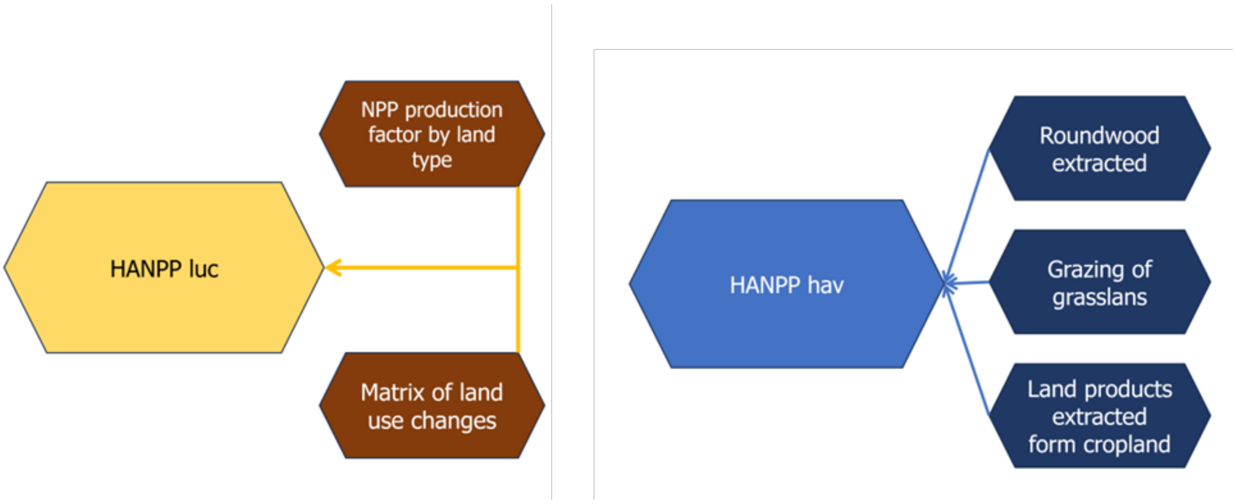


Figure 10. Variables used to calculate HANPP in WILIAM

Once both indicators (NPP and HANPP) are estimated and comparison between them is made, they can provide information about the pressure of human activities to ecosystems. Specifically, the NPP remaining for ecosystems after the human appropriation and the proportion of HANPP. Within this structure, the Planetary Boundaries framework fits well. As Richardson et al., 2023 suggest, the change in biosphere integrity is defined by the genetic diversity and the functional integrity. This second one is defining as the proportion of Holocene NPP that have been lost due to human activities. HANPP for this planetary boundary have been set on the 10% of Holocene NPP and the upper limit of the increasing zone risk on 20% (Figure 11). WILIAM extracts the data of mean Holocene NPP from Richardson et al., 2023 and compare it with the HANPP dynamically estimated to simulate the status of the functional integrity. It should be clarified that this framework is not suitable for the NPP-HANPP estimated at regional and forest level because the regional boundaries differ from WILIAM regions.

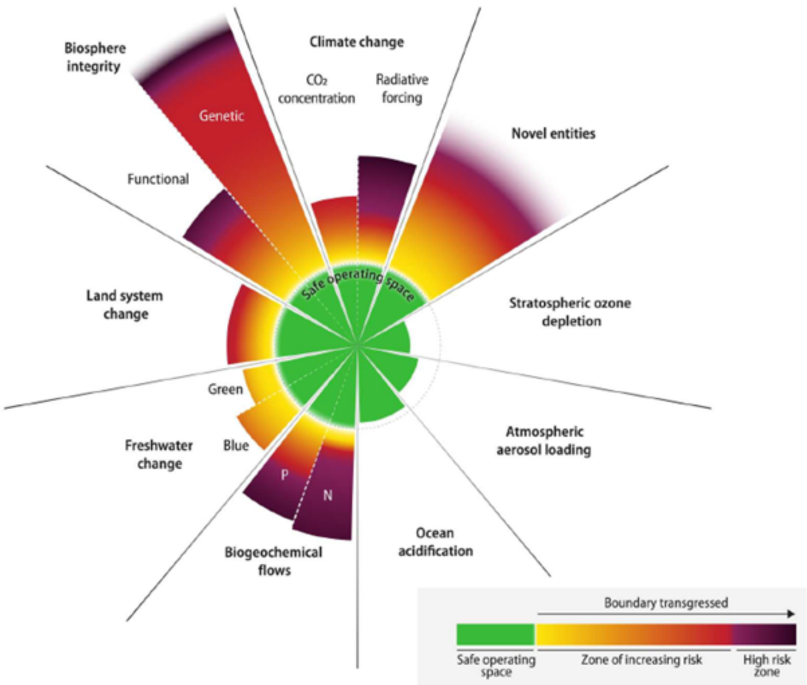


Figure 11. Planetary boundaries extracted from Richardson et al., 2023, where Biosphere integrity is already on the high-risk zone.

2.1.2.2 Biodiversity habitat index (BHI) on WILIAM

As mentioned in the introduction, BHI is used to illustrate the correlation between the loss of habitats and the loss of species richness. However, due to the FAO database origin of the WILIAM land classification, it was deemed necessary to decrease the level of aggregation used for this indicator. As a result, it is now only applied to forest ecosystems, as indicated in Figure 12.

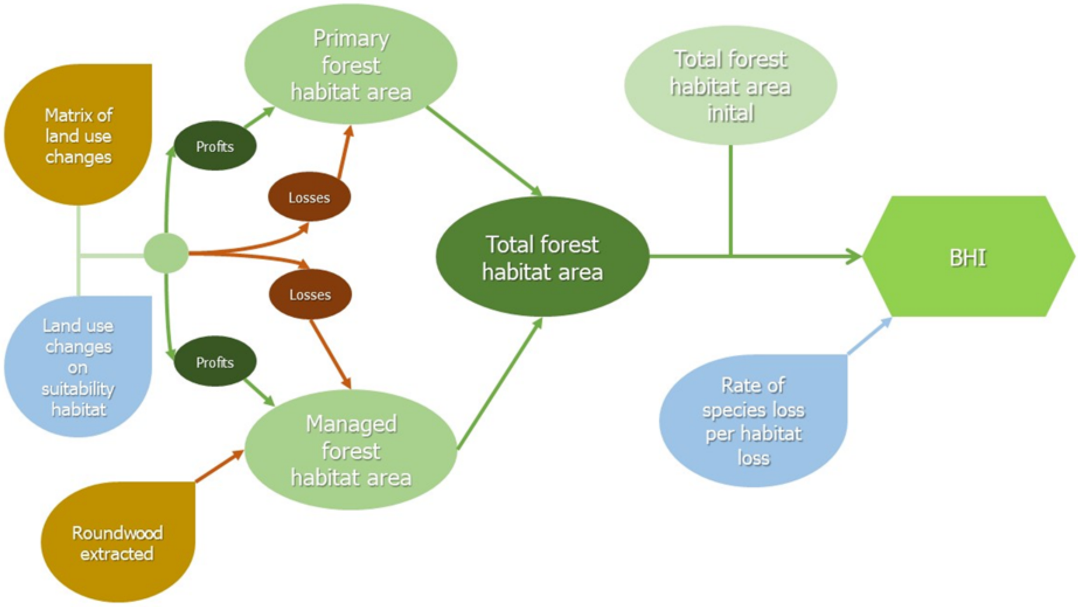


Figure 12: Biodiversity habitat index framework in WILIAM

Forest habitat loss is mainly driven by land-use change (i.e. deforestation, fragmentation etc…) as this is the starting point for estimating BHI on WILIAM. First, the biodiversity submodule weights the different land types on WILIAM as a suitable habitat factor. These suitable habitat factors rely on the concept of secondary succession of forest habitat. This concept reflects how plant communities regrow after a natural or anthropogenic disturbance (Pérez-Hernández & Gavilán, 2021). Although secondary succession differs between cases and ecoregions, WILIAM takes the traditional approach show in the Figure 13 as refence in order to homogenise (Johnson & Miyanishi, 2008).

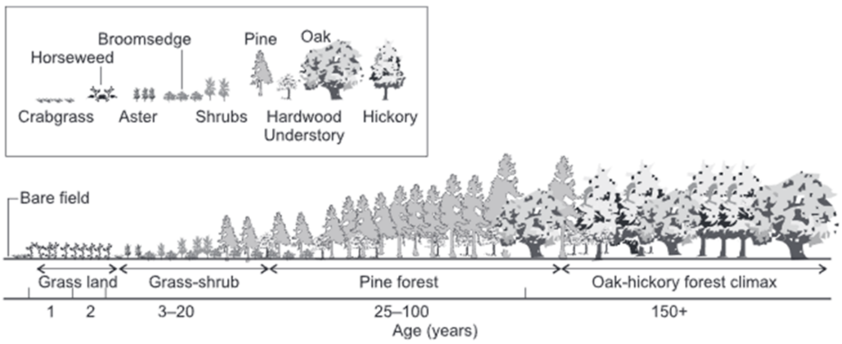


Figure 13. Ecological succession. Source: (Johnson & Miyanishi, 2008)

Table 5. Equivalence of suitable forest habitat factor and secondary succession. WILIAM Land type equals to 0 have been excluded from this table.

	WILIAM land type			
	Grassland	Shrubland	Forest managed	Forest primary
Suitable habitat factor	0.02	0.13	0.7	1

Considering that it takes an average of 150 years to return to the forest climax, which is fully suitable for forest species, and the average time taken by each successional stage, the values in the Table 5 have been proposed. This approach makes it possible to distinguish between land use changes associated with ecological succession phases and incorporate differences in the habitat fragmentation. Then the profits and losses of forest habitat due to changes on primary forest and managed forest can be estimated and compared to the initial total forest (2005, which is the first year of simulation in WILIAM) resulting on the change of forest habitat area.

The formula used for the determination of BHI is taken from Ferrier et al., 2004:

$$\frac{S_{retained}}{S_{original}} = \left(\frac{A_{retained}}{A_{original}}\right)^{z}$$

Where the quotient between retained species ($S_{retained}$) and original species ($S_{original}$) is the index BHI; the quotient between actual area ($A_{retained}$) and original area ($A_{original}$) is the change of forest habitat area estimated; and the z is a ratio of loss of species per loss of area which is set on 0.25 (Ferrier et al., 2004).

Funded by
the European Union

2.2 Simulations with WILIAM

WILIAM is a model that requires external inputs. These inputs include policies that fall under the policy spectrum. To define the rest of the scenarios, a scenario called NDC_LTT has been established as the foundation for policy changes. Table 6 outlines the policies that will affect the biodiversity indicators mentioned above.

Table 6. Policies currently available on WILIAM used for the simulations.

Name of policy	Brief description	Target
Afforestation	Increase of managed forest, this is an increase of the high-medium biodiversity forest (not the increase of tree plantations)	Increase of Forest managed area
Diet Patterns	The population starts a cultural-driven change of diet to the policy diets.	Change in the demands of area from crops to food.
Forest Lost limit	Limits to loss of forest due to demands of area from other types of lands	Limits to the extraction of forest biomass.
Forestry self-sufficiency	Change in the allocation of the demand of forestry products to producing regions.	Volume loss of forest
Share bioenergy in TI liquids and gases	Share of bioenergy (biofuels and biogas) in transformation input (TI) liquids and gases (excluding synthetic fuels)	Crops area demanded for bioenergy

The policies included in WILIAM will determine the scenarios (Table 7) that are simulated with the goal of gaining a deeper understanding of biodiversity, material resources, and biophysical limits.

Table 7. Scenarios designed based on NDC_LTT scenario.

	Policies				
Scenario	**Afforestation**	**Diet Patterns**	**Forest Lost limit**	**Forestry self sufficiency**	**Share bioenergy in TI liquids and gases**
NDC_LTT	10% of reference area (2015)	Flexitarian diet patterns. 50% population EU	80% Forest full protected	Not activated	15% at 2025
NDC_LTT Afforestation	20% of reference area (2015)	Flexitarian diet patterns. 50% population EU	80% Forest full protected	Not activated	15% at 2025
NDC_LTT Plant base pattern diet	10% of reference area (2015)	Plant_based 50 percent diet pattern 100% population EU	80% Forest full protected	Not activated	15% at 2025

Funded by
the European Union

NDC_LTT Forest self-sufficiency	10% of reference area (2015)	Flexitarian diet patterns. 50% population EU	50% Forest full protected	Reach full sufficiency forestry in 2050 starting in 2025. (EU)	15% at 2025
NDC_LTT Biofuels	No afforestation	Flexitarian diet patterns. 50% population EU	No limits	Not activated	20% at 2025

Hence, the designed scenarios are briefly described below:

1. *NDC_LTT Afforestation* prioritises increasing forest cover in all regions.
2. *NDC_LTT Plant base pattern diet"* explores the impact of changing the dietary patterns of the whole population to include more plant-based foods and less animal-based products.
3. *NDC_LTT Forest self-sufficiency* estimates the impact of transforming the European forestry market to make it self-sufficient. In this scenario, Europe, the United Kingdom, the United States, Canada, and Mexico fulfil their demand for roundwood by harvesting it from their own forest rather than importing it from other regions.
4. *NDC_LTT Biofuels* prioritises biofuels as an energy source requiring crops for energy production.

It is worth mentioning that the policies were applied in the WILIAM region related to Europe. Although there are policies that have been activated for the other regions, the results we will focus on are those that correspond to the region covered by this project.

2.3 Results and policy recommendations

The next results have been gathered by using WILIAM and cover a period from 2005 to 2050, allowing users to visualise the different indicator trends and their changes. A brief overview of these results and their interpretation is given below.

2.3.1 NPP-HANPP

As explained in the introduction, the NPP-HANPP relationship reflects human pressures on the biosphere that disrupt its functions. One of these functions is the absorption of CO_2 from the atmosphere by the photosynthesis of the vegetation cover, which is essentially NPP. Considering the vegetation cover as a carbon sink, the higher the NPP, the higher the CO2 uptake from the atmosphere. This link is not currently available on WILIAM but explains the relevance of NPP as an indicator. As we can see (Table 8), European NPP represent 3.6-3.7% of global NPP.

Table 8: NPP results of the NDC_LTT scenario.

Scenario & year of simulation	Global NPP (Gt C)	European NPP (Gt C)	% EU NPP from Global
NDC_LTT 2005	47.98	1.74	3.6
NDC_LTT 2050	48.05	1.78	3.7

Europe shows slights variations in NPP between the different scenarios simulated, but it is possible to discern distinguishable trends due to the policies applied (Figure 14). From 2020 onwards, the *Forestry self-sufficiency* and *NDC_LTT* scenarios show an impasse in its growth trend. The Afforestation scenario provides the best results in the short and medium term. *Biofuels* scenarios experiment a quick growth during the policy implementation but end with a declining trend. In contrast, the *Plant base pattern diet* scenario grows slowly but reach the best marks at the final year of simulation. The reason being that most of the NPP stems from croplands, which are less stable in the medium to long term compared to forests and natural ecosystems. This is due to the depletion of soil nutrient cycles and water availability (Xiao et al., 2019).

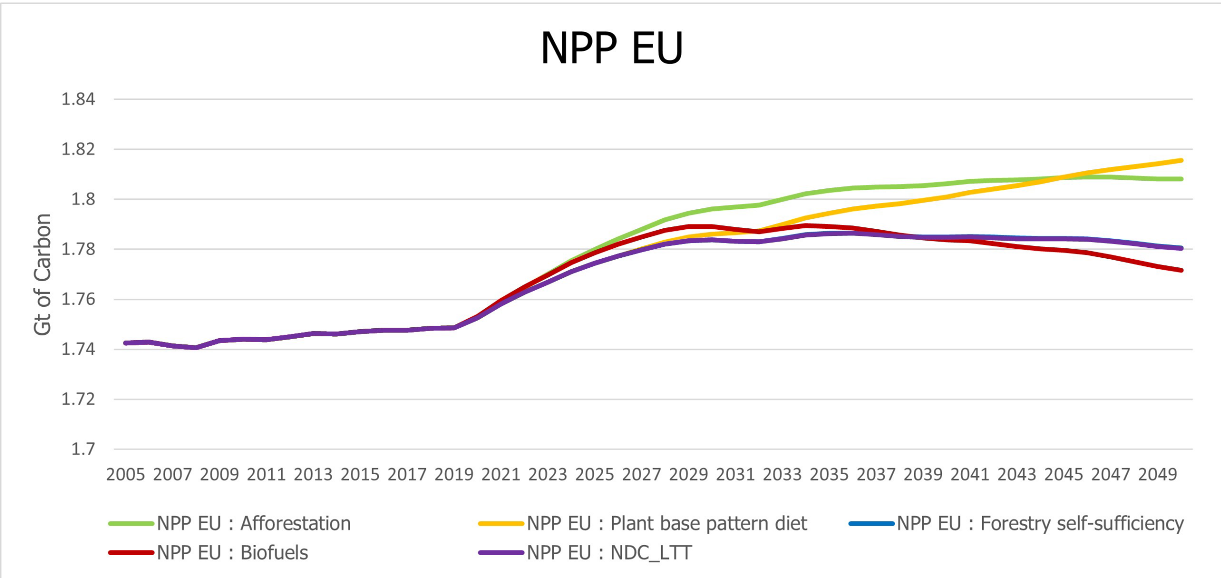


Figure 14. Net Primary Production (NPP) from EU27 WILIAM region that correspond to Europe

Human appropriation of NPP

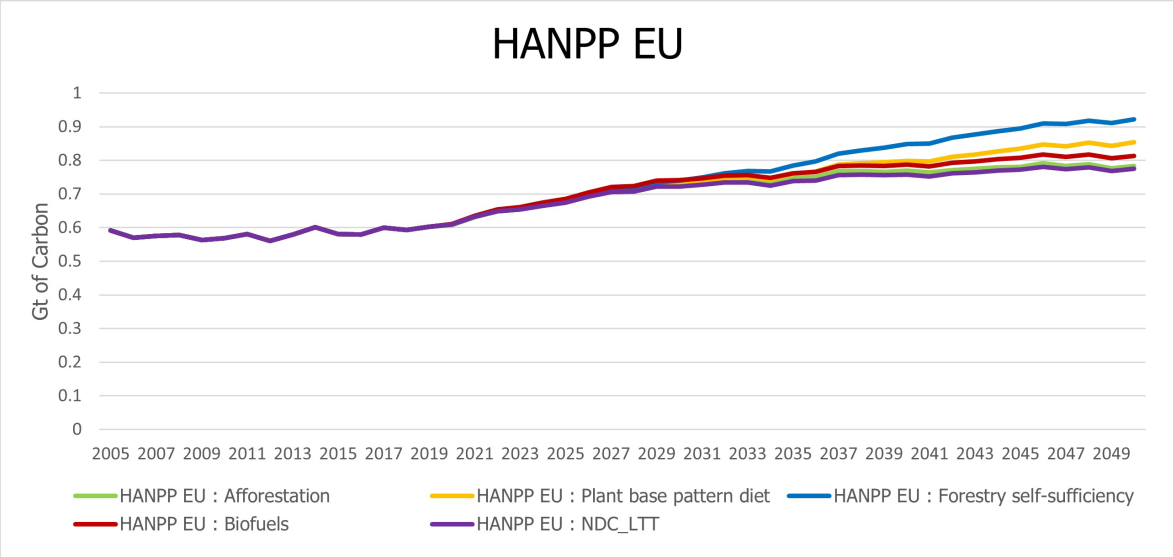


Figure 15. Human appropriation of Net Primary Production (HANPP) for Europe

On the other side, HANPP reflects the intensity of human activities that directly appropriate of the NPP produced by the vegetal cover. Trends of all scenarios are because they are variations of *NCD_LTT* (Figure 15). Highlight that this indicator show that the smallest increasing of all of them comes from the *NDC_LTT* and *Afforestation* scenario, which are focus on the restoration of natural spaces such as forests. *Plant base pattern diet* scenario show the second biggest HANPP due to the bigger demand of crops for food to avoid the shortage. Finally, reaching the European *forestry self-sufficiency* entails the lowest NPP remaining after HANPP as a result of the highest HANPP and the low NPP growth; a consequence of taking the production demanded by the region onto its own land.

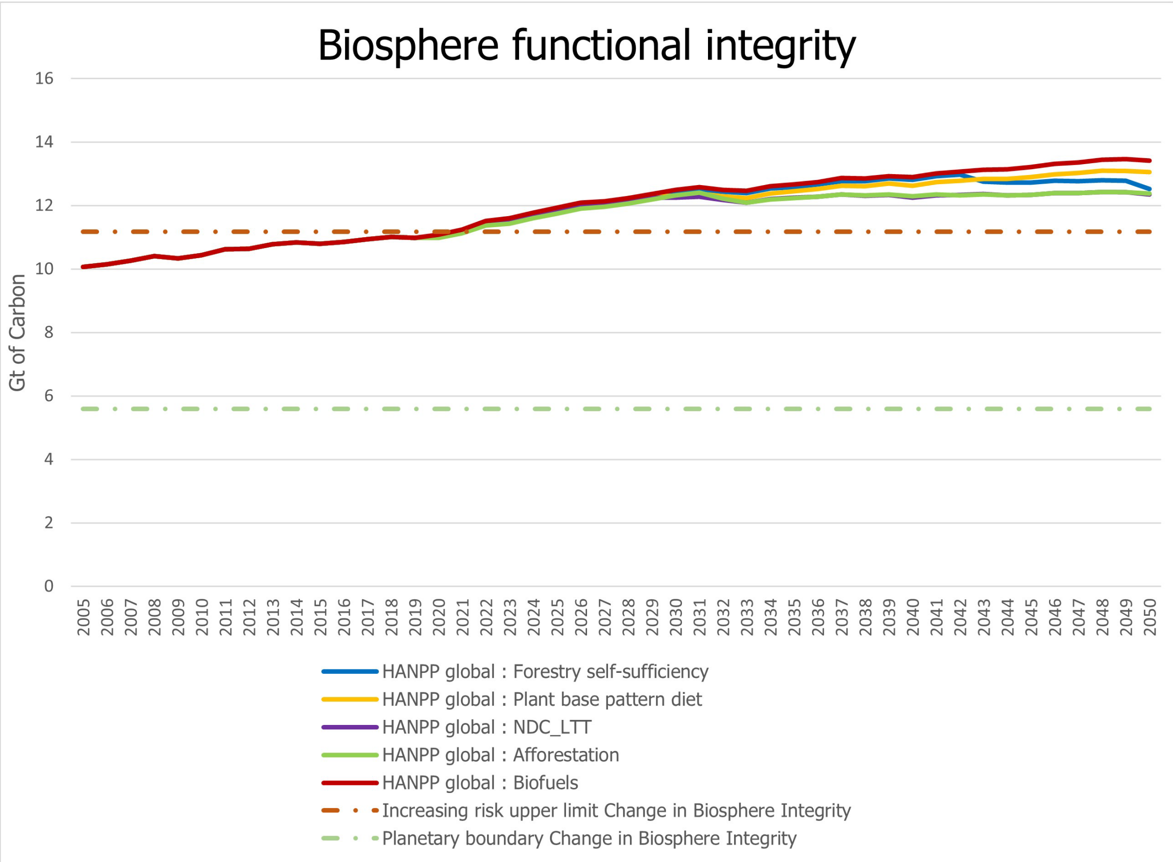


Figure 16. Biosphere functional integrity.

The planetary boundaries framework also provides us with a perspective to analyse the different outcomes of these scenarios. Richardson et al., 2023 approach of the change in biosphere planetary boundary set the mean Holocene NPP as the reference to quantify the planetary boundary and the upper limit of the increasing risk zone (10% and 20% of the mean Holocene NPP respectively). Figure 16 shows how the course of the global HANPP in all scenarios transgresses the upper limit of the increasing risk zone and become stable into the high-risk zone. Highlight the best pathways and the worst; the *Afforestation* and *NDC_LTT* scenarios stop their rise earlier than the others, and the *Forest self-sufficiency* scenario is the only one with a final downward trend; meanwhile, *Biofuels* scenario describes the sharpest rise.

2.3.2 EU Forest status: Forest NPP and Biodiversity Habitat Index (BHI)

The previous epigraph explores the biophysical limits of the biosphere and the effects of the management of material resources, therefore in this section we will get deeper into the biodiversity perspective. There are other ecosystems which are crucial to keep biodiversity in all its categories but the structure of WILIAM is more suitable to explore the status of forest land. In WILIAM forest primary are almost fully protected and the changes on forest area comes from forest under management. Taking this to account, the following results estimates biodiversity indicators trends of European forest ecosystems.

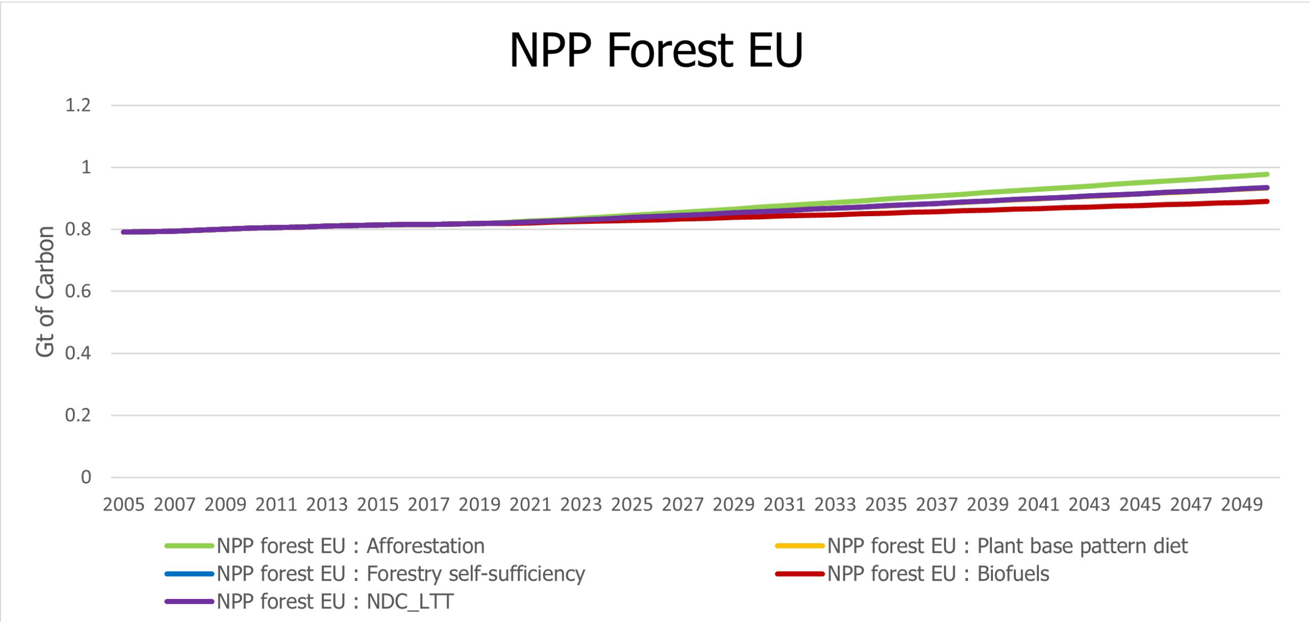


Figure 17. NPP produced by the forest of Europe.

In the Figure 17*,* there are three different clusters that share the same rising trajectory: those with a policy of afforestation of 10% of the 2015 area (*NDC_LTT, Forestry self-sufficiency* and *Plant base pattern diet*); the greater one that correspond with the afforestation of 20% (*Afforestation*); and the smooth one which is the one without afforestation policy (*Biofuels*). The differences between them comes from the total area of forest primary and managed. Regarding HANPP (Figure 18), there's again three different clusters defined by the intensity of the roundwood extraction. While *NDC_LTT, Afforestation* and *Plant base pattern diet* scenarios don't increase the extraction above of trend and HANPP *Biofuels* scenario is slightly higher, the remarkable rise comes from the *Forestry self-sufficiency* scenario due to the transfer of the roundwood extraction pressure from other regions to European forest.

Funded by
the European Union

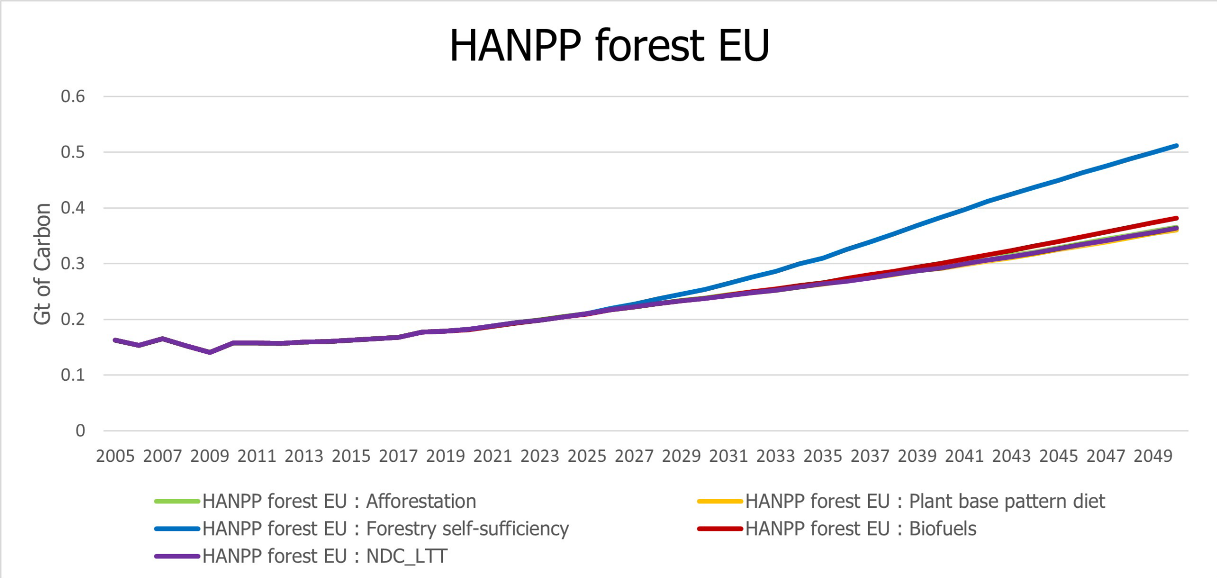


Figure 18. HANPP due to the loss of forest area and roundwood extracted from the forest of Europe

The major expression of the disturbance in the ecosystem carbon flow is the NPP that remains after being harvested or deforested. In the figure below (Figure 19) is estimated the NPP available for the ecosystem each year ranging from the 60-50% of the total NPP with a slightly downward trend in all scenarios. *Forestry self-sufficiency* experiment the more shaped decreased due to its high HANPP, and the best projection for European forest comes from the *Afforestation* scenario because of the increasing area of forest and the steady roundwood extraction.

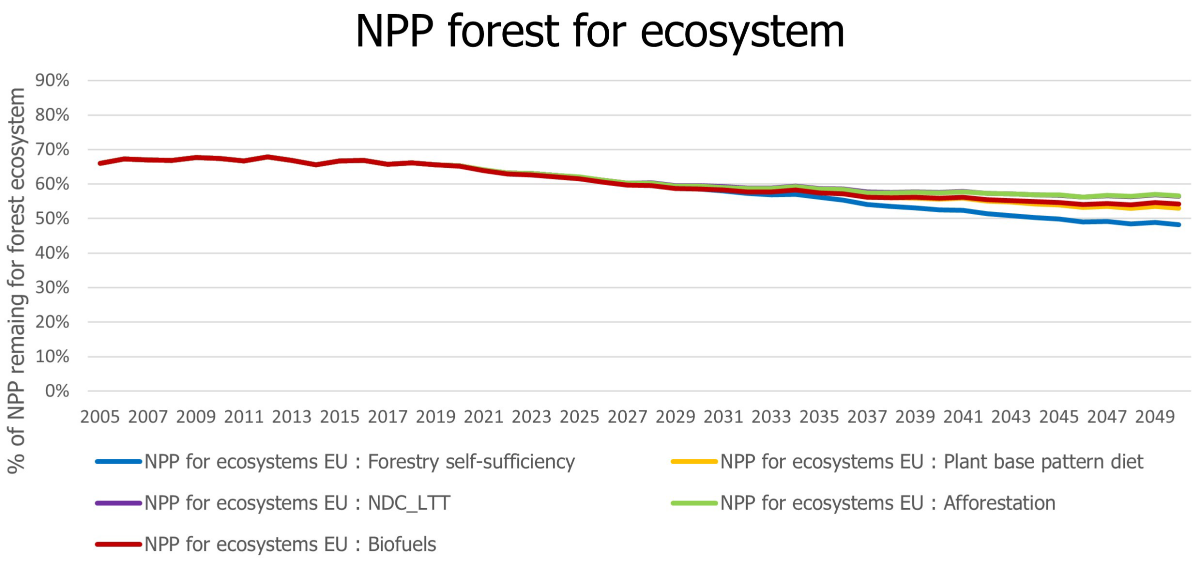


Figure 19. NPP remaining for forest ecosystem in Europe.

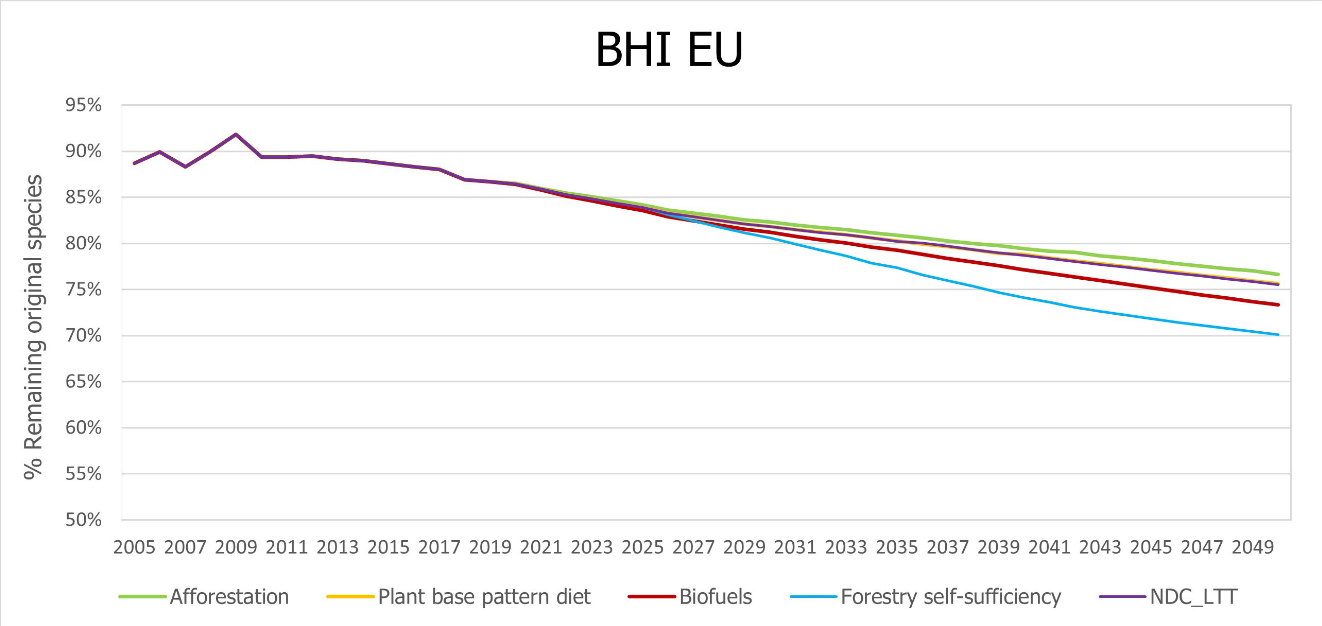


Figure 20. Biodiversity Habitat Index (BHI) of forest ecosystem in Europe. The % shows the proportion of original species remaining.

Regarding the ecosystem structure of European forests, the Biodiversity Habitat Index (BHI) shows a declining trend, indicating that these ecosystems would lose at least the 13% of species that inhabited European forests in 2005 (Figure 20). Habitat lost is driven by loss of forest area and the intensity of disturbance due to roundwood extraction in managed forest. *Afforestation* scenario shows the smallest decrease and persist as the best scenario to biodiversity indicators. *Plant base pattern diet* and *NCD_LTT* scenarios don't fall below the 75% original species remaining, because of the medium values of extraction. *Biofuels* scenario answers to the loss of forest area and consequently of NPP. *Forestry self-sufficiency* scenario is well linked with the lowest mark in NPP for the ecosystem showing the most pessimistic tendency due to the rising pressure on our local forests.

2.3.3 Policy recommendations

Both NPP-HANPP and BHI provide us with information on the causal-effect consequences of the policies implemented. The effectiveness of policies can be analysed across all sectors of our society, but here we have focused on certain impacts on the biosphere and forest ecosystem. These impacts should guide us in setting limits for managing our material resources.

The change in biosphere integrity exceeds the safety limits in all scenarios, therefore the goal to achieve is to reduce the pressure of human activities on ecosystems. Afforestation policies increase forest area and without an increment of forest HANPP this ecosystem could keep its functional integrity better than the other scenarios. Moreover, the least loss of habitat results in the lowest loss of species and damage to ecosystem structure. Although the investment on afforestation gives good results in all the indicators presented, requires land availability and strongest protection of managed forest (Doelman et al., 2020).

Forestry self-sufficiency also provides the second-best result at global scale, but it intensifies the pressure on European forests that must fulfil the region's own increasing demand rather than being outsourced. This fall of NPP for forest ecosystems results on greater disturbance of the ecosystem structure and functionality, leading to a greater loss of species, as is reflected on BHI results.

Increasing the proportion of plant-based foods in Europe's diet to 50% would require shifting from animal products to crops and expanding crop areas at the expense of grasslands and shrublands. Expanding cropland can increase the Net Primary Productivity (NPP), but it can also lead to higher Human Appropriation of Net Primary Productivity (HANPP), which ultimately has no positive impact on ecosystems. Therefore, policies that promote cropland expansion, such as *Biofuels* and *Plant Base pattern diet*, are considered the worst-case scenarios globally. In contrast, *Plant Base pattern diet* doesn't directly affect to forest, and consequently does not lead to a drastic loss of forest species, but to grassland and shrubland species.

To sum up, every policy brings both benefits and harms, and the goal to be achieved should determine policy priorities. If the priority is to restore and conserve biodiversity in a structural and functional way, then afforestation policies are the best pathway to progressing towards the SDG 15 "Life on land".

2.4 Modelling capacity improvements

In relation to the requirements of Task 5.6.2 and the current state of WILIAM development, this deliverable addresses the impact of land use competition on ecosystems and biodiversity. In the meantime, the consequences of the mining of materials that are crucial for the development of low-carbon technologies will be the subject of a forthcoming update.

Further enhancements to the current outcomes could be found by exploring the feedback between NPP and Carbon sequestration, resulting on a deeper understanding of the global climate effects of vegetal cover. The atmospheric CO_2 concentration also affects the global levels of NPP, creating negative feedback loop that balance the system; higher atmospheric CO_2 enhances atmospheric carbon sequestration by vegetal cover (Ueyama et al., 2020). In contrast, global warming reduces the productivity and increase the soil respiration (Tian et al., 2021). Both variables are needed to be integrated on NPP estimations. Regarding the production factors of each type of land, it would be necessary a differentiation by regions because of the significatively differences between bioclimatic zones.

HANPP could be underestimated because of the absence of some human activities directs impacts on NPP. Pollution and degradation of soil are also drivers of loss of NPP that are not currently affecting the model (Xiao et al., 2019).

Finally, the BHI recall for the integration of ecosystem fragmentation, whose effects drastically reduce habitat increasing species loss, especially in forest ecosystems (*Global Forest Resources Assessment 2020*, 2020).

References

Banks-Leite, C., Ewers, R. M., Folkard-Tapp, H., & Fraser, A. (2020). Countering the effects of habitat loss, fragmentation, and degradation through habitat restoration. One Earth, 3(6), 672-676. https://doi.org/10.1016/j.oneear.2020.11.016

Berendt, F., De Miguel-Diez, F., Wallor, E., Blasko, L., & Cremer, T. (2021). Comparison of different approaches to estimate bark volume of industrial wood at disc and log scale. Scientific Reports, 11(1), 15630. https://doi.org/10.1038/s41598-021-95188-z

Chase, J. M., Blowes, S. A., Knight, T. M., Gerstner, K., & May, F. (2020). Ecosystem decay exacerbates biodiversity loss with habitat loss. Nature, 584(7820), 238-243. https://doi.org/10.1038/s41586-020-2531-2

Díaz, S., & Malhi, Y. (2022). Biodiversity: Concepts, Patterns, Trends, and Perspectives. Annual Review of Environment and Resources, 47(1), 31-63. https://doi.org/10.1146/annurev-environ-120120-054300

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., Van Oudenhoven, A. P. E., Van Der Plaat, F., Schröter, M., Lavorel, S., … Shirayama, Y. (2018). Assessing nature's contributions to people. Science, 359(6373), 270-272. https://doi.org/10.1126/science.aap8826

Doelman, J. C., Stehfest, E., Van Vuuren, D. P., Tabeau, A., Hof, A. F., Braakhekke, M. C., Gernaat, D. E. H. J., Van Den Berg, M., Van Zeist, W., Daioglou, V., Van Meijl, H., & Lucas, P. L. (2020). Afforestation for climate change mitigation: Potentials, risks and trade-offs. Global Change Biology, 26(3), 1576-1591. https://doi.org/10.1111/gcb.14887

Ferrier, S., Powell, G. V. N., Richardson, K. S., Manion, G., Overton, J. M., Allnutt, T. F., Cameron, S. E., Mantle, K., Burgess, N. D., Faith, D. P., Lamoreux, J. F., Kier, G., Hijmans, R. J., Funk, V. A., Cassis, G. A., Fisher, B. L., Flemons, P., Lees, D., Lovett, J. C., & Van Rompaey, R. S. A. R. (2004). Mapping More of Terrestrial Biodiversity for Global Conservation Assessment. BioScience, 54(12), 1101. https://doi.org/10.1641/0006-3568(2004)054

Group on Earth Observations Biodiversity Observation Network (GEO BON). (2014). Essential Biodiversity Variables (EBVs). Recuperado de https://geobon.org/ebvs/what-are-ebvs/

Haberl, H., Erb, K.-H., & Krausmann, F. (2014). Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries. Annual Review of Environment and Resources, 39(1), 363-391. https://doi.org/10.1146/annurev-environ-121912-094620

Harfoot, M. B. J., Newbold, T., Tittensor, D. P., Emmott, S., Hutton, J., Lyutsarev, V., Smith, M. J., Scharlemann, J. P. W., & Purves, D. W. (2014). Emergent Global Patterns of Ecosystem Structure and Function from a Mechanistic General Ecosystem Model. PLoS Biology, 12(4), e1001841. https://doi.org/10.1371/journal.pbio.1001841

Hoskins, A. J., Harwood, T. D., Ware, C., Williams, K. J., Perry, J. J., Ota, N., Croft, J. R., Yeates, D. K., Jetz, W., Golebiewski, M., Purvis, A., Robertson, T., & Ferrier, S. (2018). Supporting global biodiversity assessment through high-resolution macroecological modelling: Methodological underpinnings of the BILBI framework [Preprint]. Ecology. https://doi.org/10.1101/309377

Huston, M. A., & Wolverton, S. (2009). The global distribution of net primary production: Resolving the paradox. Ecological Monographs, 79(3), 343-377. https://doi.org/10.1890/08-0588.1

Johnson, E. A., & Miyanishi, K. (2008). Testing the assumptions of chronosequences in succession. Ecology Letters, 11(5), 419-431. https://doi.org/10.1111/j.1461-0248.2008.01173.x

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H. M., Chaudhary, A., De Palma, A., DeClerck, F. A. J., Di Marco, M., Doelman, J. C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J.

P., Hill, S. L. L., Humpenöder, F., Jennings, N., Krisztin, T., … Young, L. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature, 585(7826), 551-556. https://doi.org/10.1038/s41586-020-2705-y

Li, J., Wang, Z., Lai, C., Wu, X., Zeng, Z., Chen, X., & Lian, Y. (2018). Response of net primary production to land use and land cover change in mainland China since the late 1980s. Science of The Total Environment, 639, 237-247. https://doi.org/10.1016/j.scitotenv.2018.05.155

Liang, J., Wang, S., Liu, K., Wang, J., Zhou, J., Liu, X., Feng, K., & Fang, C. (2023). Agricultural HANPP Embodied in Consumption: Tracing Pressure on Ecosystems Based on an MRIO Analysis. Environmental Science & Technology, 57(37), 13838-13850. https://doi.org/10.1021/acs.est.3c04225

Marull, J., Tello, E., Bagaria, G., Font, X., Cattaneo, C., & Pino, J. (2018). Exploring the links between social metabolism and biodiversity distribution across landscape gradients: A regional-scale contribution to the land-sharing versus land-sparing debate. Science of The Total Environment, 619-620, 1272-1285. https://doi.org/10.1016/j.scitotenv.2017.11.196

Minasny, B., Arrouays, D., Cardinael, R., Chabbi, A., Farrell, M., Henry, B., Koutika, L.-S., Ladha, J. K., McBratney, Alex. B., Padarian, J., Román Dobarco, M., Rumpel, C., Smith, P., & Soussana, J.-F. (2022). Current NPP cannot predict future soil organic carbon sequestration potential. Comment on "Photosynthetic limits on carbon sequestration in croplands". Geoderma, 424, 115975. https://doi.org/10.1016/j.geoderma.2022.115975

Oettel, J., & Lapin, K. (2021). Linking forest management and biodiversity indicators to strengthen sustainable forest management in Europe. Ecological Indicators, 122, 107275. https://doi.org/10.1016/j.ecolind.2020.107275

Parson, E. A., & Fisher-Vanden, A. K. (1997). INTEGRATED ASSESSMENT MODELS OF GLOBAL CLIMATE CHANGE. Annual Review of Energy and the Environment, 22(1), 589-628. https://doi.org/10.1146/annurev.energy.22.1.589

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., Bruford, M. W., Brummitt, N., Butchart, S. H. M., Cardoso, A. C., Coops, N. C., Dulloo, E., Faith, D. P., Freyhof, J., Gregory, R. D., Heip, C., Höft, R., Hurtt, G., Jetz, W., … Wegmann, M. (2013). Essential Biodiversity Variables. Science, 339(6117), 277-278. https://doi.org/10.1126/science.1229931

Pérez-Hernández, J., & Gavilán, R. G. (2021). Impacts of Land-Use Changes on Vegetation and Ecosystem Functioning: Old-Field Secondary Succession. Plants, 10(5), 990. https://doi.org/10.3390/plants10050990

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. Science Advances, 9(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Rotmans, J., den Elzen, M. (1999). Global Biogeochemical Cycles. In: Martens, P., Rotmans, J., Jansen, D., Vrieze, K. (eds) Climate Change: An Integrated Perspective. Advances in Global Change Research, vol 1. Springer, Dordrecht. https://doi.org/10.1007/0-306-47982-6_4

Samsó, R., Ramos, I., Ferreras-Alonso, N., Lifi, M., Mediavilla, M., Llases, L., de Blas Sanz, I., Capellán-Pérez, I., Parrado-Hernando, G., Calleja, M., Álvarez Antelo, D., Markovska, N., Arto, I., Calheiros, T., Papagianni, S., van Allen, O., Eggler, L., (2023). LOCOMOTION Deliverable No. D11.2: Python translation and e-Handbook for model sharing and transparency. https://www.locomotion-h2020.eu/resources/main-project-reports/

Schils, R. L. M., Bufe, C., Rhymer, C. M., Francksen, R. M., Klaus, V. H., Abdalla, M., Milazzo, F., Lellei-Kovács, E., Berge, H. T., Bertora, C., Chodkiewicz, A., Dămătîrcă, C., Feigenwinter, I., Fernández-Rebollo, P., Ghiasi, S., Hejduk, S., Hiron, M., Janicka, M., Pellaton, R., … Price, J. P. N. (2022). Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality. Agriculture, Ecosystems & Environment, 330, 107891. https://doi.org/10.1016/j.agee.2022.107891

Van Beek, L., Hajer, M., Pelzer, P., Van Vuuren, D., & Cassen, C. (2020). Anticipating futures through models: The rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. Global Environmental Change, 65, 102191. https://doi.org/10.1016/j.gloenvcha.2020.102191

Veerkamp, C. J., Dunford, R. W., Harrison, P. A., Mandryk, M., Priess, J. A., Schipper, A. M., Stehfest, E., & Alkemade, R. (2020). Future projections of biodiversity and ecosystem services in Europe with two integrated assessment models. Regional Environmental Change, 20(3), 103. https://doi.org/10.1007/s10113-020-01685-8

Xiao, X., Li, X., Jiang, T., Tan, M., Hu, M., Liu, Y., & Zeng, W. (2019). Response of net primary production to land use and climate changes in the middle-reaches of the Heihe River Basin. Ecology and Evolution, 9(8), 4651-4666. https://doi.org/10.1002/ece3.5068

Funded by
the European Union

3 Uncertainty analysis of investments against multiple SDG indicators

The previous sections emphasised the multifaceted nature of the sustainable development agenda as well as the complexity of mapping SDGs onto IAMs. As discussed in Section 1, IAMs typically represent a subset of the indicators incorporated in each SDG (or proxies thereof) and offer the capacity to quantify certain implications of mitigation from a thus limited sustainability perspective. So far, modelling science has focused on different aspects of the interplay (co-benefits and trade-offs) between climate mitigation and SDGs. Indicatively, Van Vuuren et al. (2015) had explored the impact of mitigation pathways based on different combinations of technological measures and behavioural changes to a set of sustainability objectives, Moyer and Bohl (2019) later analysed alternative development pathways to improve performance on human-development related SDGs, before Soergel et al. (2021) eventually introduced a sustainable development pathway, which constitutes a combination of mitigation and sustainable development policies to quantify climate and broader SDG outcomes. Recently, van Vuuren et al. (2022) formalised an analytical SDG target space for IAMs, which encompasses a comprehensive set of indicators that can be mapped onto IAM research to facilitate this process. This target space also formed the basis for the IAM COMPACT SDG mapping exercise in Section 2, essentially forming an accounting process aiming to help understand broader implications of climate action for the environment and society. Drawing on this space, Tagomori et al. (2024) sought to understand the synergies and trade-offs between climate policy and SDGs and in particular long-term climate impacts of near-term SDG-driven action, while Fuhrman et al. (2023) took a more technology-oriented approach, focusing on the impact of NETs and CDR technologies on SDGs and the broader energy–water–land systems, building on Fuhrman et al. (2019). Others took a regional approach; for instance, Moreno et al. (2024) analysed the impact of the new, more ambitious EU policy context (as reflected in the 'Fit for 55' and net-zero aspirations) on SDG progress in the EU and across Member States, while Zhang et al. (2024) carried out a similar analysis for China.

Despite numerous studies quantifying sustainability indicators, there has been a limited number of studies that integrate uncertainty into IAM-based decarbonisation narratives with respect to SDG progress. In the following sections, we aim to quantify implications of different decarbonisation pathways for multiple SDGs, considering different types of—including parametric and stochastic—uncertainties, as well as varying socioeconomic futures. To do so, we first develop a multi-level integration of GCAM and a multi-objective optimisation process (AUGMECON) to allocate mitigation budges to economic sectors (Section 3.1), and second, we link WILIAM with a stochastic multicriteria acceptability analysis to understand the potential uptake of different policy mixes (section 3.2). Both GCAM and WILIAM were found to be among the models with the highest level of indicator representation in the IAM COMPACT ensemble (see Section 1), but also incorporate different economic theories (partial equilibrium for GCAM and system dynamics for WILIAM), hence allowing to explore implications on a wide range of SDG-related implications and through different lenses.

3.1 GCAM x AUGMECON

3.1.1 Introduction

Due to the various levels of interactions among the different sustainability indicators (van Soest et al., 2019), progress in SDGs can be of competitive nature—hence the focus on co-benefits and trade-offs. Due to the accounting nature of the treatment of SDGs in IAMs, however, goals and targets associated with the sustainability agenda cannot influence the models' solution process, meaning that models are primarily economic tools that inherently prioritise economic aspects (whether driven by temperature targets or policies); to bypass this caveat, modellers need to hardcode specific policies as input to the models and then explicate their impact on SDGs, hence significant attention has been placed on developing 'sustainable development pathways'. In both cases the trade-offs of different SDGs, as well as the potential output of policies, may be narrowly viewed based on these limitations.

Here, we seek to bypass such limitations by introducing a combination of an IAM (GCAM) and a multi-objective optimisation algorithm (AUGMECON-R), to optimise the allocation of global mitigation efforts across five economic sectors in terms of performance in core sustainable development dimensions under uncertainty, to follow different end-of-century temperature-compliant trajectories. In doing so, we aim to unlock a wider spectrum of potential trade-offs, synergies, and impacts at both the sectoral and the sustainability level.

The analysis in this section is performed in collaboration with the Horizon 2020 NDC ASPECTS project, and mainly its deliverable 'D2.4: Report and academic article manuscript on global SDG impacts of new-generation global mitigation pathways'. A subsection in this report focuses on performing a sectoral stocktake of the mitigation potential of core economic sectors, before using the introduced multi-objective optimisation framework to produce a high-level quantified overview of mitigation co-benefits and trade-offs with selected SDG outcomes with a view to optimising progress in these outcomes for different levels of mitigation across different economic sectors, under emission budgets consistent with 2C, 1.7C and 1.5C futures. On top of this, our analysis here further delves into these optimisation outcomes within a dedicated stochastic uncertainty context.

3.1.2 Methods

The integration of multi-objective integer programming (MOIP) optimisation algorithms with Integrated IAMs has been attempted in the past with a view to expanding the typical economic minimisation objective of IAMs to additional dimensions/objectives. For example, van de Ven et al. (2022) and Koasidis et al. (2022) aimed to maximise emissions reductions and employment implications in major economies triggered by green recovery packages, given economic budget constraints. A similar integration of an IAM with an AUGMECON-based portfolio analysis framework has been attempted to maximise performance across a limited number of SDGs within specific geographical contexts (again under economic budget constraints), by allocating R&D subsidies to low-carbon technologies (van de Ven et al., 2019; Forouli et al., 2020). Here, we diverge from common practice of MOIP optimisation in IAM research, by optimising progress across selected SDG indicators under carbon (rather than economic) budget constraints.

We break down our analysis into four steps: i) definition of the problem space; ii) identification of the maximum potential for mitigation in each sector and the total mitigation required to achieve specific temperature goals; iii) simulation of individual scenarios with gradually varying sectoral allocations of mitigation effort using GCAM; and iv) synthesis of optimal portfolios using AUGMECON-R and analysis of the impact of uncertainty using Monte-Carlo simulations.

In the first step, the core decisions include the choice of models, the sectors to be used, and the SDGs to be analysed. Notably, the GCAM model and the link with AUGMECON-R was selected for two reasons: first, alongside WILIAM, GCAM features the representation of the most SDG indicators among the IAM COMPACT model ensemble (see Section 2) and additionally has been shown to reach ambitious temperature targets (including 1.5°C-compatible mitigation levels for each sector, which is necessary for this analysis); and, second, the GCAM – AUGMECON-R combination has been instigated and proven efficient in the recent literature. Although this choice inevitably affects the selection of sectors to examine, as a recursive-dynamic partial equilibrium IAM, GCAM can represent the majority of economic sectors. As such, in this exercise we include five core sectors:

- power supply
- industry
- buildings
- AFOLU
- transport

Our choice also plays a role in the sustainability dimensions selected to analyse vis-à-vis climate action. As elaborated in Section 2, GCAM features high representation of SDG dimensions. Based on our mapping, as well as drawing from Moreno et al., (2024) where high-level potential trade-offs have already been identified to emerge among several SDG indicators (e.g., notably, between economy and environmental dimensions), we select the following five sustainability dimensions:

- Poverty: average food basket price/GDPpc (index) (proxy for SDG2)
- Health: premature mortality (measured in individual persons) (proxy for SDG3)
- Economy: GDPpc growth (%) (proxy for SDG8)
- Land: % of unmanaged land/total land as a proxy for biodiversity (proxy for SDG15)
- Water: scarcity (index), defined as water withdrawals/renewable water supply (proxy for SDG14)

The second step includes the identification of the maximum mitigation potential of each sector, as well as the total maximum mitigation effort required (both by 2050) to ensure compliance with three global temperature targets: limiting mean global temperature increase to 1.5°C, 1.7°C, and 2°C. The rationale of including these three targets lies in shedding light on differences in the trade-offs across different pathways and mitigation efforts. Numerical values in these choices are based on extensive analysis of the sectoral stocktake performed in the NDC ASPECTS project (see report D2.4); said analysis was based on the ranges for each sector explicated from the AR6 scenario database (Byers et al, 2022) for a Current Policies and 2°C- and 1.5°C-compatible scenarios until 2050, combined with actual data on sectoral emissions up to 2020 (EDGAR). This led to the sectoral potentials and total mitigation effort required by 2050 compared to a current policies baseline presented in Table 9.

Table 9. Sectoral Mitigation potential and total mitigation required to achieve temperature goals.

Sector	Mitigation Potential by 2050 (Gt CO_2)
Industry	180.8
Buildings	39.3
Transportation	79.0
AFOLU	86.7
Power Supply	269.1
Temperature Target	**Total Mitigation required to reach each given target by 2050 (Gt CO_2)**
1.5°C	300
1.7°C	415
2°C	560

We split the maximum potential presented in Table 9 across sectors in increments of 5 $GtCO_2$ and run multiple sequential GCAM simulations, on top of a current policy baseline as defined in the IAM COMPACT scenario definition space, based on different levels of effort allocated to each sector independently. These start from zero effort to the maximum sectoral level, to later be used in the MOIP algorithm of step 4. To ensure linear independence of the scenarios, upon incrementally increasing the effort within a sector, all other sectors are fixed to their baseline values. This implies that GCAM is used to produce 131 independent scenarios, each one incorporating a different level of additional to the current policies mitigation effort in one sector. The 5 $GtCO_2$ step is selected to reduce computational complexity but also provide an adequate resolution of the produced outputs.

The produced outcomes can then be used to run the MOIP algorithm. The sectors described constitute the alternatives, the sustainability dimensions form the objectives, the total mitigation effort required (per temperature target) acts as the budgetary constraint, while the results of the GCAM model across the 131 scenarios form the payoff table. Essentially, the algorithm seeks to identify combinations of different levels of mitigation levels for each sector to achieve best performance across the 5 sustainability dimensions, constrained by the mitigation effort required to achieve a temperature target. This means that the three problems (one for each temperature target) are run independently, with the total mitigation effort in each case acting as a control variable to ensure that the calculated allocations are consistent with the given targets; the algorithm is constrained within a ±5 $GtCO_2$ range, to ensure that the solutions calculated are in line with the targets selected to avoid under- or over-performance—this was found necessary based on a set of initial test runs. As such, the formulation of each one of the three MOIP problems is as follows:

$$\max\{economy, unmanaged\ land\}\ and$$
$$\min\{poverty, mortalities, water\ scarcity\},$$
$$subject\ to \sum_{i=1}^{5} sectoral\ mitigation\ effort_i \geq total\ mitigation\ effort\ required - 5GtCO_2,$$
$$\sum_{i=1}^{5} sectoral\ mitigation\ effort_i \leq total\ mitigation\ effort\ required + 5GtCO_2.$$

Towards delving into the trade-offs emerging within the sustainability space, we follow the abovementioned formulation using all 5 objectives, but we also perform independent runs based on exhaustive two-dimensional combinations each time, to identify intricate dynamics between pairs of SDGs.

To ensure internal consistency, both the minimisation objectives and the 'more than' constraint are inverted to maximation objectives and a 'less than' constraint, respectively, through inverting their sign—e.g., instead of minimising mortality, avoided mortality was maximised instead. Also, as implied by the sectoral potential of Table 9, a constant increment of 5$GtCO_2$ implies that in the payoff table the alternatives do not incorporate the same number of levels. To form a uniform payoff table, outstanding levels not used are zeroed out, which on the one hand restricts the resolution compared to a non-constant increment but on the other does not produce a micro-selection behaviour in the sectors with low mitigation potential and consequently low SDG benefits and potentially unnecessarily complicated trade-offs, hence avoiding possible biases in the selection process.

Considering the goal of the study, which is to understand the impact of uncertainty regarding the outcomes of the optimisation process on the optimal sectoral allocations and the consequent performance in each SDG (proxy) indicator, we treat GCAM results as uncertain. That is, we assume that GCAM results (impact of a certain mitigation allocation to one sector on each sustainability dimension) follow a normal distribution with a mean value fixed on the GCAM output and a standard deviation of 5% (a protocol defined in van de Ven et al., 2022 and Koasidis et al., 2022). Based on this assumption, we run 100 iterations to produce a wider spectrum of Pareto-optimal allocations based on this stochastic uncertainty; in the next section, the modelling protocol focuses on the uncertainty of specific parameters, thereby ensuring that a wide range of uncertainties is quantified. Within the framing of this study, the iterations performed can be used to define a robustness level based on the number of appearances of each mix of sectoral allocations compared to the total number of iterations. Alternatively, we also focus on the appearance of each specific sectoral level used across all solutions in the iterations.

For solving the MOIP problems, we use the AUMECON-Py tool (Forouli et al., 2022), an open-source implementation and expansion of the AUGMECON-R algorithm (Nikas et al., 2022) building on the ε-constraint family and the augmented (AUGMECON) versions of optimisation methods. Towards accurately interpreting the produced results, contrary to the usually single-objective 'optimisation' process of IAMs, the outcome of this process is not a deterministically defined optimal solution, but rather a set of Pareto-optimal (non-dominated) solutions, which essentially constitute the set of solutions that no other alternative combination of mitigation effort across sectors performs better across all sustainability dimensions. The Monte Carlo uncertainty analysis even expands this definition to produce combinations of Pareto frontiers based on the multiple runs performed.

3.1.3 Results and discussion

By running the 131 independent GCAM scenarios, then parsing the results in the three AUGMECON-Py problems, and finally performing the uncertainty analysis in the form of 100 Monte Carlo iterations, our goal is to first identify the performance of each mitigation effort along the five sustainability dimensions. A notable difference of this process compared to an IAM modelling exercise only accounting for the performance of mitigation across each SDG lies in that the multi-objective optimisation setup contributes to fleshing out the performance that can be achieved along all dimensions simultaneously.

Notably, we highlight that a 1.5ºC-compliant scenario would reduce premature mortalities by 106-184 thousand avoided deaths, while increasing the usage of unmanaged land compared to total land by 0.2-2.36%. However, such a scenario would also be associated with an increase in poverty as reflected in the average food basket price on top of per capita GDP (1.1-3.4), while also leading to negative impact on per capita GDP growth by 0.15-0.35%; the impacts on water scarcity—as expressed by the amount of water withdrawals compared to total renewable water supply—are less profound, with scarcity however marginally deteriorating between 0.18-0.5 $*10^{-3}$. By relaxing the temperature constraint to 1.7ºC and 2ºC of warming, we observe similar trends for socioeconomic and environmental indicators, albeit to a lesser extent (see ranges in Table 10); the pattern seen in water scarcity leads to a marginally positive performance in the best-case scenario, although the range is still limited to marginal changes. Generally, the intra-SDG variance (i.e., the difference between the worst and best case for each SDG indicator independently) does not markedly change across scenarios, meaning that mitigation does not significantly amplify the uncertainty in the performance across each SDG. What is amplified, instead, is the trade-off between the selected SDG indicators themselves, with the dynamics between socioeconomic and environmental indicators becoming more prevalent as mitigation efforts intensify. This highlights that additional mitigation should also be associated with a careful evaluation on the performance (and thus appropriate policy design) along multiple sustainability dimensions to fully exploit co-benefits such as in the health and land domains, but also alleviate economic and poverty deterioration.

Table 10. Best and worst performance of the three mitigation cases across the five sustainability dimensions, including the configuration and performance of the most robust portfolio.

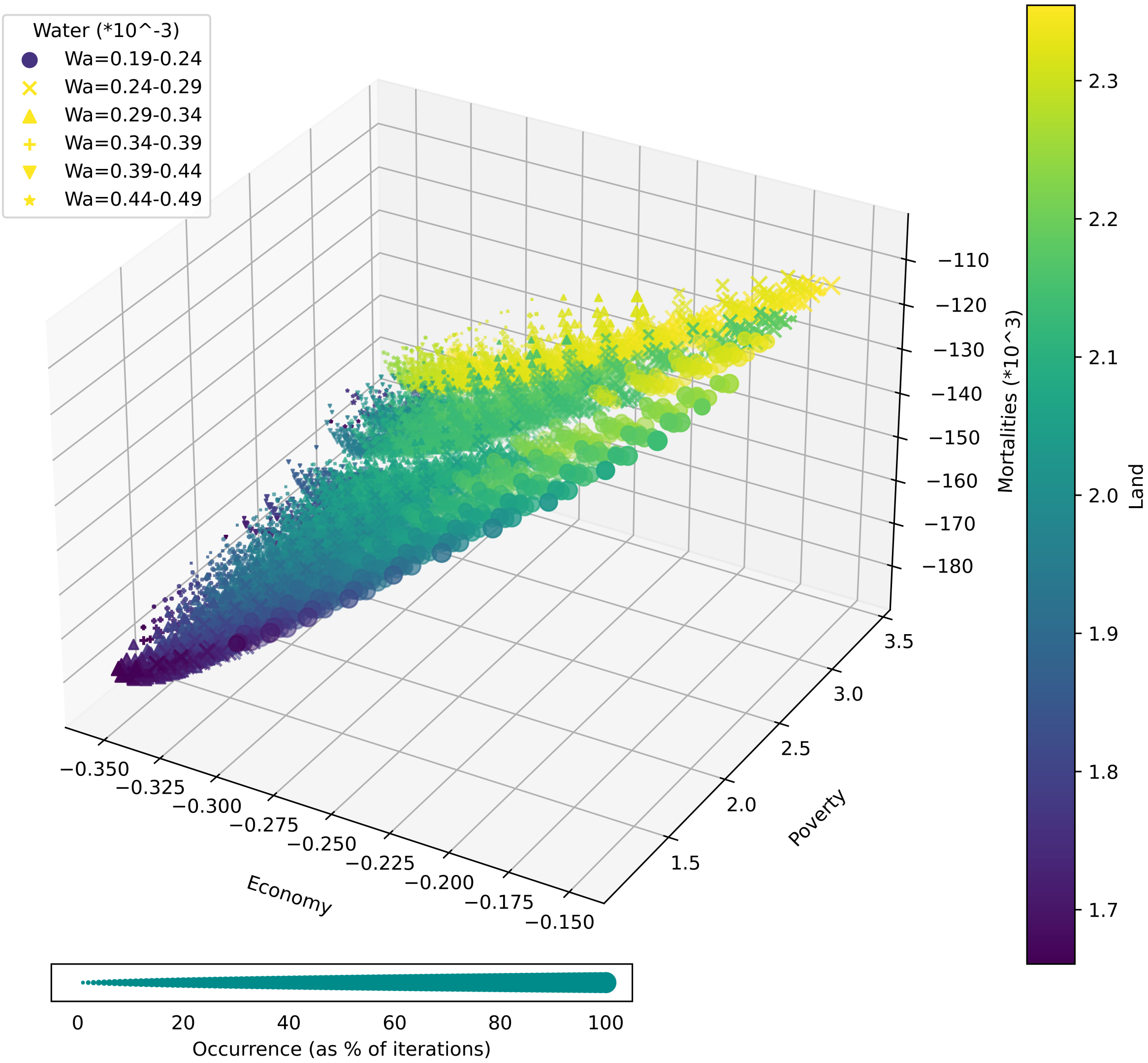
		1.5C	1.7C	2C
Economy (%)	Worst	-0.35	-0.32	-0.28
	Best	-0.15	-0.09	-0.06
	Most Robust*	-0.29	-0.09	-0.07
Poverty (index)	Worst	3.4	3.1	2.9
	Best	1.1	0.38	0.16
	Most Robust	1.3	2.9	0.8
Mortality (thousand individuals)	Worst	-106	-66	-39
	Best	-184	-177	-141
	Most Robust*	-164	-83	-84
Water Scarcity (index)	Worst	$0.5*10^{-3}$	$0.45*10^{-3}$	$0.5*10^{-3}$
	Best	$0.18*10^{-3}$	$-0.09*10^{-3}$	$-0.15*10^{-3}$
	Most Robust*	$0.21*10^{-3}$	$0.1*10^{-3}$	$-0.04*10^{-3}$
	Worst	0.2	0.07	0.02

Funded by the European Union

Unmanaged Land (%)	Best	2.36	2.34	2.2
	Most Robust*	0.61	2.3	0.55
***Synthesis of most robust portfolio ($GtCO_2$ mitigated)**	AFOLU	20	80	20
	Buildings	35	5	5
	Industry	180	50	5
	Power Supply	270	270	270
	Transport	50	5	5
Synthesis of weighted average portfolio ($GtCO_2$ mitigated)	AFOLU	58	46	39
	Buildings	24	11	7
	Industry	163	98	48
	Power Supply	260	232	185
	Transport	52	27	20

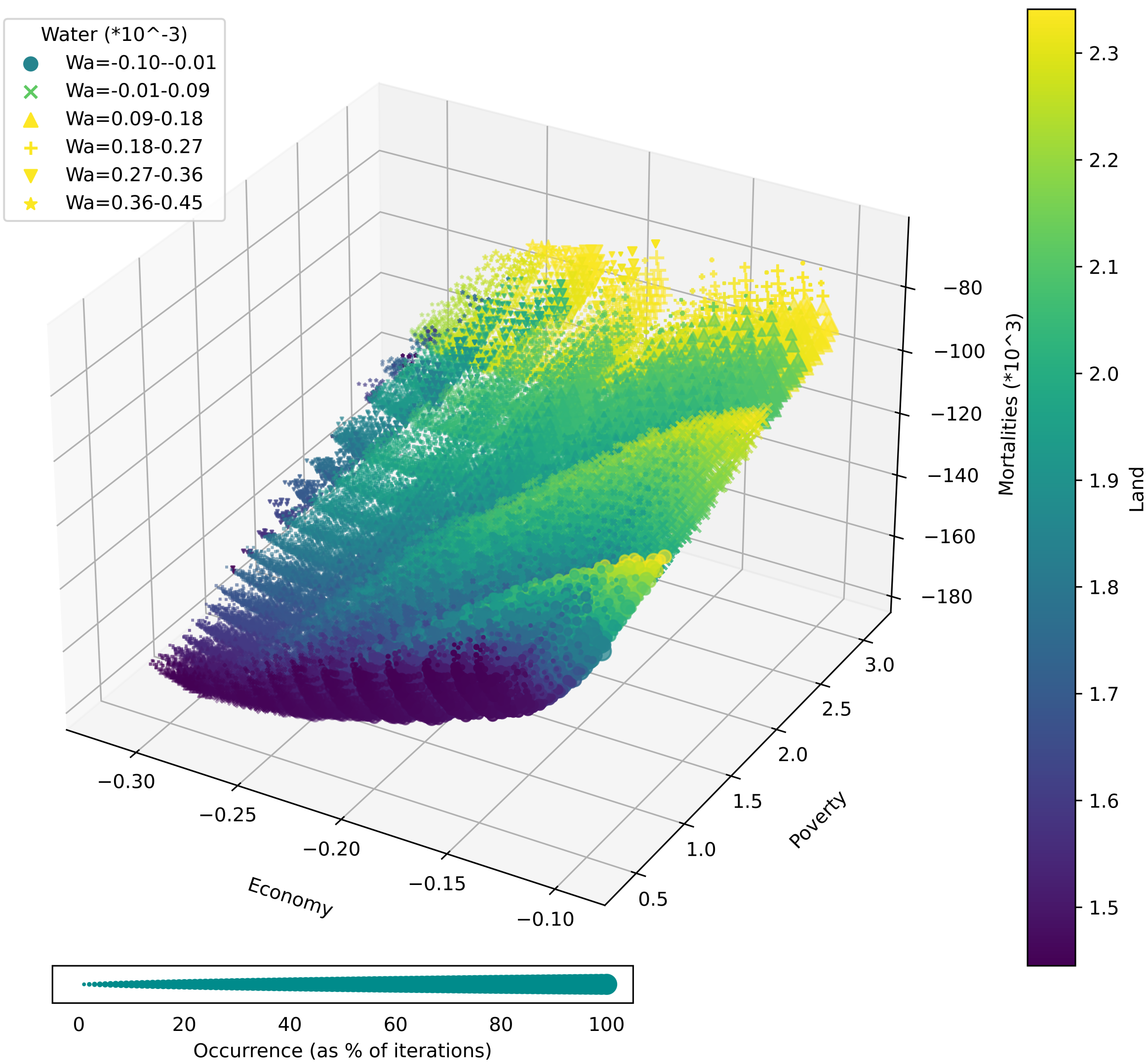
We should note that the best and worst performance of each SDG presented in Table 10 cannot be achieved at the same time, meaning that for example the least amount of deterioration cannot necessarily be combined with the best performance on land use, with the dynamics and trade-offs among the five dimensions showcasing considerable complexity, as also highlighted in the Pareto-type plots in Figure 21. These plots essentially constitute the full spectrum of the possible performance on each SDG indicator, meaning that each marker annotates a different sectoral allocation of mitigation effort that was found Pareto-optimal, with marker position (along the three axes), colour, and marker shape indicating the performance across the five sustainability dimensions, and the marker size indicating the robustness level (i.e., the number of times this portfolio appeared in the 100 Monte Carlo iterations). Despite the complexity of the plots, we can extract some high-level takeaways related to the dynamics of the SDGs as well as draw some comparison of the three mitigation scenarios.

Notably, the set of Pareto frontiers in the case of the 1.5°C case differs in shape from the other two. This is also reflected in the number of Pareto-optimal solutions found by the algorithm and the Monte Carlo iterations in each case, with the 1.5°C case comprising over 180,000 solutions, whereas in the 1.7°C and 2°C cases over 600,000 and 560,000 solutions were found, respectively. This expectedly stresses that the margins for limiting global warming to 1.5°C are becoming increasingly thinner, with the number of potential sectoral mitigation effort allocations becoming limited and increasing threefold in the cases of 1.7°C and 2°C. This, in turn, also impacts the dynamics among the examined SDG indicators. Notably, although an overall trade-off between the socioeconomic and environmental dimensions can be identified, it is evident in the two lower ambition scenarios that each time one of the pairs, economy-poverty and health-land, can showcase good progress while combined with favourable performance in only one dimension of the other pair, following the rectangular shape of the plot. However, this triangular shape observed in the 1.5°C case further underpins the reinforcement of the trade-offs, which become harder to bridge. Such a dynamic both raises the challenges associated with the 1.5°C endeavour and can be interpreted as a call for designing policies with the view towards alleviating potential negative impacts of the transformation.

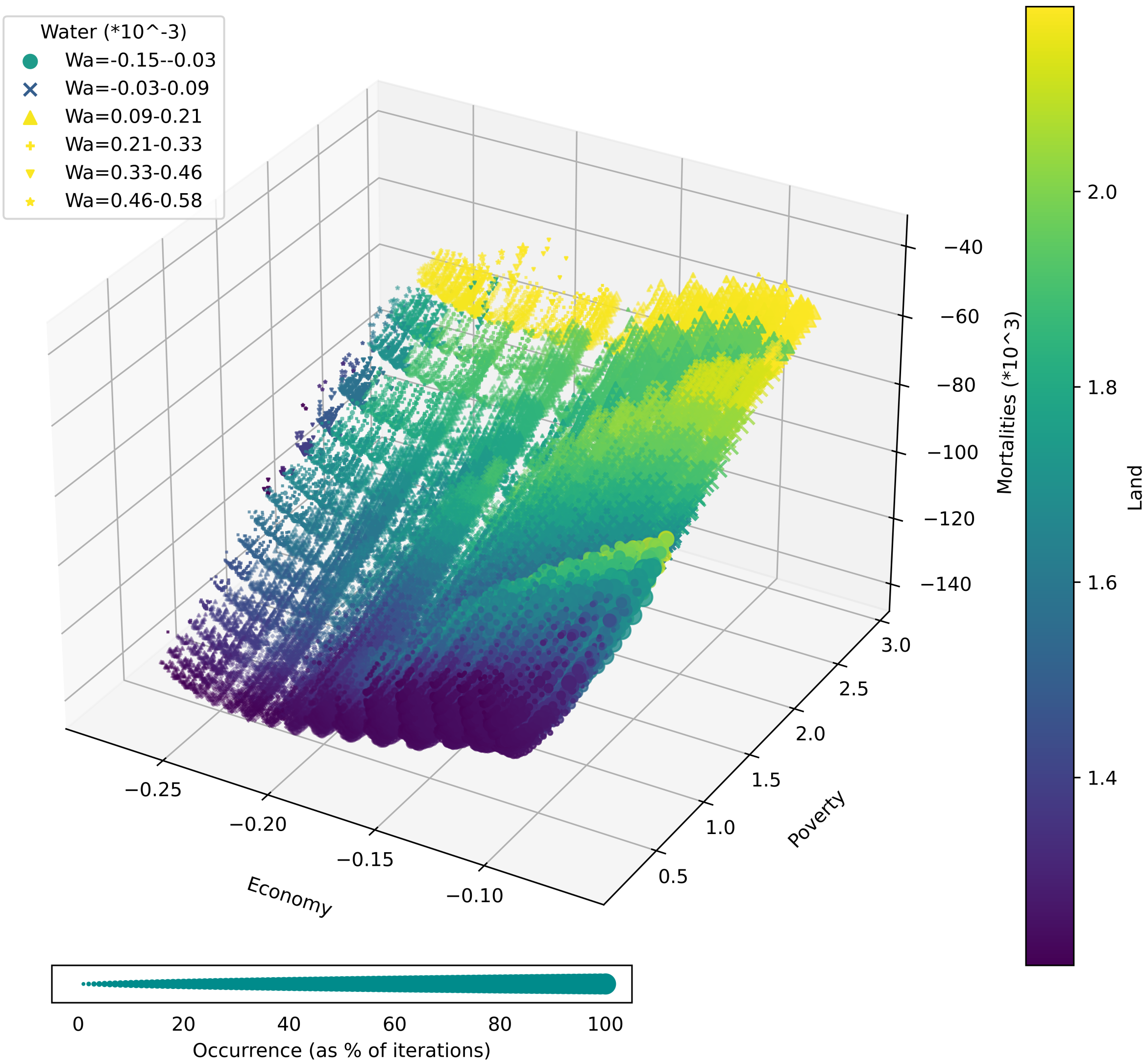


Water (*10^-3)
Wa=0.19-0.24
Wa=0.24-0.29
Wa=0.29-0.34
Wa=0.34-0.39
Wa=0.39-0.44
Wa=0.44-0.49
Mortalities (*10^3)
−110
−120
−130
−140
−150
−160
−170
−180
Poverty
1.5
2.0
2.5
3.0
3.5
Economy
−0.350
−0.325
−0.300
−0.275
−0.250
−0.225
−0.200
−0.175
−0.150
Land
1.7
1.8
1.9
2.0
2.1
2.2
2.3
0
20
40
60
80
100
Occurrence (as % of iterations)

(a) 1.5ºC case


Water (*10^-3)
Wa=-0.10--0.01
Wa=-0.01-0.09
Wa=0.09-0.18
Wa=0.18-0.27
Wa=0.27-0.36
Wa=0.36-0.45
Economy
−0.30
−0.25
−0.20
−0.15
−0.10
Poverty
0.5
1.0
1.5
2.0
2.5
3.0
Mortalities (*10^3)
−80
−100
−120
−140
−160
−180
Land
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
0
20
40
60
80
100
Occurrence (as % of iterations)

(b) 1.7ºC case



(c) 2ºC case

Figure 21. Total solution space of the performance of each identified sectoral allocation of mitigation effort across the three temperature scenarios, including the uncertainty analysis.

In terms of robustness, we can observe fluctuating trends in the 1.7ºC and 2ºC cases with no obvious section within the Pareto-optimal solution space dominating, yet in the 1.5ºC case it appears that the two "edges" of the near-triangular shape where GDP per capita growth and poverty prevalence showcase the worst performance feature lower levels of robustness, while the third "edge" showcases consistently higher robustness. In this case, the edges also highlight the trade-offs clearly—e.g., the bottom left corner of the solution space indicates effort allocations across economic sectors with a focus on maximising health gains and minimising poverty loses, and the upper right corner allocations that maximise land gains and minimise economic losses, with smooth and more robust mitigation portfolios in between.

The complexity in the robustness of the emerging portfolios is also evident in the set of the most robust portfolios for each temperature scenario. At this stage, we should indicate that the term "most robust portfolio" does not constitute the best portfolio—although robustness could indeed be deemed as one of the evaluation criteria used to make a decision—but rather a portfolio that consistently arises in the uncertainty analysis (e.g., one that performs well for specific dimensions throughout the iterations with no other portfolio easily dominating). This implies that essentially no portfolio can be deemed as deterministically better than any other, which is why we accompany the results of this most robust portfolio with a weighted average one (see Table 10). Notably, in the

Funded by
the European Union

1.5°C case, the most robust sectoral mitigation portfolio appears to be one that reduces gains in most other objectives only to minimise substantial poverty losses, and to some extent increase health gains. In the 1.7°C case, the most robust portfolio completely disregards the potential for mortality reductions towards maximising performance in the land and economic dimensions, whereas in the 2°C case the focus instead shifts to minimising negative impacts in terms of poverty and GDP growth.

Although robustness is only one indicator, these takeaways offer some preliminary indications that the space to confidently achieve big positive impact across several sustainability objectives is limited. For instance, to ensure maximum performance from a land perspective (1.7°C robust case), there is a large shift (exhausting the available mitigation potential) towards AFOLU, while increasing mitigation effort gains ground in buildings, industry, and transport instead. In all cases, however, efforts in the power supply sector reach the maximum available potential.

To better understand inter-sectoral dynamics, we plot the mitigation (solution) space per sector produced by all Monte Carlo runs for each temperature target, considering robustness (number of appearances) in Figure 22. It is evident that, to keep mean global temperature increase to a compliant with 1.5°C pathway according to GCAM, the mitigation potential by 2050 is near-exhausted across all sectors, expectedly hinting that sectoral mitigation effort allocation uncertainty is reduced as climate efforts intensify, despite the persistent underlying uncertainty in terms of dynamics with the five sustainability dimensions (albeit with increased trade-off intensity). This again points to the narrow route towards 1.5°C, but also to our GCAM-AUGMECON framework seemingly anchoring to certain sectoral mitigation effort allocations with only minor flexibility. Instead, the two sectors with the highest mitigation efforts in all three cases (power and industry) showcase a significant action space in the other two cases (1.7 and 2°C). We notably observe that, in all scenarios, the power supply sector plays a prominent role representing the highest emission reductions (only a few outliers excluded from the plot in the 2°C case did power supply did not contribute as much). Industry also plays a prominent role, especially in the 1.5°C case but also largely in the 1.7°C case (where the interquartile box appears closer to the upper limit, hinting at the tendency to use up the maximum sectoral potential available). Although all three remaining sectors require near-maximum mitigation effort (within the sectoral action space identified by GCAM) in the 1.5°C case but less so in the more lenient temperature target scenarios, the transport and AFOLU sectors showcase the largest shift in the 1.5°C compared to the other two cases, as evident in the bump of the boxplots (in the AFOLU case, the median value is extremely close to the upper limit, and we broadly see the highest uncertainty among the three sectors, due to its contribution to the explicit land-related sustainability indicator).

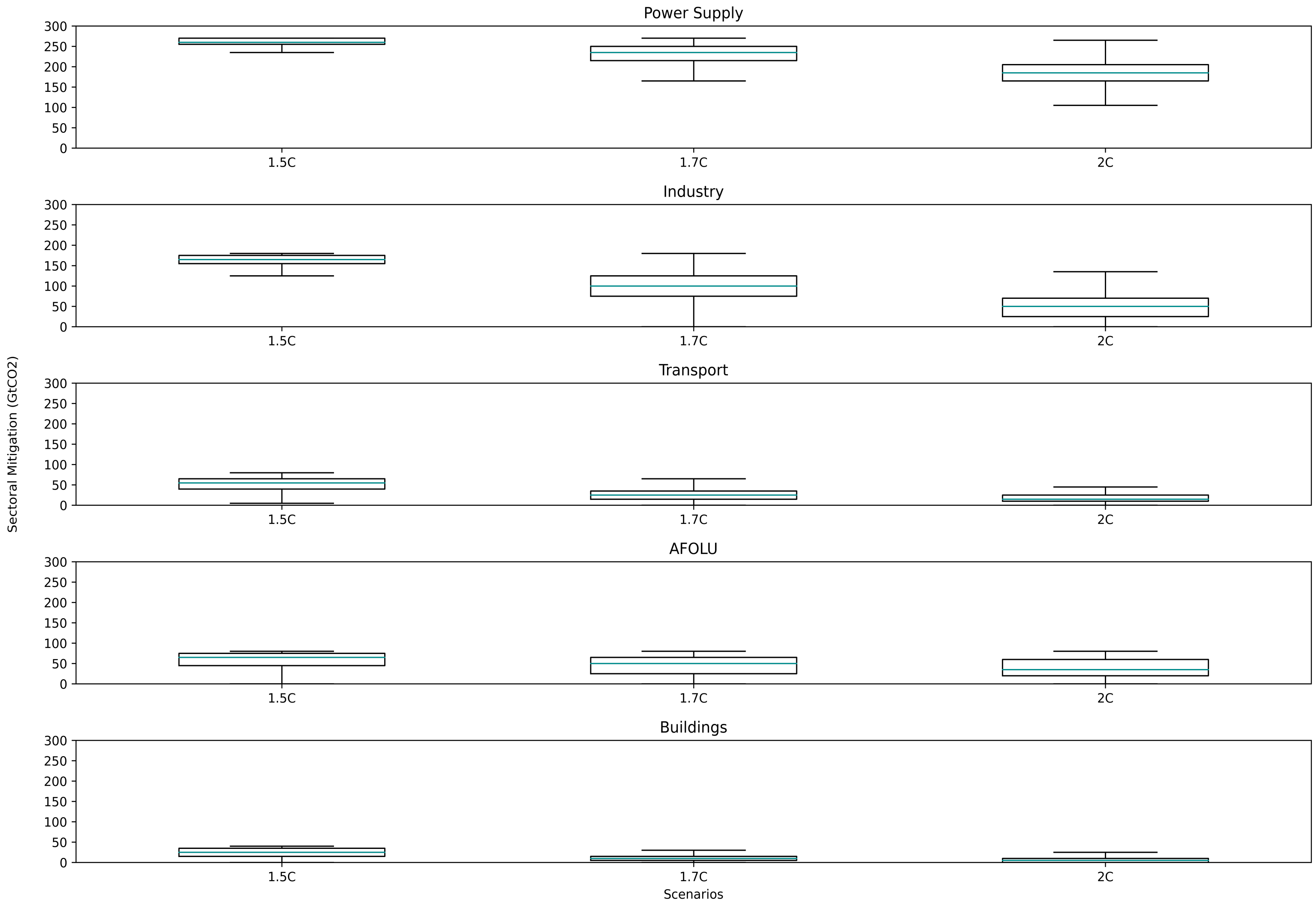
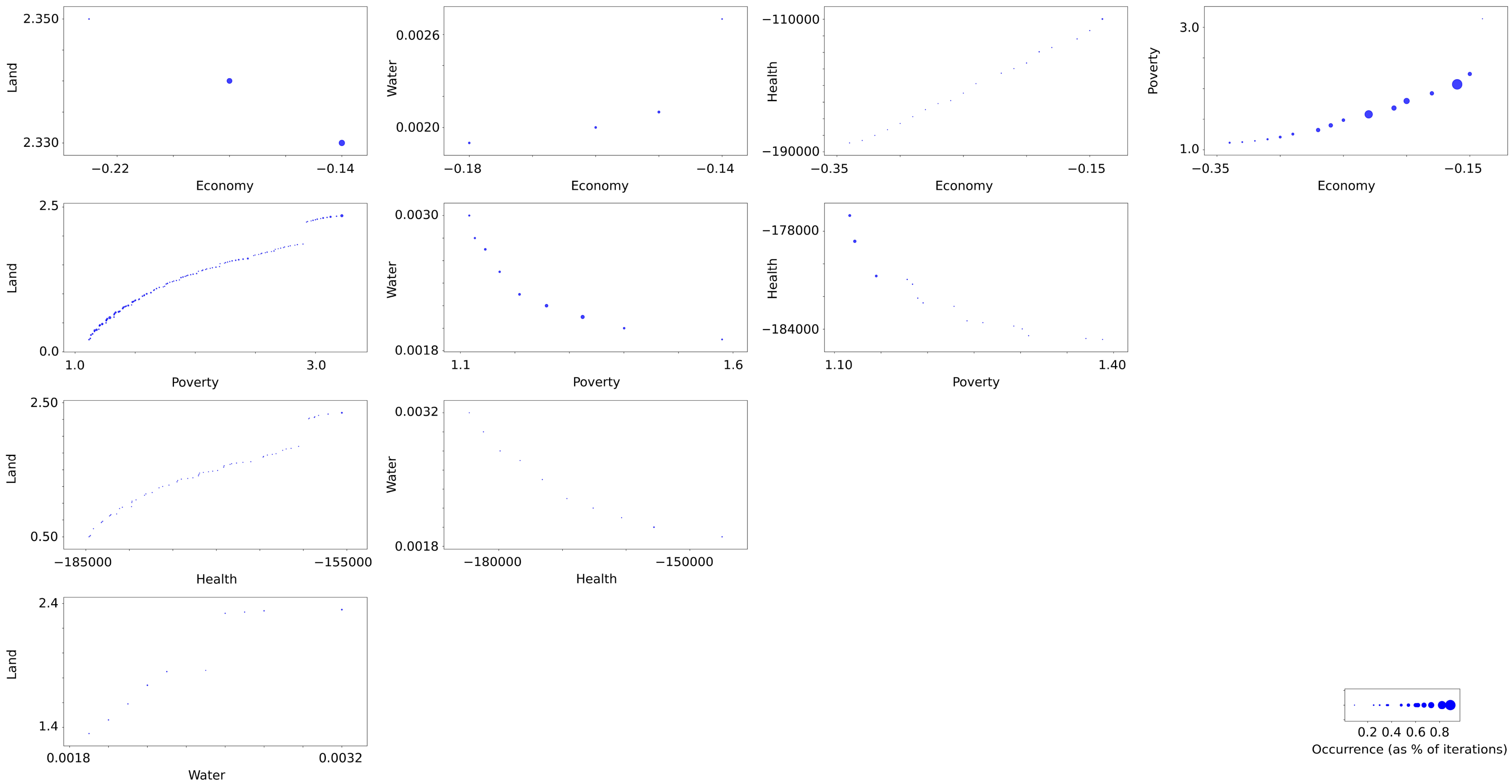


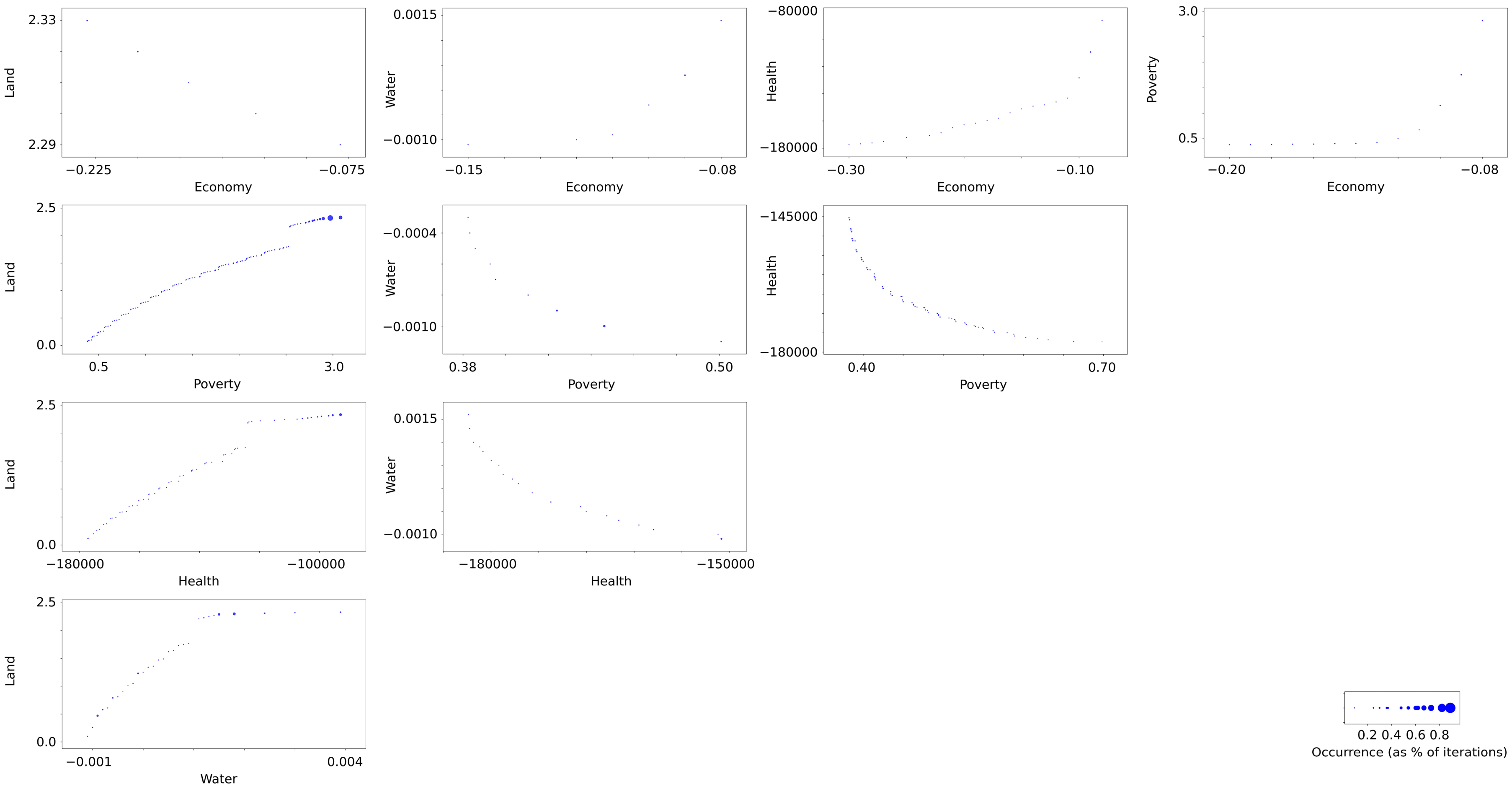
Figure 22. Sectoral allocation of mitigation effort to achieve each temperature goal. The boxes represent the 25-75% quartiles, the green lines represent the median value (which should be close to the weighted average portfolio presented in Table 10), and the limits of the sample are adapted to remove outliers based on the boxplot function of mathplotlib (data within the 1.5 interquartile range).

It is thus evident that there exist significant dynamics and trade-offs between the selected sustainability dimensions and the sectoral allocations of mitigation effort. These dynamics also make it hard to identify coherent strategies moving forward. For example, there is no easy justification as to why the multi-objective optimisation algorithm maximises performance in the land objective in the most robust portfolio for the 1.7^{o}C case (Table 9), whereas in the two other cases robustness appears to sacrifice performance in the same objective. These observations stress the complex interplays among the often-conflicting priorities of the broader sustainable development agenda. To shed light on such interplays, we choose to reduce the complexity of the problem space, by performing similar analysis in a series of bi-objective problems instead of the 5-objective problem presented previously. Essentially, we perform an optimisation process based on all possible bilateral combinations of pairs of two sustainability dimensions. Although this exercise does not necessarily provide results in terms of holistic sustainability along all five selected indicators, it remains useful to understand how dimensions interact with one another, and how these interactions are reflected in the sectoral configurations. The results of this process are illustrated in Figure 23.

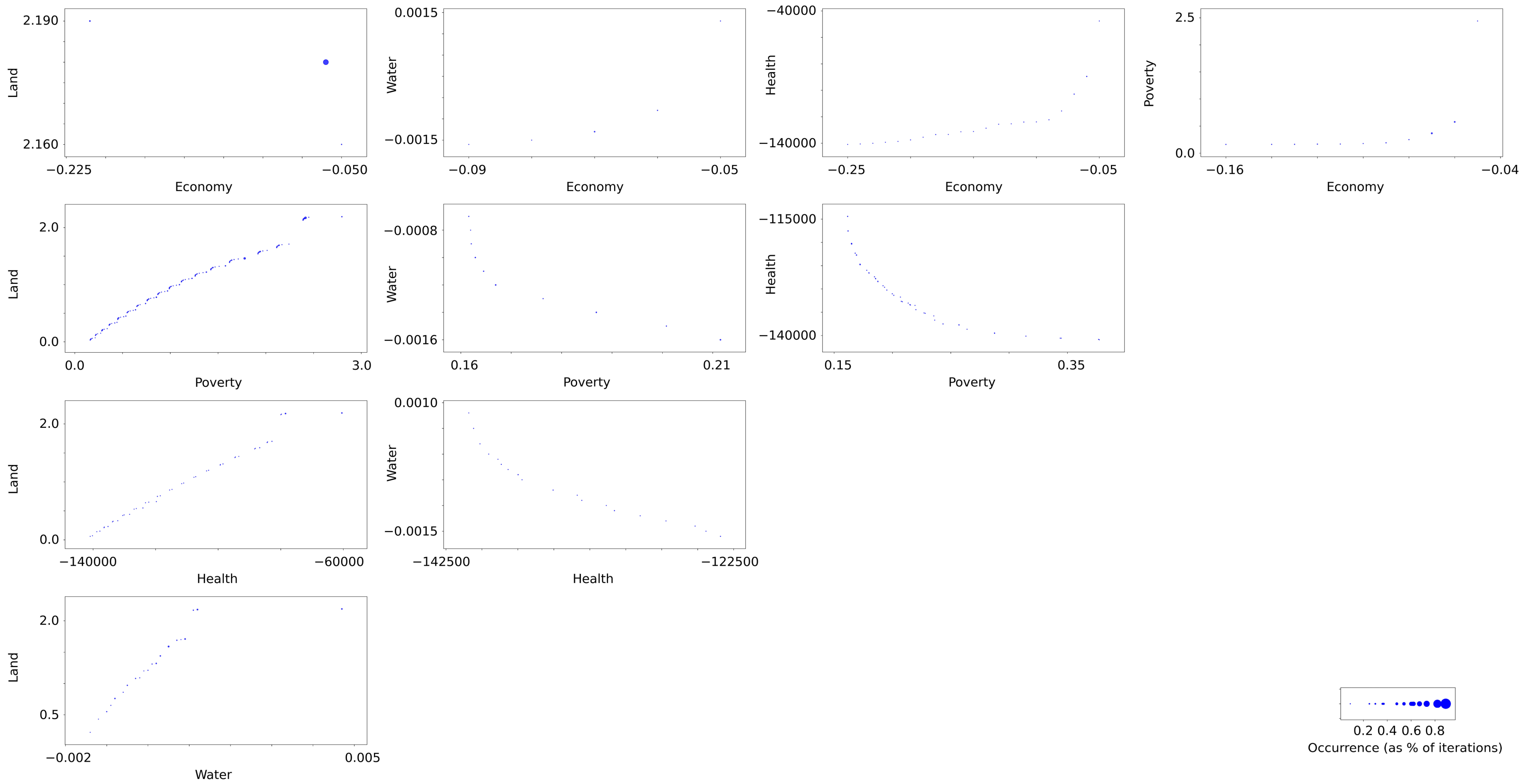


Land
Economy
Water
Health
Poverty
2.350
2.330
−0.22
−0.14
0.0026
0.0020
−0.18
−110000
−190000
−0.35
−0.15
3.0
1.0
2.5
0.0
0.0030
0.0018
1.1
1.6
−178000
−184000
1.10
1.40
2.50
0.50
−185000
−155000
0.0032
−180000
−150000
2.4
1.4
0.0018
0.2 0.4 0.6 0.8
Occurrence (as % of iterations)

(a) 1.5ºC case


2.33
2.29
Land
−0.225
−0.075
Economy
0.0015
−0.0010
Water
−0.15
−0.08
Economy
−80000
−180000
Health
−0.30
−0.10
Economy
3.0
0.5
Poverty
−0.20
−0.08
Economy
2.5
0.0
Land
0.5
3.0
Poverty
−0.0004
−0.0010
Water
0.38
0.50
Poverty
−145000
−180000
Health
0.40
0.70
Poverty
2.5
0.0
Land
−180000
−100000
Health
0.0015
−0.0010
Water
−180000
−150000
Health
2.5
0.0
Land
−0.001
0.004
Water
0.2 0.4 0.6 0.8
Occurrence (as % of iterations)

(b) 1.7ºC case



(c) 2ºC case

Figure 23. Trade-offs between sustainability dimensions in the bi-objective configuration problems for the three temperature targets**.**

A first output of this process is that the term 'trade-off' itself is a complex notion that depends on the variables involved, with the dynamics reflected in Figure 23 showcasing all types of different behaviours relating to the slope (i.e., downward/upward sloping depending on the cost-benefit characterisation) and the concavity/convexity/linearity. Given the discrete nature of the problem and the algorithm selected, some steps also appear in some cases (e.g., in the poverty-land problem for all three temperature cases), as well as evident 'knee' sections of the curves, highlighting the need to elaborate trade-offs such as the ones identified in the literature—for example, the economy-health and economy-land pairs that are among those socioeconomic and environmental trade-offs typically identified in the literature—based on their fundamental characteristics and behaviours. Specifically, irrespective of the performance along each dimension, in the economy-health problem studies in this exercise, the pattern of the trade-off drastically shifts from an increasing concave frontier in the 2°C case towards an increasing linear one in the 1.5°C case; in the economy-land problem, it starts from a downward convex trend and shifts to a linear one as temperature targets become stricter (even faster, evident also in the 1.7°C). This indicates that, in a 2°C scenario, GCAM shows it is still possible to somewhat manage the trade-off among the two objectives (economy-health and economy-land) near the position of the 'knee' of the curve, but this becomes much harder as mitigation effort increases—especially so for the economy-land case.

Focusing on the detailed sectoral implications from the trade-offs produced by the Pareto frontiers in Figure 23, we mainly explore the interplay between the two socioeconomic (economy, poverty) and two environmental (land, heath) dimensions; impacts on water and the produced solution spaces are too small to produce meaningful sectoral trends. We can observe significant interplays in the transport and AFOLU sectors. Notably, minimising impacts on GDP per capita growth points to reduced mitigation effort in transport; instead, maximising efforts in this sector is almost a prerequisite to achieving considerable reductions in mortality due to air pollution. A similar trend can be observed in the AFOLU sector: maximising performance in the land objective expectedly relies on 'agro' and 'land' policies, while optimising performance for poverty implies lower shares of mitigation on the AFOLU sector, given its potential impact on food prices.

Depending on the bi-objective problem selected, the allocation of effort to these sectors could imply reductions on one to provide space for the other (and thus maximise performance on one objective), and vice versa. This was, for example, the case in the economy-health problem, with maximising performance in terms of mortality reductions requiring high mitigation efforts in transport and lower in AFOLU—and vice versa upon pursuing minimum reductions in GDP per capita growth. This may be because, first, these two sectors feature adequate mitigation potential to allow for such fine-tuning behaviours, contrary to, e.g., the building sector that typically displays a secondary, supporting role in the optimisation exercise (see, for example, the poverty-land problem, where reduced allocation of mitigation effort to buildings allows optimal land performance based on AFOLU-related efforts). These dynamics also lead to some counter-intuitive results, e.g., on the poverty-health problem, where reducing pollution-related deaths implies reduced mitigation in the built environment, arguably to provide enough space for maximising transport emissions cuts, despite the importance of buildings for indoor air quality. Second, it is necessary to make use of the highest mitigation potential in the two most prominent sectors—power supply and industry—to ensure compliance with a 1.5°C target meaning that evident dynamics revolving around the two sectors can be found primarily in the 1.7°C and 2°C cases, given the flexibility provided by the more lenient temperature targets. Contrary, despite the vivid intra-objective dynamics in the bi-objective problems for the transport and AFOLU sectors, there are no consistent patterns throughout for power supply and industry across shifts between temperature scenarios. For instance, when maximising economic performance, on top of the requirement for minimum mitigation efforts in transportation and depending on the leniency of the temperature target, there emerges a preference towards lower mitigation efforts in industry. In such problems, as for example in the economy-poverty 1.7°C case, we observe that efforts in the power sector are maximised to provide leeway for transport and industry for higher economic output—and vice versa (reducing power supply mitigation by over 100GtCO_2) in order to minimise undesired poverty implications. Similarly, in the economy-health problem, lower mitigation effort is observed in the power sector, hinting at reduced shares of biomass for energy production.

This dynamic between the paths implied by the 1.5ºC and 1.7ºC scenarios (similar trends albeit exacerbated in the 2ºC case) has implications on how we view the two targets. The current discourse is rightly focused on achieving the lowest temperature increase possible, which for the time is defined as the 1.5ºC goal. To achieve this, it is necessary to fully decarbonise the power supply sector as early as possible (see also Boitier et al., 2023), due to the sector's potential but also due to the technoeconomic feasibility to do so, since a large chunk of the required mitigation technologies are already widely available. However, this would also require technologies that are not yet readily available, or at least not to the desired extents, including notably CCS, which thus raises feasibility and realism questions for the 1.5C target (Jewell and Cherp, 2020).

This discussion is currently constrained to a climate mitigation perspective. Instead, we argue that this is particularly important from a broader sustainability view, since 1.5ºC and 1.7 or 2ºC pathways are not necessarily aligned across all sustainability dimensions. In particular, a 1.5ºC pathway, which nations collectively embark on but eventually does not materialise, may lock the world into accelerated, complete decarbonisation in the power sector, whereas this might not be optimal across all dimensions in a 1.7ºC or 2ºC world, risking losses in terms of co-benefits with other sustainability objectives (e.g., in SDGs 1/poverty and 3/health). Put simply, this can be expressed as a gap between an insufficient attempt to constrain global warming to 1.5ºC before shifting to a 1.7ºC pathway, compared to independently pursuing the 1.7ºC goal—not just from a climate-economic (e.g., stranded asset, path dependency, etc.) perspective, but also from a broader sustainable development one. This discussion does not imply that the 1.5ºC goal should not be pursued in favour of a more lenient target, but rather that maintaining a 1.5ºC-compliant pathway only on the merits of currently unproven solutions may risk misalignment between the optimal strategy for other sustainability goals in a 1.7ºC (or 2ºC) scenario.

Finally, as already observed in the economy-poverty problem, although considerable focus is being placed on the trade-offs between socioeconomic and environmental dimensions, other dynamics within each dimension may also exist. From a socioeconomic angle, this is evident in the use of the AFOLU sector—with a view to maximising economic gains on average (as in GDP per capita) rather than for the entire society (as in poverty prevalence) and the interplay between industry and electricity generation that is discussed above. Similar patterns are also present between the two environmental dimensions discussed here: maximising performance in the land objective requires large-scale efforts in the AFOLU sector and limited in buildings, whereas for maximum performance on health we see shared mitigation efforts between the two sectors.

3.2 WILIAM x MCDA

This section sets out an analysis to different decarbonization pathways. The exercise is summarized in Figure 24. After drawing three alternatives to a business-as-usual scenario, WILIAM is used to simulate them and provide results about SDGs. These results are then inputs for the Stochastic Multicriteria Acceptability Analysis (SMAA), a method to weight the importance of policy criteria in selecting the more appropriate decision making.

The objective of this task is to select the *best* pathway, according to a criterion. This criterion is a weighted function accounting all SDGs captured by the IAM and considering the restriction of having a shared climate goal, i.e., the same global surface temperature change by 2050 for all pathways.

This section is structured as follows:

- 3.3.1. Describes the method used to build narratives and pathways, from qualitative attributes to quantitative inputs for WILIAM.
- 3.3.2. Reviews which SDGs are present in WILIAM. It is also included a first analysis of interactions, trade-offs and benefits across SDGs.
- 3.3.3. Finally, SMAA is explained, step by step, to understand the optimal choice.
- 3.3.4. Limitations and further developments of the three steps, i.e., scenarios, WILIAM, and SMAA.

Funded by
the European Union

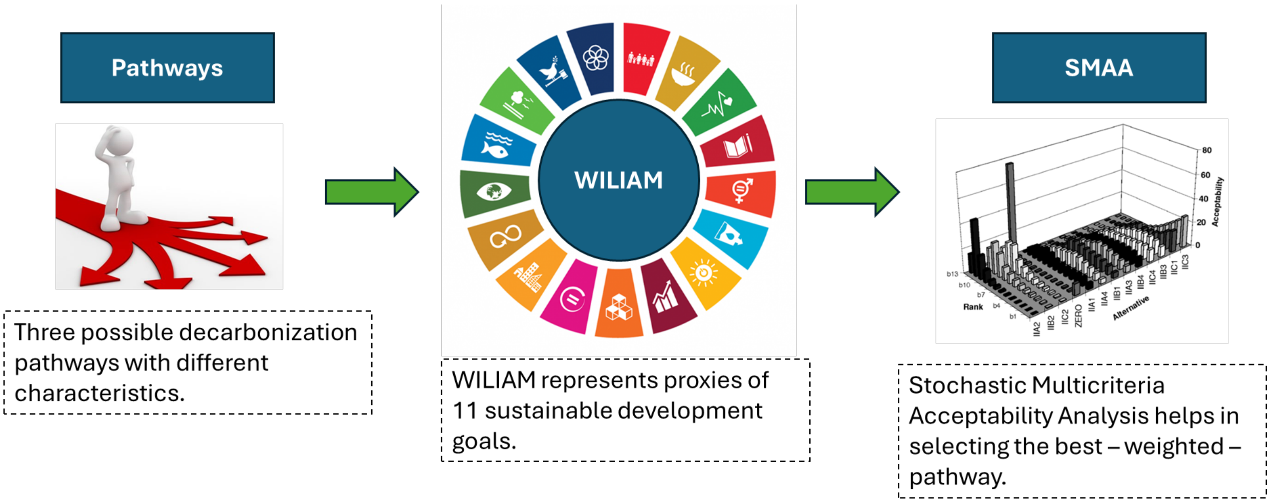


Figure 24. Overview of the study about SDGs employing the WILIAM model and the MCDA method.

3.3.1 Narratives & Pathways

Scenarios essentially offer a structured exploration of potential future developments, built upon a defined set of assumptions. By envisioning diverse futures and evaluating their consequences under different actions, scenarios provide insights into strategic decision-making (Nakicenovic, Kimura, and Ajanovic, 2005), (Intergovernmental Panel on Climate Change (IPCC) 2023). Although scenarios typically employ quantitative methods to assess future trajectories, they are often preceded by qualitative storylines which catch those numeric futures through words. Thus, together with the approach to potential futures via numeric variables and external assumptions, narrative elements are essential to provide a general context to pathways (Van Vuuren et al. 2012).

In this subsection, the first goal is to construct a coherent and consistent mitigation scenario that projects potential future pathways aimed at reducing greenhouse gas emissions and avoiding, as far as possible, an increase in Climate Change impacts. Since this type of scenario is very common in literature, it is possible, through a literature review, to identify a set of common characteristics among different pathways within a mitigation scenario framework. Thus, these existing narratives can serve as a basis for the creation of one's own narratives. Below is a table from (Van Vuuren et al. 2012) with the common qualitative characteristics in the most typical mitigation narratives (which largely correspond to the SSPs marked by the IPCC). A qualitative attribute table is used to clearly define the narratives defined below, according to the general understanding of how the potential future pathways could evolve over from nowadays till the end of the simulation in WILIAM (2050). For the present study, Table 11 covers all the attributes implemented in WILIAM for representing the narratives.

The first step to achieve the objectives of this study is to develop truly sustainable decarbonisation pathways. Specifically, we establish four basic global narratives to comply with the following criteria:

- Span a range of potential futures addressing socio-economic challenges.
- Incorporate various scenario assumptions related to key systems: energy (both demand and supply), technological advancements, land-use changes (as seen in (Van Vuuren et al. 2012) or (Riahi et al. 2017), and also behavioural shifts (changes in lifestyle or demand) enabled by the unique capabilities of WILIAM. Refer to the qualitative attribute table for further detailed assumptions for each system.
- Demonstrate significance in terms of mitigation, sharing a common goal of decarbonisation pathways.

- Consider a sustainable perspective aligned with global sustainable development in the narrative, offering "more truly" sustainable pathways beyond the reference scenario.

Initially, a reference scenario is defined as necessary for comparison purposes i.e. a basis of how things would evolve without substantial changes in trends, to which the other scenarios are compared.

The remaining three pathways are created on the logical assumption that authorities have limited economic resources. In an effort to enhance and mitigate the current situation, different investment strategies are explored, all centred around promoting the energy transition. Consequently, three distinct narratives emerge, all sharing a common thread: dedicating a fixed portion of resources to energy transition while allocating the remaining funds differently in each case. This variation among narratives is achieved through the enactment of specific policies tailored to each storyline. **This approach allows for an assessment of which resource distribution yields optimal performance in terms of impacts on SDGs, guiding where investments and policies efforts should be prioritized.**

The three mitigation pathways share the same climate target (1.84ºC in 2050, continues to increase after that year), which implies a higher ambition than the BAU scenario. It is also worth noting that all policies implemented in these scenarios are mitigation policies. Consequently, all scenarios have common attributes while each scenario is differentiated with some attributes intensifying specific policies upon the common portfolio. Nevertheless, it is important to highlight that the monetary budget may vary across scenarios due to the absence of cost quantification of policies in WILIAM.

Business-As-Usual (BAU, reference scenario)

The world continues with historical trends in social, economic, and technological developments, reflecting patterns from the past. This encompasses existing policies, along with their level of implementation, without explicit climate policies (Van Vuuren et al. 2012).

Narrative 1. Energy transition with high technology development (ET)

In this scenario, the world transitions towards a decarbonisation pathway centred on technological advancements, efficiency, and extensive integration of renewables in the energy sector. This scenario places less emphasis on social aspects or environmental considerations, with the primary goal being the decarbonization of the energy system.

Specific attributes (exogenous policies on top of BAU scenario) defining this scenario are:

- Annual energy savings per economic output (energy intensity) is intensified by 50%.
- Renewables are promoted more than fossil fuel-based energy generation in the energy mix. Similarly, renewables are highly prioritized in new capacity expansions.
- Availability of non-mature technologies such as offshore floating, oceanic, and carbon capture and storage (CCS).
- 75% of rooftop areas in buildings are used for monocrystalline silicon photovoltaic panels and 25% for solar thermal technologies. Annual efficiency improvement of solar photovoltaic panels increases 10%.
- Capacity investment cost to develop technologies is lower than historical values.
- Efficiency of fuel consumption in transport is increased 15%.
- Water efficiency improves 25%.
- From 2025 to 2050, the new forest plantations and afforestation program accumulated will be equivalent to 14% of the total forest area in 2015.
- 50% flexitarian diet – 50% business-as-usual diet by 2050 in most countries (except China, East of Asia and Oceania, India, and Russia).

- Lower material intensities of Cu, Al, Fe, and Ni. Recycling of these materials is increased to 51%, 90%, 50%, and 38%, respectively. For the rest of materials, the annual recycling rate increases 50%% till the end of the scenario (2050).

Narrative 2. Energy transition combined with promotion of Lifestyle Changes (ET-LC)

To significantly limit global warming, there is a need to not only transform how energy is produced but also how resources are consumed. This entails instigating behaviour change. In this narrative, mitigation efforts are divided between an energy transition coupled with assumptions about lifestyle or behavioural change that curtail demand and consequently reduce resource consumption. The focus and investment are directed towards promoting lifestyle modifications and structural alterations that facilitates these shifts on both individual and collective scale. This approach will help assess the positive and/or negative impacts of these combined policies (related to energy and social aspects) on specific SDGs in comparison to a purely energy mitigation pathway (narrative 1).

Specific attributes (exogenous policies on top of BAU scenario) defining this scenario are:

- The average people in households increases twice from 2015 to 2050.
- Aggressive carbon tax to production and households reaching 325 $/t CO_2 by 2050 in EU-27, UK, and USCMA regions, while 101 $/t CO_2 in the rest of the world. Recycling of carbon taxes are invested into a 10% basic income budget to low-income households (25%), reduce debt (25%) and social benefits (50%).
- Higher limitation in consuming energy over non-durable goods to 10%.
- Limit the annual growth of consumption to 2% (durable and non-durable goods).
- Diet transitions to 50% plant-based. The rest follows historical patterns driven by GDP_{pc}.
- Higher government consumption in education (40% since 2030).

Narrative 3. Energy transition with Environmental Considerations promoting policies in the land-use sector (ET-EC)

In this scenario the world perceives the need of a more sustainable path, especially one that takes into account environmental boundaries, and therefore polices are defined as more ambitions in regard to environmental protection. In particular, the management and conservation of these common resources (as e.g. forest/wood, biodiversity, etc.) is taken through more ambitious policies in the land-use sector (protection of natural habits, forests, afforestation, etc). The efforts for mitigation are not only put in the energy system but also in the land use sector, including land management measures.

- Afforestation: 30% increase in forest land is projected to be reached by 2050. The same policy is applied for all regions.
- Policy of increase of forest plantations, this refers to the increase in single-species tree plantations. The value applied is of 30% also. The policy is applied in 2025 until 2050 when the objective is reached (as in the case of afforestation)
- Protection of primary forest. The value or intensity of this policy is of 100%. If this policy is applied, the primary forest is protected, and its area does not fall. The protection starts in 2025 and ends in 2050. The objective is expressed as a share of the initial area of primary forest in 2015 (the value of 100% means that an area equal to the primary forest in 2015 is protected). If the value is 0% it would mean that there are no limits to deforestation.
- Protection of managed forest. The value or intensity of this policy is of 40% If this policy is applied, the

managed forest is protected and its area does not fall below a certain value. The protection starts in 2025 and ends in 2050. The value is the share of the initial area of managed forest in 2015 (100% means that an area equal to the managed forest in 2015 is protected).

- Change to regenerative agriculture. This policy consists of transitioning to regenerative agriculture, with an objective that varies from 0 to 100% (0 % means no change, while 100% means a complete transition to regenerative agriculture). The transition starts in 2025 and ends completely in 2040. The specific values are differenced among WILIAM political regions:
    - EU27, UK, USMCA=50%
    - CHINA, RUSSIA= 35%
    - EASOC, INDIA, LATAM, =25%
    - LROW= 10%
- Urban land density. If this policy is applied, the ratio of m^2 of urban land area per person reaches the given target. The policy is applied in 2025 until 2050 when the objective is reached. Values:
    - EU27, UK, = 20 % reduction of the ratio of m2/person (higher density)
    - CHINA, USMCA, LATAM = 13 % reduction of the ratio of m2/person (higher density)
    - EASOC, INDIA, RUSSIA = 33-17 % reduction of the ratio of m2/person (higher density)
    - LROW= 33 % reduction of the ratio of m2/person (higher density)

Table 11: Qualitative attribute table for the narratives implemented in this study.

Attributes	Business-as-Usual (BAU)	Pathway 1 - ET	Pathway 2- ET-LC	Pathway 3- ET-EC
Demography (8869 million people worldwide in 2050)				
Fertility	Medium			
Mortality	Medium			
Migration	Bilateral migration rates are constant values of 2020			
Economy				
Carbon tax in 2050	No	No	Yes	No
Basic income	No	No	Yes	No
Carbon revenues recycling	No	No	Social benefits & Debt reduction	No
Government consumption & investment	Past Trends	Past Trends	Higher for education	Past Trends
Energy/Technology				
Renewables	Medium	High	Medium	Medium
Energy Efficiency Improvement	Past Trends	High	Past Trends	Past Trends
Unmature technologies (CCS, offshore floating wind)	No	Yes	No	No
Rooftop solar	Medium	High	Medium	Medium
Capacity investment costs	Past Trends	Low	Past Trends	Past Trends
LAND				
Afforestation/New plantations	No	Low	Low	Yes (high)
Protection of managed and primary forest	No	No	No	Yes

Technology Improvement Agriculture	Past Trends	Yes	Past Trends	Past Trends
Regenerative agriculture	Past Trends	Past Trends	Past Trends	Yes (40 % approx.)
Urban land density (person/m2)	Past Trends	Past Trends	Past Trends	Increase nº of people inhabiting a given area
SOCIETY/LYFESTYLE CHANGES				
Diet	Past Trends	50% transition to flexitarian	Transitions to 50% plant-based	Past Trends
Passenger demand	Past Trends	Past Trends	Lower	Past Trends
Transport mode	Past Trends	Past Trends	Electrification & biking	Past Trends
Hypothesis for the uncertainty analysis				
Population	Medium	Low Medium High		
Minimum EROI solar and wind technologies	Medium	Low (5) =5 Medium (8) =8 High (10) =10		
Government budget balance	Negative (past trends by 2050)	Positive (1% by 2050)		

The hypothesis of Energy Returned on Energy Invested (EROI) is used in section *4.3.3 Stochastic Multicriteria Acceptability Analysis (SMAA).* The minimum EROI is the minimum ratio of the energy delivered from a process divided by the energy required to get it over its lifetime, indicating the net energy available for the society.

The uncertainties around the estimation of the EROImin is very big, as the reduced availability of discretionary energy, as intermediary operations become less efficient, is a gradual non-linear process with increasing and cascade consequences over time. In addition, this EROImin ultimately depends on social decisions [68]. The values used are based on different works (Fizaine et al., 2006; Lambert et al., 2012) which have suggested a minimum static EROI of the system of 10-15:1. Brandt et al. 2017 found that if the EROI is considered less than 5:1, the social system starts to face serious problems.

3.3.2 SDG indicators evaluated in WILIAM

This subsection presents the variables from WILIAM v1.3 (Lifi et al., 2023; Samsó et al., 2023) with modifications for introducing indicators based on the SDG target space discussed above, in Section 2.3. Table 12 sets out the inputs provided by the modelers on which variables best represent the SDGs. They have been extracted from the general table available in Annex I, where this same information can be found for all models in the consortium.

Some points on certain variables need to be clarified before the running of the simulations:

- 3.1. Life expectancy at birth: Despite being a very precise indicator that can be used to represent the well-being and quality of life of societies, in this case the "life expectancy" cannot be considered as a measure of progress of SDG 3 since in WILIAM this variable is an exogenous input, i.e. an assumption made by the modelling team and not an endogenously calculated value. Consideration of this indicator within the final results would lead to biased conclusions.
- 8.2. Annual GDP per capita growth: This variable is very useful to describe the evolution of a region's economy and should therefore be taken into account as an indicator, but its instability, with pronounced variations from one year to the next, should also be mentioned. This particularity has to be taken into account, in particular in the SMAA.

- 15.4. Other natural land as share of total land area: This specific variable is relevant for SDG target 15.1 which covers non-forested terrestrial ecosystems (e.g. mountains or drylands). As we have kept this variable as interesting for SDG 15 (life on land) as all the natural habitats play a crucial role in the biodiversity conservation, we have to keep in mind that sometimes its behaviour and dynamics make it compete with Forest Land which is the ecosystem, for example, with more richness in general in terms of biodiversity. "

Table 12: WILIAM indicators to track progress on the SDGs. Source: Own elaboration.

Cluster	SDG	Indicator	Units
People	SDG3 - Good Health and Well-Being	3.1. Life expectancy at birth	Years
		3.2. Under-five mortality rate	Deaths/1000
	SDG4 - Quality Education	4.1. Medium & High education	% population
Prosperity	SDG8 – Decent Work and Economic Growth	8.1. GDPpc vs average GDPpc of OECD countries	%
		8.2. Annual growth GDPpc	M USD$/year
		8.3. Unemployment rate	%
	SDG9 - Industry, Innovation and Infrastructure	9.1. Direct CO_2 emissions from industry	Gt/Year
		9.2. % of GDP invested on R&D	%
Planet Integrity	SDG13 - Climate Action	13.1. GHG emissions	$GtCO_2eq$/Year
		13.2. Global Mean Temperature increase	ºC
		13.3. Cumulative carbon emissions from 2020	$GtCO_2$
		13.4. Cumulative land-use change emissions since 2005	$GtCO_2eq$
	SDG14 - Life Below Water	14.1. Aragonite saturation state	dmnl
		14.2. Average marine acidity at the surface	pH
	SDG15 - Life on Land	15.1. Forest area as proportion of total land	%
		15.2. Primary forest as share of total terrestrial land area	%
		15.3. Global area of forested land as % of original forest cover	%
		15.4. Other natural land as share of total land area	%
		15.5. Non-agricultural land	%
Sustainable Resources	SDG2 - Zero Hunger	2.1. Food availability	kg/(person·day)
	SDG6 - Clean Water and Sanitation	6.1. Agricultural water use	hm^3
		6.2. Fertilizer use	t
		6.3. Water stress index	WSI month/season
	SDG7 - Affordable and Clean Energy	7.1. Final energy intensity	TJ/M USD$
Peace, Institutions & Implementation	SDG17 - Partnership for the Goals	17.1. Total government revenue	M USD$/year

3.3.2.1 SDG interactions for each individual narrative

This subsection intends to relate subtasks 5.6.1 and 5.6.3 by explaining how the narratives set above can address SDG interactions. To do it, the main reference considered is **(van Soest et al., 2019)** as the research by **(Pradhan, Costa, Rybski, & Lucht, 2017)** mainly highlights interrelationships between goals that cannot be represented in WILIAM, such as SDG1, SDG10 or SDG12.

Thus, as the narratives have been created from a climate-related perspective, all the detected interactions include SDG13 (Climate Action) as one of the elements involved within the analysed pair.

- Narrative 1 (ET): The policies and assumptions adopted for this pathway are oriented towards fostering clean energy and, consequently, improving mainly SDG7 indicators. This narrative will assess whether the expected synergy between **SDG 13 and 7** (cleaner energy, lower emissions to not surpass a temperature limit) is met based on WILIAM's outputs.

- Narrative 2 (ET-LC): This is arguably the most difficult relationship to establish, as lifestyle changes are related to behavioural SDGs, which are complex to model or, at least, to model the potential interactions. The reduction in consumption resulting from a lower demand could be assessed through **SDG 17** (in particular with the "Total Government Revenue" indicator) and, consequently, the assumed trade-off between this SDG and the **Climate Action** target (lower demand would lead to better climate performance, but also lower governmental revenues and profits to firms). This study did not implement policies oriented to reduce the working time of workers. Global trends in working hours, legal progress and discussion in terms of gender and age may be found in the book (Messenger et al., 2007). A policy of working time reduction has been highlighted as one of the most powerful, feasible, economic alternatives to green growth scenarios (D'Alessandro et al., 2020).

- Narrative 3 (ET-EC): It is easy to spot that there is a strong link between environmental measures, focusing on the protection and enhancement of forests, and climate targets. An important synergy is expected between **SDGs 13 and 15** (Life on Land), due to the increase and protection in forest area and thus lower emissions from land-use changes and higher carbon sequestration. The application of the policy of regenerative agriculture has also effects on SDG 13 as it expected to decrease agriculture emissions. On the other hand, although not identified as such in the literature, it could be analysed whether the increase in forest area could affect the **SDG 2** (Zero Hunger) in some way by changing the availability of land for cultivation.

These are the relationships considered "relevant" in the literature that can be discussed with the established narratives. However, the results of all the indicators listed in Table 12 have been analysed and are covered in subsection 4.3.5.

Tables 13-16 sum up the outputs for the main interactions presented above. The results shown for each narrative represent the percentage change of their absolute value with respect to that of the BAU, which is shown in the corresponding row. Green shades with different intensities are used to show indicator improvements (I>1%), red shades for worse performances (I≤-1%) and orange shades for similar performances (-1%≤1%).

Table 13. SDG interactions for the ET pathway.

SDGs 13-7 interactions					
SDG	SDG 13				SDG 7
Indicator	GHG emissions	Global Mean Temperature increase	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Final energy intensity
Units	$GtCO_{2eq}$/Year	ºC	$GtCO_2$	$GtCO_2$	TJ/M$
BAU	68	2,0	1278	35	5480

ET	↑26,5%	↑7,7%	↑26,1%	↑60,0%	↑15,5%

Regarding the ET pathway (Table 13), the results are in line with the literature and make sense as the higher performance of more efficient technologies implies lower "final energy intensity" and, consequently, lower GHG emissions, temperature increase, etc. Although the other narratives also improve on SDG13, they do so through other approaches explained below, keeping energy intensity almost fixed.

Table 14. SDG interactions for the ET-LC pathway

SDGs 13-17 interactions					
SDG	SDG 13				SDG 17
Indicator	GHG emissions	Global Mean Temperature increase	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Total government revenue
Units	$GtCO_{2eq}$/Year	ºC	$GtCO_2$	$GtCO_2$	M$/Year
BAU	68	2,0	1278	35	104043000
ET-LC	↑26,7%	↑7,9%	↑21,3%	↑45,3%	↓-65,7%

In terms of the lifestyle change narrative, Table 14 shows that there is a notable trade-off as, although climate indicators improve their values for 2050 compared to BAU, public revenues collapse as the climate improvement is preceded by a drastic decline in demand and production of goods and thus in tax collection (around -65,7%). This theory is supported by the fact that the other narratives do not make their climate boost conditional on lower revenues.

Table 15. SDG interactions for the ET-EC pathway (a)

SDGs 15-2 interactions						
SDG	SDG 15					SDG 2
Indicator	Forest area as proportion of total land	Primary forest as share of total terrestrial land area	Global area of forested land as % of original forest cover	Other natural land as share of total land area	Non-agricultural land	Food availability
Units	%	%	%	%	%	kg/(person*day)
BAU	0,4	0,1019	91	0,3	86	1,9
ET-EC	↑18,7%	↑4,9%	↑18,7%	↓-18,7%	↑0,5%	≈0,0%
ET	↑5,3%	↑2,1%	↑5,3%	↓-2,4%	↑1,3%	↓-14,1%
ET-LC	↑4,6%	↑2,5%	↑4,6%	↓-0,8%	↑1,5%	↓-7,4%

The potential interrelationship outlined above to link SDGs 15 and 2 does not offer relevant synergies, as benchmarked, but generates better results than narratives 1 and 2, which show significant trade-offs (-14,1% and -7,4%, respectively), as presented in Table 15. Finally, for the ET-EC pathway the values in Table 16 show what could be expected, as this is the narrative with the largest improvements for almost all SDG 13 indicators, and at the same time for SDG 15 ones. This enhancement is particularly strong for the indicators "Cumulative emissions from land-use change since 2005" (177,9% increase compared to BAU values) and forest area (18,7% increase). Thus, it is possible to ensure the creation of a strong synergy between these two objectives through the implementation of some appropriate measures. Finally, in this simulation this narrative does not have negative effects on SDG2, so we assume that the afforested land does not compete with agriculture, but it does with other natural land (the indicator *15.4. Other natural land as share of total land area* explained in the previous section indicates a reduction of the rest of natural habitats).

Table 16. SDG interactions for the ET-EC pathway (b)

SDGs 13-15 interactions									
SDG	SDG 13				SDG 15				
Indicator	GHG emissions	Global Mean Temperature increase	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Forest area as proportion of total land	Primary forest as share of total terrestrial land area	Global area of forested land as % of original forest cover	Other natural land as share of total land area	Non-agricultural land
Units	$GtCO_{2eq}$/Year	ºC	$GtCO_2$	$GtCO_2$	%	%	%	%	%
BAU	68	2,0	1278	35	0,4	0,1019	91	0,3	86
ET-EC	↑26,5%	↑7,7%	↑26,1%	↑60,0%	↑18,7%	↑4,9%	↑18,7%	-18,7%	↑0,5%

3.3.2.2 Comparison among narratives: SDG indicators analysis

This subsection intends to discuss the performance of each SDG by comparing the quantifiable values obtained for each indicator in the three narratives to the BAU simulation. Thus, an individual SDG analysis is provided below:

<u>SDG3. Good Health & Well-Being</u>

As commented in Subsection 4.3.2, the **life expectancy** indicator is dismissed since its results clearly represent an exogenous input and are determined by the modellers' assumptions. Regarding **"Under five mortality rate"** (Indicator 3.2), none of the narratives offers significant changes compared to BAU results.

<u>SDG4. Quality Education</u>

The indicator used to quantify the progress of SDG 4 is the "**Medium & High Education"** (Indicator 4.1) measured in terms of share of population. The most affected pathway is the ET-LC (4,9% increase), which makes sense since to obtain these new behavioural trends it is necessary to directly influence people's high-level education. For the ET and ET-EC, the variations are not meaningful.

<u>SDG8. Decent Work & Economic Growth</u>

The following three indicators quantifies the economic development of the region under analysis.

- 8.1. GDP per capita vs. GDP per capita of OECD countries. Measures the balance between OECD countries and the rest of the World. An increase of this value implies a more balanced global economy across regions. All the three pathways show a clear positive trend on this way, being ET-LC the most distributive pathway.
- 8.2. Annual growth of GDP per capita. This mainstream indicator measures the economic growth as a whole. In comparison to the reference (BAU) scenario, the three pathways experiment an increase of 11-21%, suggesting that policies stimulate the economy.
- 8.3. Unemployment rate. People not working. ET-LC experiments a strong increase of unemployment caused by the lower consumption of goods and services (the economy is frozen), what implies, in absence of working time reduction measures, a lower need of human capital.

Funded by the European Union

SDG9. Industry, Innovation and Infrastructure

WILIAM can assess the development of the SDG on industry through two indicators with overall good results. However, these recognize modelling limitations in the IAM used for this study:

o 9.1. Direct CO_2 emissions from industry. WILIAM lacks a bottom-up modelling for all industries (IPUUs). The current approach calculates emissions throughout constant intensities (tonnes/dollars, historical values in 2015). So, the more economic output of the sector, the higher emissions we will show.

o 9.2. Share of GDP invested on R&D. R&D is not disaggregated by sector. The proxy here was to consider the total government expenditure as % of GDP. In order to better address this index, WILIAM should have explicit sectorial functions, or at least, the share of R&D by economic sector, and the percentage of government expenditure to R&D (a share of the education budget).

SDG13. Climate Action

The climate goal presents the greatest improvements among all of them, in line with expectations, as all narratives are ultimately designed to achieve better environmental outcomes. Four indicators are assessed:

o 13.1. GHG emissions: this includes all the gases. The performance is better in the ET-EC scenarios. This difference in terms of GHG emissions (although sharing a common temperature increase objective) is due to the inertia of the climate system which delay the policy effects in the temperature.

o 13.2. Global Mean Temperature: this is the shared objective among narratives for this experiment.

o 13.3. Cumulative Carbon Emissions from 2020: The same as in 13.1, but the difference of the rest of scenarios with respect to the ET-EC scenario is less due to the fact that this indicator does not include other gases apart from CO_2 which are reduced in the case of for example better agriculture practices applied in the ET-EC.

o 13.4. Cumulative Land-Use Change Emissions since 2005: First, it is necessary to mention, that all climate indicators are improved, specially the GHG emissions and temperature indicator which would be the most important as it defines how much we are closer to the objectives of limiting global warming. However, for the particular case of this indicator, the differences are the highest. This is because this indicator is focused on the emissions due to land use changes. The ET-EC has the best performance because it increases the land occupied by forests, which is the land with more carbon stock (less land-use carbon emissions associated, or even negative in the case of afforestation, due to the carbon uptake by forests).

SDG14. Life Below Water

Aquatic species' life relies on several parameters such as oxygen and nutrient concentrations, but WILIAM allows to assess it using two interconnected indicators which are dependent on the dissolved carbon in water and, consequently, on CO_2 emissions:

o 14.1. Aragonite Saturation State: An increase in aragonite concentration favours life below water, in particular for species with calcium carbonate structures (corals, molluscs, etc.) All three narratives give better results than the BAU simulation due to the reduction of carbon emissions, with the ET-EC pathway (the one with the largest emission decrease) standing out.

o 14.2. Average marine acidity at the surface: All the narratives show minor modifications in pH (around +0,5%), generating small acidity reduction compared to the BAU because of the lower CO_2 atmospheric concentration. These changes should not lead to significant impacts for subaquatic species because they are within the range of normal values.

SDG15. Life on Land

Four out of the five land indicators perform better for all narratives compared to BAU results, especially the environmental pathway on which afforestation policies are focused.

o 15.1. Forest area as proportion of total land: clearly the best performance is for the ET-EC scenario, as the afforestation policy is applied with high intensity in this scenario. On the other hand, in the rest of scenarios also the performance is good because afforestation policies are also applied, although the intensity is lower.

- 15.2. Primary forest as share of total terrestrial land area: In this case, clearly the ET-EC has also better performance because in these scenarios is where policies of primary forest protection are applied.

- 15.3. Global area of forested land as share of original forest cover: it occurs exactly the same as with the indicator 15.1, and the same reason explain the difference among narratives.

- 15.4. Other natural land as share of total land area: This indicator behaves exactly the opposite to the others, showing the worst results for the ET-EC. This is because the new forest land enters in competition with the rest of natural habitats (e.g. grassland, shrubland, other land, etc.). However, it is necessary to mention (as commented before), that forest land is the ecosystem with more biodiversity and ecosystem richness. However, a good balance in all habitats should be assured.

- Non-agricultural land: In this case in all scenarios the behaviour is worst in the ET-EC scenarios also. But in all cases the performance is better with respect the BAU scenario (as opposite to the prior indicator). The reason is because in this non-agricultural area, "forest land" is also included.

SDG2. Zero Hunger

None of the narratives provides hopeful results on improving the **food availability** status compared to the BAU despite including some agriculture-related policies. It is worth noting that for the BAU the values in 2050 are somewhat better than the current ones, but for the ET & ET-LC food availability considerably decreases. This is due on one hand because the agricultural land decreases in the first scenarios due to less food demanded and increase in crop yields in the case of the ET. This remarks some limitations WILIAM has to represent currently this SDG which intends to evaluate food security instead of less food demand." The results are worse in the ET scenario with respect of the ET-LC, even including higher improvements in Technology Improvement Agriculture, probably due to the different diet applied.

SDG6. Clean Water and Sanitation

The indicators for this goal provide an interesting variability among the narratives, making it difficult to select one over the rest:

- 6.1. Agricultural water use: A relevant improvement appears for the ET (shown as a reduction in water usage of around 31,8%) derived from the increase in water efficiency. In the ET-LC, the water use reduction is also noticeable, but with lower intensity (8,5%) and is due to the lower demand and economic outputs for water. Finally, the ET-EC pathway does not bring any substantial change since both water efficiency and demand remain similar to BAU.

- 6.2. Fertilizer use: As for this indicator, the three narratives coincide in a lower fertilizer demand, improving the overall performance of the indicator, but with different intensities. The biggest reduction takes place in the ET-EC (31,8%) because although the extent of arable land is larger, the proportion of industrial agriculture is much smaller. The ET and ET-LC narratives also reduce fertiliser use (7,7% and 8,6%, respectively), but in this case because the land used for cultivation is lower than in BAU.

- 6.3. Water stress index: Only the ET-LC pathway shows relevant impacts on the water stress compared to the BAU outputs, with a reduction of about 4,1%, caused by the lower demand in blue water in almost all world regions and their different sectors. This decrease is also boosted by the smaller temperature increase that affects positively the amount of global water available. For both ET and ET-EC, the variations in water demand and temperature decrease are not sufficient to generate a remarkable change.

SDG 7. Affordable & Clean Energy

This goal is only evaluated based on the "**Final Energy Intensity**" and as expected, it just shows relevant variations in the narrative focused on energy considerations (ET pathway), resulting in an intensity reduction of

15,5% compared to BAU thanks to the powerful investment in clean energies. It is worth noting that for the other narratives and therefore also for the BAU, energy intensity is also significantly reduced compared to current levels as all include energy measures to some extent.

SDG 17. Partnerships for the Goals

The available indicator for this goal is the "**Total Government Revenue**", which varies widely from one pathway to another. In the case of ET-EC, the indicator hardly differs from BAU, but for ET-LC the large reduction in demand caused by the change of mentality leads to a decrease in production and thus in taxes collected and finally in public revenues, which fall by 65,7%.

Tables 17 and 18summarise the outputs obtained by simulating each narrative and are presented following the same approach as in Section 4.3.4.

Table 17. SDG indicator results for the simulation of the three pathways (a)

	People			Prosperity					Planet Integrity				
SDG	SDG 3		SDG 4	SDG 8			SDG 9		SDG 13			SDG 14	
Indicator	Life expectancy at birth	Under-five mortality rate	Medium & High education	GDPpc vs average GDPpc of OECD countries	Annual growth GDPpc	Unemployment rate	Direct CO2 emissions from industry	% of GDP invested on R&D	GHG emissions	Cumulative carbon emissions from 2020	Cumulative land-use change emissions since 2005	Aragonite saturation state	Average marine acidity at the surface
Units	Years	deaths/1000	%	%	M$_2015/Year	%	Gt/Year	%	$GtCO_{2eq}$/Year	$GtCO_2$	$GtCO_2$	dmnl	pH
BAU	72	24	58%	0,37	3583980	0,06746	20768	19	68	1278	35	2,3	7,9666
ET	≈0,0%	≈0,0%	↓-0,7%	↑268,2%	↓-20,7%	↑1,0%	↑61,9%	↓-0,8%	↑26,5%	↑26,1%	↑60,0%	↑4,4%	≈0,3%
ET-LC	≈0,0%	≈0,0%	4,9%	↑271,6%	↑16,8%	↓-85,3%	↑43,8%	↑9,4%	↑26,7%	↑21,3%	↑45,3%	↑3,7%	≈0,2%
ET-EC	≈0,0%	≈0,0%	≈0,0%	↑267,7%	↑12,0%	↑4,1%	↑3,5%	≈-0,4%	↑38,2%	↑32,6%	↑177,9%	↑5,7%	≈0,4%

Table 18. SDG indicator results for the simulation of the three pathways (b)

	Planet Integrity					Sustainable Resources					Peace, Institutions & Implementation
SDG	SDG 15					SDG 2	SDG 6			SDG 7	SDG 17
Indicator	Forest area as proportion of total land	Primary forest as share of total terrestrial land area	Global area of forested land as % of original forest cover	Other natural land as share of total land area	Non-agricultural land	Food availability	Agricultural water use	Fertilizer use	Water stress index	Final energy intensity	Total government revenue
Units	%	%	%	%	%	kg/(person*day)	hm^3	t	Water stress index	TJ/M$	M$/Year
BAU	0,4	0,1019	91	0,3	86	1,9	2541730	145212000	19	5480	104043000
ET	↑5,3%	↑2,1%	↑5,3%	↓-2,4%	↑1,3%	↓-14,1%	↑31,8%	↑7,7%	≈-0,1%	↑15,5%	↑10,3%
ET-LC	↑4,6%	↑2,5%	↑4,6%	↓-0,8%	↑1,5%	↓-7,4%	↑8,5%	↑8,6%	↑4,1%	≈0,1%	↓-65,7%
ET-EC	↑18,7%	↑4,9%	↑18,7%	↓-18,7%	↑0,5%	≈0,0%	≈-0,2%	↑31,8%	≈0,3%	≈0,1%	↑0,6%

3.3.3 Stochastic Multicriteria Acceptability Analysis (SMAA)

The conventional multicriteria decision analysis (MCDA) approaches usually consider the preference information by selecting importance weights for criteria. The stochastic multicriteria acceptability analysis (SMAA) methods, however, examine the weight space to show the preferences that would make an alternative the best choice (or any given rank) for the decision-makers. In addition, the SMAA methods allow for assessing uncertainties in both preference information and criteria measurements. Therefore, SMAA applies to many real-life problems where the decision-makers are unable or unwilling to provide their preference, or it is difficult to reach consensus over the preferences. In these situations, the weight information can be provided as intervals that represent all decision-makers' preferences, or with some other weight distribution accepted by all decision-makers (Tervonen et al., 2007). The SMAA-2 method from (Lahdelma & Salminen, 2001) is one of the SMAA methods and has been used in this study as a multicriteria assessment tool. The following description of this method was taken from (Lahdelma & Salminen, 2001).

The decision problem is considered as a set of alternatives that are evaluated based on criteria. As discussed, SMAA methods are developed for the case in which the weight and criteria values are not precisely known, thus they are represented by stochastic variables. The results of SMAA are rank acceptability indices, central weight vectors, and confidence factors for various alternatives.

The rank acceptability indices are the share of all feasible weights that make the alternative acceptable for a particular rank. This is computed as a multidimensional integral over the criteria distributions and favourable rank weights. The most acceptable (best) alternatives are those with high acceptability for the best ranks. The rank acceptability indices are within the range [0, 1], where 0 shows the alternative will not obtain a given rank in any circumstances, and 1 indicates that it will always obtain the given rank no matter how uncertain the weights are.

The central weight vectors represent the preferences of a typical decision-maker supporting a specific alternative. It is also computed as a multidimensional integral over the criteria and weight distributions. By presenting the central weight vectors to the decision-makers, an inverse approach for decision support can be applied, in the sense that instead of eliciting preferences, and building a solution to the problem, the decision-makers can learn what kind of preferences lead to which alternatives without providing any preferences information.

Finally, the confidence factors are the probability for an alternative to obtain the first rank when the central weight vector is chosen. Such factors could be computed as a multidimensional integral over the criteria distribution. For every given weight vector, the confidence factors can be calculated similarly. The confidence factors measure the accuracy of the criteria measurements in determining the most efficient alternatives. If the problem formulation is to choose an alternative to implement, the ones with low confidence factors should not be selected. More accurate criteria data should be collected to make a robust decision if they are deemed attractive.

As described, in order to implement the SMAA-2 method, one needs to compute a few multidimensional integrals that are practically impossible to calculate analytically. Therefore, Tervonen et. al. (Tervonen et al., 2007) suggest Monte Carlo simulation as a solution to this problem and discuss their algorithm for this purpose. In this report, we use a software named JSMAA, which is an open-source software for SMAA computations (Tervonen, 2014).

3.3.3.1 Uncertainties

The strength of SMAA analysis lies in the consideration of various uncertainties for the criteria measurement and preferences of decision-makers. In this study, the impacts of three uncertain parameters, namely minimum EROI of solar and wind technologies, population, and government budget balance, were examined on the criteria measures. The assumptions of the runs for the three uncertain parameters are presented in the following table.

Table 19. Assumptions for the uncertainty analysis

Attributes	Business-as-Usual (BAU)	narrative 1 - ET	narrative 2- ET-LC	narrative 3- ET-EC
Population	Medium	Low (minimum historical values in the period 2005-2020)		

		Medium (mean historical values in the period 2005-2020) High (maximum historical values in the period 2005-2020)
Minimum EROI solar and wind technologies	Medium	Low (5) Medium (8) High (10)
Government budget balance	Negative (past trends by 2050)	Positive (1% by 2050)

Such uncertainties will result in variations in some of the criteria which are used to assess the pathways. For instance, GHG emissions are shown in Figure 25, are highly sensitive to the different assumptions regarding EROI, population, and government budget balance. This means that uncertainties could play a critical role in the criteria that decision-makers care about. Using different levels for each uncertain parameter, 18 pathways for each scenario narrative, and in total 54 pathways plus the one from the BAU scenario will be available to be used as the input to the SMAA analysis.

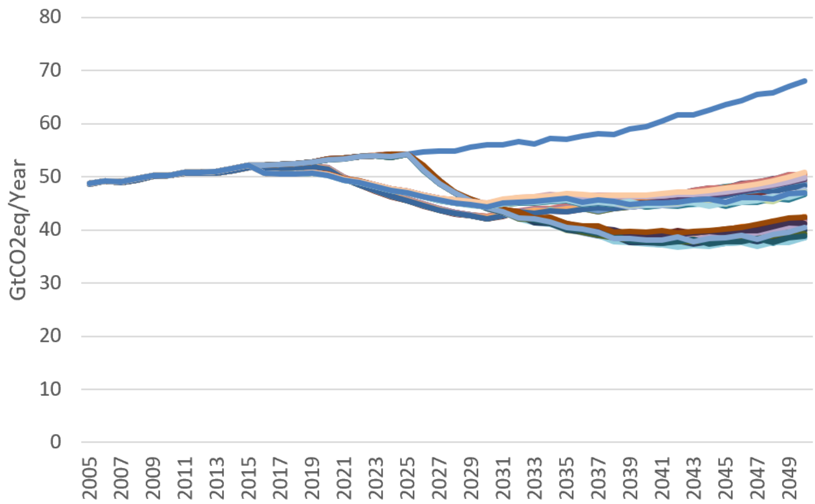


Figure 25. GHG emissions in different uncertain pathways.

Apart from the uncertainties in criteria measures, the preferences of decision-makers are uncertain as there are many stakeholders, some of whom are unable or even unwilling to reveal their preferences, and also it is difficult to reach consensus over the preferences. To address this issue, two uncertain preference schemes have been evaluated in this study. In the first scheme, we assume that there is no information on the preferences of decision-makers regarding the SDG indicator, thus, the uniform range [0, 1] is considered for the weight of each SDG criterion. However, for the second scheme, we used the information from (Koasidis et al., 2021) to extract an ordinal relationship between the SDGs from the perspective of various stakeholders. In this scheme, the weights of the criteria are uncertain as maintain the following order.

$$SDG15 \geq SDG14 \geq SDG2 \geq SDG7 \geq SDG6 \geq SDG3 \geq SDG9 \geq SDG4 \geq SDG8$$

It should be noted that SDG13 and SDG17 are not considered in the second scheme as (Koasidis et al., 2021) does not provide any information on the preferences of stakeholders about them.

3.3.3.2 Results of SMAA analysis

Among the results of WILIAM, some variables can be attributed to one SDG. Therefore, after summing over the time horizon (2024-2050) to produce a cumulative indicator (CI) for the variable (v) under the SDG for each pathway, we first normalize the cumulative indicator using the formula below. Then we take an average from the various variables under the SDG to have a single indicator for each SDG. The same process is done for all the pathways. As a result, using the within-narrative uncertain pathways, a range for each SDG indicator could be derived for the BAU, ET, ET_LC, and ET_EC narratives which will subsequently be used in the SMAA analysis.

$$Normalized\ CI_{v,pathway} = \frac{CI_{v,pathway} - Min(CI_{v,all\ pathways})}{Max(CI_{v,all\ pathways}) - Min(CI_{v,all\ pathways})}$$

Weight scheme 1

Assuming there is no information on the preferences of stakeholders, the result of the SMAA analysis in Figure 26 shows that the BAU narrative will almost never be chosen as the most acceptable alternative and will be ranked the least acceptable alternative on 87% of occasions. On the other hand, it is shown that 46% of all the feasible weights make the ET narrative the most acceptable option for the stakeholders. This is partly due to the significant performance of this narrative in reducing the final energy intensity (SDG7). Besides, ET_EC and ET_LC narratives have been ranked first with less likelihood than ET has been. Furthermore, it has been observed that ET, ET_EC, and ET_LC have rarely been chosen as the least favourite alternative. Overall, the acceptability of ET and ET_EC seem to be close in this weight scheme.

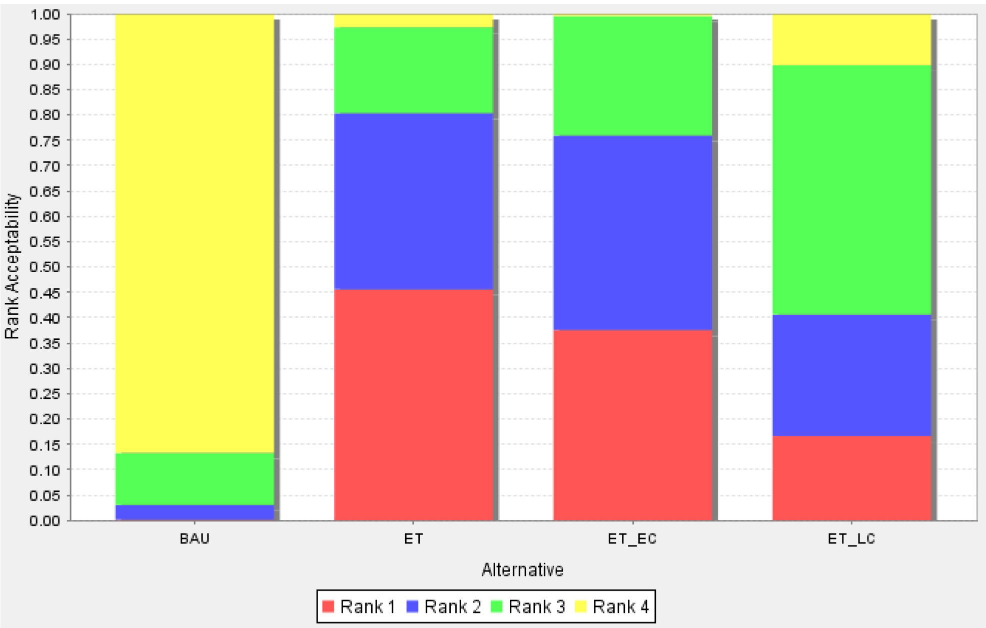


Figure 26. Rank acceptability indices of different narratives using weight scheme 1.

Figure 27 shows the central weight vectors which represent the preferences of a typical decision maker who chooses the alternatives as the first rank. The decision maker in favour of the BAU narrative is likely to value SDG 2, 3, and 17 more than the others, and not to allocate high weights to SDG 4, 6, 7, 13, 14, and 15. Conversely, the typical choosers of ET and ET_EC are more probably inclined to value all SDGs more or less equally, although with some variations. The main differences between the ET and ET_EC supporters are observable in SDG 2, 7, 9, and 15, representing zero hunger, affordable and clean energy, industry-innovation-infrastructure, and life on land. Regarding the ET_LC central weight vector, the corresponding decision-maker considers SDG4 and 9 (i.e. Quality education and industry-innovation-infrastructure) as the most important criteria while weighting the others approximately similarly. It is noteworthy that the confidence factors for the BAU, ET, ET_EC, and ET_LC central weight vectors are 0.23, 0.99, 0.98, and 0.95 respectively. Therefore, it suggests that the impacts of uncertainties within the narratives are fairly small which means that the accuracy of measurements of SDGs is high.

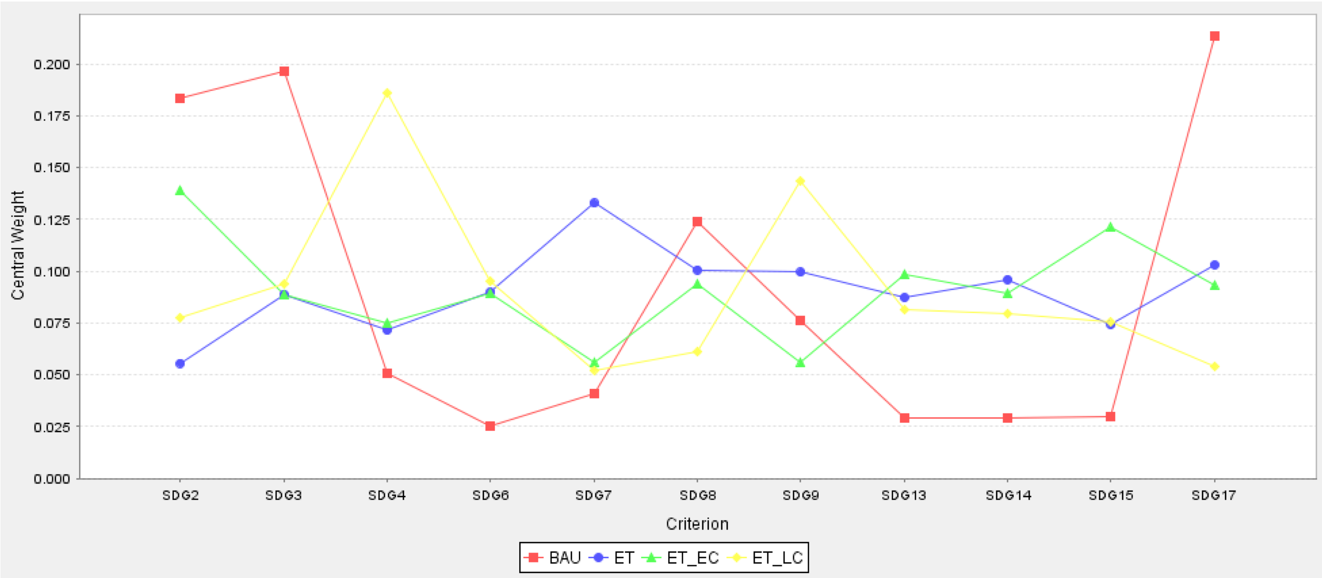


Figure 27. Central weight vectors of different narratives using weight scheme 1.

Weight scheme 2

In this case, we have information on the priorities of decision-makers regarding the SGD indicators. Accordingly, the SMAA analysis was done to evaluate the acceptance of various narratives. The rank acceptability indices of this scheme are presented in Figure 28. The result clearly shows that in this case, the decision-maker is able to rank the alternatives decisively. It is observed that ET_EC is chosen as the rank first in 99% of the feasible weight space since from the SDG15 (life on land) perspective it performs very well compared to the other narratives. ET narrative, the most favourite alternative using the last weight scheme, has, however, been regarded as the second rank using the current scheme. This could partly be explained by the higher value this narrative obtains in SDG14 (life below water) and SDG7 (affordability and clean energy) criteria compared to ET_LC. Besides, ET_LC and BAU narratives are the third and fourth choices of the decision-makers like before. Nevertheless, there is an 11% chance that ET_LC will be the second option instead of ET.

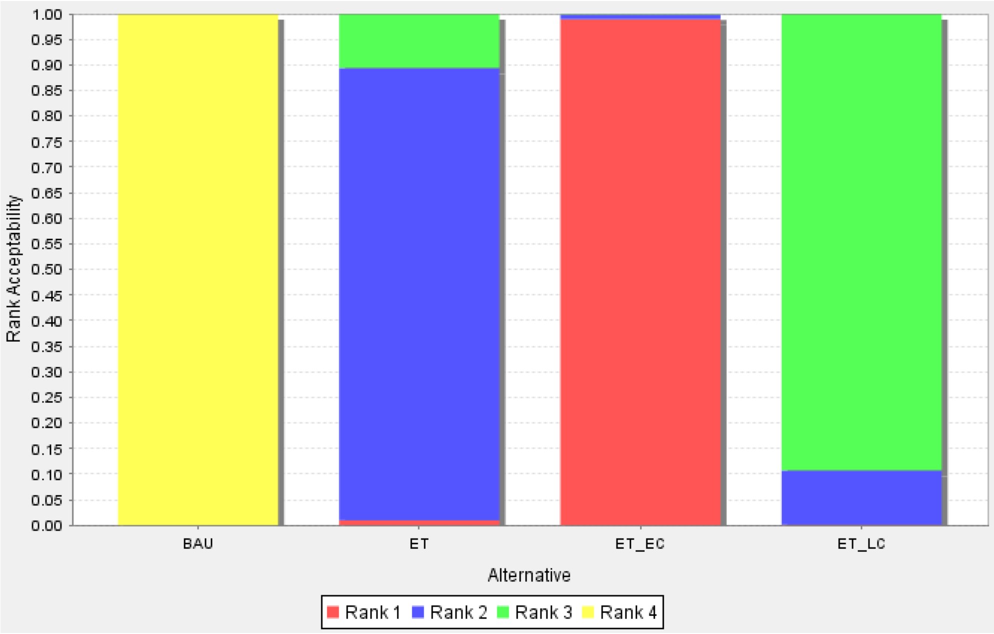


Figure 28. Rank acceptability indices of different narratives using weight scheme 2.

Meanwhile, the central weight vectors demonstrated in Figure 29 indicate that the most significant difference between the typical decision-maker who ranks ET_EC first is the weight allocated to SDG15 (life on land) which is much higher compared to the extent other typical decision-makers value it. However, it was shown in Figure 28 that ET and ET_LC have rarely been considered the most appropriate alternative (in less than 1% of the weight space). Notably, the confidence factor of the vector for the ET narrative is 1 which means that if the decision maker opts for a weight vector similar to the central weight vector of ET, this narrative will certainly be chosen as the best alternative. Therefore, it indicates that the uncertainties of SDG measurements are very negligible.

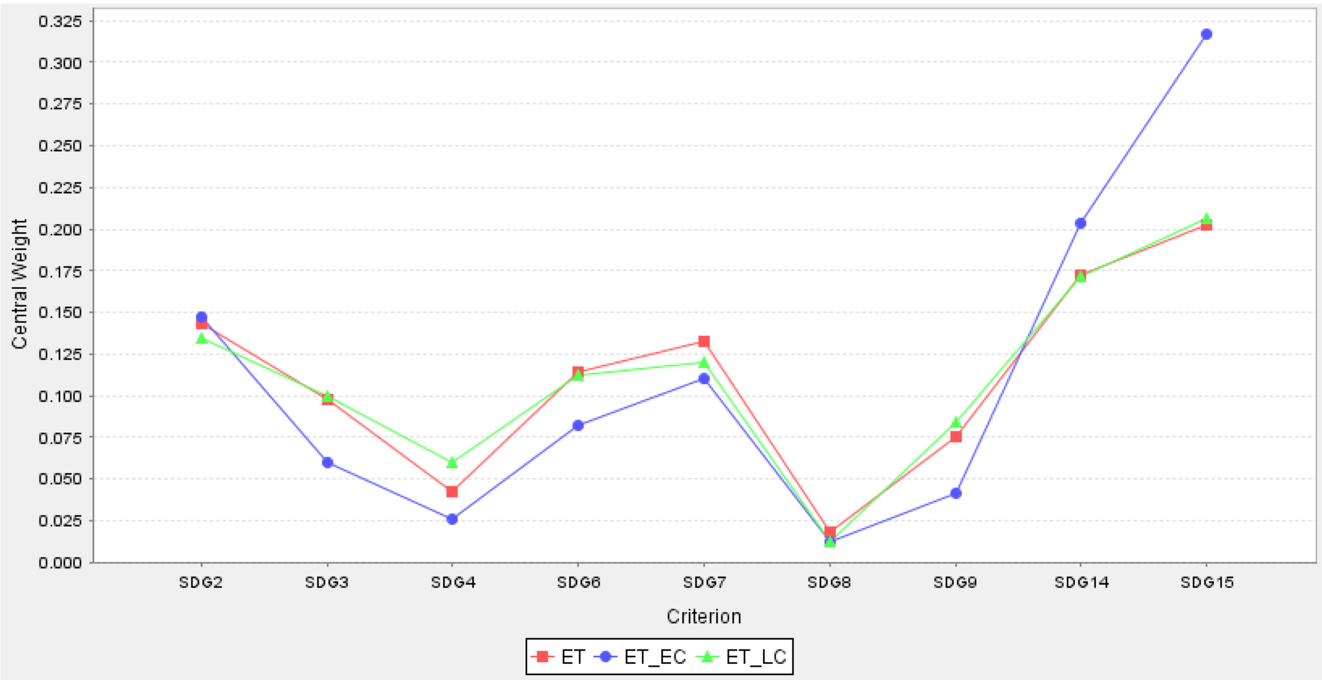


Figure 29. Central weight vectors of different narratives using weight scheme 2.

3.3.4 Limitations and further work

We have identified some limitations when implementing the whole exercise. Next steps may partially address them, while others remain inherent to the methodology.

SDGs as criteria for policymaking:

- Literature highlights an inherent inconsistency between socio-economic development and ecological sustainability (Spaiser et al., 2017) On this way, SDGs may guide, e.g., corporate social responsibility towards wrong directions such as greenwashing depending on how which SDGs are selected and how they are weighted for the analysis. Specifically, the vague definition of SDGs is a weakness, and the measurement of impacts is difficult to validate an assessment model (Lu et al., 2021).

Narratives and pathways:

- Narratives are limited by the efforts available for this study. Additional ideas may bring policymakers into a broader realm of opportunities. The higher the number of pathways, the higher quality of analysis we could provide. A deeper analysis of data from historical data and future innovations would provide theoretically informed examinations (Schill et al., 2015; Tollefson et al., 2015). In short, possible scenarios or narratives that are better suited to test "alternative worlds".

WILIAM (IAM):

- Additional shared goals should be integrated in the analysis. For example, the monetary budget varies across scenarios due to the absence of cost quantification of policies in WILIAM.

- Critical dimensions such as ending poverty in all its forms everywhere (SDG 1), achieve gender equality and empower all women and girls (SDG 5), or promote peaceful societies, access to justice, effective institutions (SDG 16) could not be yet addressed in WILIAM. So, missing SDGs must be discussed separately in this study and the choice may change or not according to that parallel assessment. Similarly, the variables used in WILIAM as proxies of SDGs is a simplification of the information explaining the indicators, i.e., an incomplete version of the official SDG index and dashboards, according to the methodology established by (Lafortune et al. 2018) Finally, WILIAM does not represent the healthcare system of regions so SDG 3 lacks important effects on this indicator.

- WILIAM lacks a bottom-up modelling for all industries (IPUUs, related to SDG 9). The current approach calculates emissions throughout constant intensities (tonnes/dollars, historical values in 2015). So, the more economic output of the sector, the higher emissions we will show.

- Research funding is not disaggregated by sector (SDG 9). To better address this index, WILIAM should have explicit sectorial functions, or at least, the share of R&D by economic sector, and the percentage of government expenditure to R&D (a share of the education budget).

- System dynamics stress on providing understanding about the behaviour of complex systems rather than predictions (Forrester, 2007). Future is uncertain and one cannot guarantee the successful technological/social/economic response demanded by a narrative. Models are mathematical abstractions of reality that may help in the decision making in real life.

Stochastic Multicriteria Acceptability Analysis (SMAA):

- In this study, the narratives are not actual choices one could opt for, however, they are landscapes one could imagine aiming at. In future works, the alternative should be defined so that the decision-makers can rank them to implement using their levers.

- The uncertainties considered in this study are only for a few parameters and could be expanded to evaluate other influential parameters. Besides, the uncertainty ranges are rather limited in our case while it could be much wider. These could potentially affect the narratives chosen according to the analysis.

- Furthermore, the distributions of uncertainties are simplified and assumed to be uniform throughout the analysis which could not be the case. Further investigations should be made to assess this assumption.

- Finally, one could evaluate various other weighting schemes to better understand how even limited information on the decision-maker's preferences can alter the acceptability of alternatives.

3.3.5 Conclusions

The results of this deliverable are preliminary, aiming to test the methods. Then, these need to be refined and further discussed to enhance the quality of the assessment and comparison to related studies. Consequently, a first formal takeaway emerged from this exercise is the fact that SDGs are not yet sufficiently developed in the global assessment models of IAM-COMPACT. The few models containing SDGs proxy them throughout output variables from each module, and do not provide feedback to the system.

Regarding the exercise itself, we can sum up some conclusions:

- Narrative 1 (ET) addresses the synergy between SDG 13 and 7 (clean energy to bend the global temperature change). Results show that, related to the BAU scenario, all the indicators suggest a positive synergy between both SDGs.

- Narrative 2 (ET-LC) focuses on SDG 17 (reduction in consumption and total government revenues). Results suggest a strong trade-off between SDG 13 and 17. Meanwhile the first clearly grows, the second is deeply damaged (> 65%).

- Narrative 3 (ET-EC) expects the synergy between SDG 13 and 15 (promotion of life on land), and the effect on SDG 2 (zero hunger). In this case, results do not show a clear direction in the relationship between both SDGs (15 and 2). Some land-use indicators increase, and others decrease, while food availability does not change in this scenario.

- Assuming there is no information on the preferences of stakeholders, the result of the SMAA analysis shows that the BAU narrative will almost never be chosen as the most acceptable alternative and will be ranked the least acceptable alternative on 87% of occasions. Regarding the ET_LC central weight vector, the corresponding decision-maker considers SDG4 and 9 (i.e. Quality education and industry-innovation-infrastructure) as the most important criteria while weighting the others approximately similarly. It is noteworthy that the confidence factors for the BAU, ET, ET_EC, and ET_LC central weight vectors are 0.23, 0.99, 0.98, and 0.95 respectively. Therefore, it suggests that the impacts of uncertainties within the narratives are small which means that the accuracy of measurements of SDGs is high. That 46% of all the feasible weights make the ET narrative the most acceptable option for the stakeholders.

- In case we had information on the priorities of decision-makers regarding the SGD indicators, ET_EC would be chosen as the rank first in 99% of the feasible weight space since from the SDG15 (life on land) perspective it performs very well compared to the other narratives.

References

Brandt, A. R. (2017). How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI). BioPhysical Economics and Resource Quality 2017 2:1, 2(1), 1–12. https://doi.org/10.1007/S41247-017-0019

Boitier, B., Nikas, A., Gambhir, A., Koasidis, K., Elia, A., Al-Dabbas, K., ... & Mittal, S. (2023). A multi-model analysis of the EU's path to net zero. Joule, 7(12), 2760-2782.

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., van der Wijst, K., Al -Khourdajie, A., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Stromman, A., Winkler, H., Auer, C., Brutschin, E., … van Vuuren, D. (2022). AR6 Scenarios Database [Data set]. In Climate Change 2022: Mitigation of Climate Change (1.1). Intergovernmental Panel on Climate Change. https://doi.org/10.5281/zenodo.7197970

Fizaine, F., & Court, V. (2016). Energy expenditure, economic growth, and the minimum EROI of society. Energy Policy, 95, 172–186. https://doi.org/10.1016/j.enpol.2016.04.039

Forouli, A., Nikas, A., Van de Ven, D. J., Sampedro, J., & Doukas, H. (2020). A multiple-uncertainty analysis framework for integrated assessment modelling of several sustainable development goals. Environmental Modelling & Software, 131, 104795.

Forouli, A., Pagonis, A., Nikas, A., Koasidis, K., Xexakis, G., Koutsellis, T., ... & Doukas, H. (2022). AUGMECON-Py: A Python framework for multi-objective linear optimisation under uncertainty. SoftwareX, 20, 101220.

Forrester, J. W. (2007). System dynamics—the next fifty years. System Dynamics Review, 23(2–3), 359–370. https://doi.org/10.1002/SDR.381

Fuhrman, J., Bergero, C., Weber, M., Monteith, S., Wang, F. M., Clarens, A. F., ... & McJeon, H. (2023). Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. Nature Climate Change, 13(4), 341-350.

Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W., & Clarens, A. F. (2019). From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. Frontiers in Climate, 1, 11.

Jewell, J., & Cherp, A. (2020). On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5° C?. Wiley Interdisciplinary Reviews: Climate Change, 11(1), e621.

Koasidis, K., Nikas, A., Van de Ven, D. J., Xexakis, G., Forouli, A., Mittal, S., ... & Doukas, H. (2022). Towards a green recovery in the EU: Aligning further emissions reductions with short-and long-term energy-sector employment gains. Energy Policy, 171, 113301.

Lifi, M., de Blas, I., Capellán-Pérez, I., Mediavilla, M., Miguel, L. V., Parrado-Hernado, G., LLases, L., Álvarez Antelo, D., Calleja, M., Wergles, N., Ferreras, N., Ramos, I., Arto, I., Calheiros, T., Capela Lourenço, T., Spinato Morlin, G., D'Alessandro, S., van Allen, O., Eggler, L., Papagianni, S., Oakes, R. (2023). D9.3: 'Synthesis of the model, selected results, and scenario assessment'. https://www.locomotion-h2020.eu/resources/main-project-reports

Moreno, J., Campagnolo, L., Boitier, B., Nikas, A., Koasidis, K., Gambhir, A., ... & Vielle, M. (2024). The impacts of decarbonization pathways on Sustainable Development Goals in the European Union. Communications Earth & Environment, 5(1), 136.

Moyer, J. D., & Bohl, D. K. (2019). Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals. Futures, 105, 199-210.

NDC ASPECTS. (2024). Deliverable 2.4: Report and academic article manuscript on global SDG impacts of new-generation global mitigation pathways.

Nikas, A., Fountoulakis, A., Forouli, A., & Doukas, H. (2022). A robust augmented ε-constraint method (AUGMECON-R) for finding exact solutions of multi-objective linear programming problems. Operational research, 22(2), 1291-1332.

Samsó, R., Ramos, I., Ferreras-Alonso, N., Lifi, M., Mediavilla, M., Llases, L., de Blas Sanz, I., Capellán-Pérez, I., Parrado-Hernando, G., Calleja, M., Álvarez Antelo, D., Markovska, N., Arto, I., Calheiros, T., Papagianni, S., van Allen, O., Eggler, L., (2023). LOCOMOTION Deliverable No. D11.2: Python translation and e-Handbook for model sharing and transparency. https://www.locomotion-h2020.eu/resources/main-project-reports

Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., ... & Popp, A. (2021). A sustainable development pathway for climate action within the UN 2030 Agenda. Nature Climate Change, 11(8), 656-664.

van de Ven, D. J., Nikas, A., Koasidis, K., Forouli, A., Cassetti, G., Chiodi, A., ... & Gambhir, A. (2022). COVID-19 recovery packages can benefit climate targets and clean energy jobs, but scale of impacts and optimal investment portfolios differ among major economies. One earth, 5(9), 1042-1054.

Van de Ven, D. J., Sampedro, J., Johnson, F. X., Bailis, R., Forouli, A., Nikas, A., ... & Doukas, H. (2019). Integrated policy assessment and optimisation over multiple sustainable development goals in Eastern Africa. Environmental Research Letters, 14(9), 094001.

van Soest, H. L., van Vuuren, D. P., Hilaire, J., Minx, J. C., Harmsen, M. J., Krey, V., ... & Luderer, G. (2019). Analysing interactions among sustainable development goals with integrated assessment models. Global Transitions, 1, 210-225.

Van Vuuren, D. P., Kok, M., Lucas, P. L., Prins, A. G., Alkemade, R., van den Berg, M., ... & Stehfest, E. (2015). Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model. Technological Forecasting and Social Change, 98, 303-323.

van Vuuren, D. P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D., ... & Soergel, B. (2022). Defining a sustainable development target space for 2030 and 2050. One Earth, 5(2), 142-156.

Intergovernmental Panel on Climate Change (IPCC). 2023. *Climate Change - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Lafortune, G., Fuller, G., Moreno, J., Schmidt-Traub, G., & Kroll, C. (2018). SDG Index and Dashboards Detailed Methodological paper.

Lambert, J., Hall, C., Balogh, S., Poisson, A., & Gupta, A. (n.d.). EROI of Global Energy Resources Preliminary Status and Trends.

Lu, J., Liang, M., Zhang, C., Rong, D., Guan, H., Mazeikaite, K., & Streimikis, J. (2021). Assessment of corporate social responsibility by addressing sustainable development goals. Corporate Social Responsibility and Environmental Management, 28(2), 686–703. https://doi.org/10.1002/CSR.2081

Nakicenovic, Nebojsa, Osamu Kimura, and Amela Ajanovic. 2005. *Purposes of Scenarios (Global Hydrogen and Electricity Storylines*. International Institute for Applied Systems Analysis (IIASA).

Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir Kc, Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, Kristie Ebi, Tomoko Hasegawa, Petr Havlik, Florian Humpenöder, Lara Aleluia Da Silva, Steve Smith, Elke Stehfest, Valentina Bosetti, Jiyong Eom, David Gernaat, Toshihiko Masui, Joeri Rogelj, Jessica Strefler, Laurent Drouet, Volker Krey, Gunnar Luderer, Mathijs Harmsen, Kiyoshi Takahashi, Lavinia Baumstark, Jonathan C. Doelman, Mikiko Kainuma, Zbigniew Klimont, Giacomo Marangoni, Hermann Lotze-Campen, Michael Obersteiner, Andrzej Tabeau, and Massimo Tavoni. 2017. 'The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview'. *Global Environmental Change* 42:153–68. doi: 10.1016/j.gloenvcha.2016.05.009.

Funded by
the European Union

Schill, C., Lindahl, T., & Crépin, A. S. (2015). Collective action and the risk of ecosystem regime shifts: insights from a laboratory experiment. Ecology and Society, Published Online: Mar 04, 2015 | Doi:10.5751/ES-07318-200148, 20(1). https://doi.org/10.5751/ES-07318-200148

Spaiser, V., Ranganathan, S., Swain, R. B., & Sumpter, D. J. T. (2017). The sustainable development oxymoron: quantifying and modelling the incompatibility of sustainable development goals. International Journal of Sustainable Development & World Ecology, 24(6), 457–470. https://doi.org/10.1080/13504509.2016.1235624

Tollefson, J. (2015). Can randomized trials eliminate global poverty? Nature, 524(7564), 150–153. https://doi.org/10.1038/524150A

Van Vuuren, Detlef P., Keywan Riahi, Richard Moss, Jae Edmonds, Allison Thomson, Nebojsa Nakicenovic, Tom Kram, Frans Berkhout, Rob Swart, Anthony Janetos, Steven K. Rose, and Nigel Arnell. 2012. 'A Proposal for a New Scenario Framework to Support Research and Assessment in Different Climate Research Communities'. *Global Environmental Change* 22(1):21–35. doi: 10.1016/j.gloenvcha.2011.08.002.

Annex I

Target Spaces suggested by main references

Table 20. SDG target space proposed by (van Vuuren, et al., 2022)

Van Vuuren et al. (2022)		
Clusters	**SDGs Included**	**Proposed indicators**
People	SDG1	1.2.1. Number of people living under extreme poverty conditions
	SDG3	Healthy life expectancy
		3.2.1. Under-5 mortality rate
	SDG4	4.1.1. Share completing lower secondary education
	SDG5	Gender gap in mean years of schooling (>aged 15 years)
		Female estimated earned income over male
Prosperity	SDG8	8.5.2. Unemployment rate
		GDP/capita compared to average OECD GDP/capita
	SDG9	9.4.1. Private and government-financed gross domestic R&D expenditure (GERD) in per cent GDP
		Proportion of people using the internet
		Proportion of adult people with access to financial services
		Travel time to the nearest city
	SDG10	10.2.1. Number of people with <50% of national median income
	SDG11	11.1.1. Number of people living in slums
		11.6.2. Share of people exposed to annual average PM2.5>25 µg/m3
Planet Integrity	SDG13	13.2. Paris goals
	SDG14	Phosphorous flow from freshwater systems into the ocean
		14.2.1. Proportion of fish stocks within biologically sustainable levels
	SDG15	Global area of forested land as % of original forest cover
		Area of forested land as % of potential forest per biome
		Industrial and intentional biological fixation of N

Funded by the European Union

		Biodiversity Intactness Index
Sustainable Resources	SDG2	2.1.1. Number of people undernourished
		Number of people with obesity
	SDG6	6.1.1. Population without access to improved water source piped
		6.2.1. Population without access to improved sanitation facility
		Area under water stress (water stress index for most water-scarce month/season)
	SDG7	7.1.2. Population cooking with traditional biomass
		7.1.1. Population without basic electricity access
	SDG12	12.3.1. Food loss and waste indexes
		Municipal material recovery
Peace, Institutions & Implementation	SDG16	16.1.2. Battle-related deaths and fatalities from violence
		Equality before the law and individual liberty index
		Equal Access Index
	SDG17	Statistical Capacity Score
		17.1.1. Total Government Revenue
		Member of international NGOs

Table 21. SDG target space proposed by (Soergel, et al., 2021)

Soergel et al. (2021)		
Clusters	**SDGs Included**	**Proposed indicators**
People	SDG1	1.2.1. Number of people living under extreme poverty conditions
		Food expenditure share
	SDG3	3.9.1. Disability adjusted life years (DALYs) lost from particulate matter (PM 2.5)
	SDG4	4.6.1. Share of people >15 w/o education
		4.1.2 Completion rate (primary education, lower secondary education, upper secondary education)
	SDG5	Education gender gap in (a) secondary eduation (age 20-24 with at least lower secondary education); and (b) primary eduction (age 15-19 with at least primary education)

Funded by the European Union

Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita
		8.1.1. Annual growth rate of real GDP/capita
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)
		Direct CO_2 emissions from industry
	SDG10	10.2.1. Number of people with <50% of national median income
		Average income of bottom 40% relative to national average
	SDG11	11.6.2. Share of people exposed to annual average PM2.5>25 µg/m3
		11.1.1. Number of people living in slums
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)
		Global Mean Temperature (GMT) increase according to Paris Goals
		Cumulative CO_2 emissions, counted from 2011
		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage
		Cumulative land-use change emissions
	SDG14	Aragonite saturation state
		Saturation state of calcite
		14.3.1. Average marine acidity (pH) measured at the surface
		Net primary production of biomass in oceans
		New (export) production of biomass in oceans
	SDG15	Industrial and intentional biological fixation of N
		Biodiversity Intactness Index
		15.1.1. Forest area as a proportion of total land area
		Primary forests as share of total terrestrial land area (excluding surface water)
		Land area afforested
		Other natural land as share of total land area
		Percentage of land that is non-agricultural
Sustainable Resources	SDG2	2.1.1. Number of people underweight
		2.2.2. Prevalence of underweight in children

		Prevalence of overweight
		2.2.2. Prevalence of overweight in children
		Prevalence of obesity
		2.2.2. Prevalence of obesity in children
		Food availability
		Agricultural commodity price index
	SDG6	Agricultural water use
		Fertilizer use
		Nitrogen surplus on cropland
		Water consumption for electricity
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)
		Useful energy per capita for passenger transport.
		Useful energy per capita for buildings
		7.1.2. Energy obtained from traditional biomass combustion in buildings
		7.2.1. Share of electrified Final Energy
		7.2.1. Share of Electricity and Hydrogen in passenger transport
		Final energy intensity in MJ/$GDP
	SDG12	Food waste per capita & day
		12.2.1. Agricultural material footprint (biomass usage per capita)
Peace, Institutions & Implementation	SDG16	16.1.2. Battle-related deaths and fatalities from violence
		Equality before the law and individual liberty index
	SDG17	Net international climate finance
		Relative change in GDP

SDG indicators coverage by the IAM COMPACT models

Below are all the inputs made by the modellers on the SDG indicators that their models can represent. They include the indicators listed in the Target Space created for this task, but in some cases they have also added other indicators from the original UN list and others that they have considered appropriate.

Table 22. SDG indicators covered by ATOM

ATOM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Other Indicators	SDG13	Adoption levels for technologies, as solar PV and storage systems, smart appliances, and electric vehicles, by households in the residential sector	Directly	-	%
	SDG7	Projections on new solar Pv capacity additions by households/citizens in a monthly resolution: on-site PV energy generation, and consumption projections in the residential sector	Directly	-	W/cap

Table 23. SDG indicators covered by CALLIOPE

CALLIOPE					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
Sustainable Resources	SDG7	7.2.1. Share of electrified Final Energy	Directly	-	%

Table 24. SDG indicators covered by CHANCE

CHANCE					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
People	SDG1	Food expenditure share	Proxy	We can have the share, but we would need consumer prices to simulate its evolution. Only for Europe	%
	SDG5	Female estimated earned income over male	Proxy		%
Prosperity	SDG10	10.2.1. Share of population with <50% of national median income	Proxy		%
		Average income of bottom 40% relative to national average	Proxy		%
Other Indicators	SDG7	Energy Poverty indicators	Proxy		%

Table 25. SDG indicators covered by CHINA-MAPLE

CHINA-MAPLE					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG8	8.1.1: Annual growth rate of real GDP per capita	Directly	-	%
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr

		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr
Sustainable Resources	SDG2	Food availability	Directly	-	kg/cap·d
	SDG6	Fertilizer use	Directly	-	Mt/yr
		Nitrogen surplus on cropland	Directly	-	Mt N/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Directly	-	GJ/cap·yr
		Useful energy per capita for passenger transport.	Directly	-	GJ/cap·yr
		Useful energy per capita for buildings	Directly	-	GJ/cap·yr
		7.1.2. Energy obtained from traditional biomass combustion in buildings	Directly	-	%
		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP

Table 26. SDG indicators covered by CICERO-SCM

CICERO-SCM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly Exogenous	Each gas separately	Tg/yr

		Global Mean Temperature (GMT) increase according to Paris Goals	Proxy Endogenous	Temperature increase relative either to start of run or to preindustrial (user choice)	ºC
		Cumulative CO2 emissions, counted from 2011	Proxy Exogenous	Net CO_2 emissions per year as input, broken down by fossil and land use	Gt CO_2/yr
		Cumulative land-use change emissions	Proxy Exogenous		Gt CO_2 eq/yr

Table 27. SDG indicators covered by CLEWS

CLEWS					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Proxy	Model gives absolute number, needs to be divided by total	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
		Cumulative CO2 emissions, counted from 2011	Proxy		Gt CO_2/yr

Funded by the European Union

		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage	Proxy	Annual emissions need to be summed up	Gt CO_2/yr
		Cumulative land-use change emissions	Proxy		Gt CO_2 eq/yr
	SDG15	15.1.1: Forest area as a proportion of total land area	Proxy	Model gives absolute number, needs to be divided by total	%
		Primary forests as share of total terrestrial land area (excluding surface water)	Proxy		%
		Percentage of land that is non-agricultural	Proxy		%
		Land area afforested	Directly	-	km^2
Sustainable Resources	SDG2	Food availability	Proxy	Annual domestic food production and imports (Production By Technology Annual variable) - can be processed into kg / cap day if we have current and projected population data	kg/cap·d
		Agricultural commodity price index	Proxy	From post-processing: average annualised cost of production of different foods	dmnl

Funded by the European Union

	SDG6	Agricultural water use	Directly	-	km^3/yr
		Fertilizer use	Directly	-	Mt/yr
		Water consumption for electricity	Directly	-	km^3/yr
	SDG7	7.1.2. Energy obtained from traditional biomass combustion in buildings	Proxy	Model gives absolute value, needs to be divided by the total in post-processing	%
		7.2.1. Share of electrified Final Energy	Proxy		%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Proxy		%
		Final energy intensity in MJ/ $ GDP	Proxy		MJ/$ GDP
	SDG12	12.2.1. Agricultural material footprint (biomass usage per capita)	Proxy	Model gives absolute value, needs to be divided by the population	t/cap or kg/$

Table 28. SDG indicators covered by DREEM

DREEM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Sustainable Resources	SDG7	Useful energy per capita for buildings	Proxy	Final energy consumption per household	GJ/cap·yr
		7.1.2. Energy obtained from traditional biomass combustion in buildings	Directly	-	%
		7.2.1. Share of electrified Final Energy	Directly	-	%

Funded by the European Union

		7.2.1. Renewable energy share in the total final energy consumption	Directly	-	%
Other Indicators	SDG1	Effect of energy-efficiency policies in energy poor households	Directly	-	$/yr
		Identification of energy poor households	Directly	-	-
	SDG3	Thermal comfort	Directly	-	-
	SDG7	Decentralised RES generation/Self-consumption cost-benefit ratios	Directly	-	%
		Market-oriented regulatory designs that eliminate aspects of subsidisation	Directly	-	-
		Investment in energy efficiency as a proportion of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services	Directly	-	$/yr
	SDG11	Levelized cost of saved energy of energy-efficiency measures	Directly	-	$/GJ
		Demand-Flexibility cost-benefit ratio	Directly	-	%
	SDG13	Footprint impact of consumption /Decarbonisation pathways in the building sector	Directly	-	Gt CO_2 eq/yr

Table 29. SDG indicators covered by DYNERIO

DYNERIO					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita	Directly	-	%
		8.5.2. Unemployment rate	Proxy	Employed people by country	%

Funded by the European Union

	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG15	15.1.1: Forest area as a proportion of total land area	Directly	-	%
		Other natural land as share of total land area	Directly	-	%
Sustainable Resources	SDG2	Agricultural commodity price index	Directly	-	dmnl
	SDG6	Agricultural water use	Directly	-	km^3/yr
		Fertilizer use	Directly	-	Mt/yr
		Water consumption for electricity	Directly	-	km^3/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Proxy	Residential energy consumption by country (population must be given exogenously)	GJ/cap·yr
		Useful energy per capita for passenger transport.	Proxy	Energy consumption by transport by country (population must be given exogenously)	GJ/cap·yr
		Useful energy per capita for buildings	Directly	-	GJ/cap·yr

		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	Just Electricity	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP
Other Indicators	SDG8	Employed people by skill level	Directly	-	ppl
	SDG2	Food production by commodity\and country	Directly	-	-
	SDG12	Raw materials extraction	Directly	-	-

Table 30. SDG indicators covered by ENERGY-PLAN

ENERGYPLAN					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
		Cumulative CO_2 emissions, counted from 2011	Proxy	Total system CO2 emissions can be calculated for any year, but requires modelling of that specific year	Gt CO_2/yr

Funded by
the European Union

		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr
	SDG7	7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%

Table 31. SDG indicators covered by EXPANSE

EXPANSE					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Other Indicators	SDG3	PM2.5 Emissions	Directly	-	μg/m^3
		Annual premature deaths	Directly	-	Thousand/yr
		Years of life lost	Directly	-	yr
	SDG8	Direct employment in electricity generation, transmission, and storage	Directly	-	thousands of full-time equivalents
	SDG13	Annual CO_2 emissions from the electricity sector	Directly	-	Gt CO_2/yr
	SDG15	Land needed for electricity generations, transmission and storage	Directly	-	km^2
	SDG7	Various indicators related to how electricity is generated (e.g. share of renewables, generation in TWh by source)	Directly	-	-
	SDG16	Regional inequality among European regions in terms of electricity generation and its impacts	Directly	-	Gini index

Table 32. SDG indicators covered by GCAM

GCAM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
People	SDG1	Food expenditure share	Proxy	Food expenditures from model, to be divided by income level groups	%
	SDG3	3.9.1. Disability adjusted life years (DALYs) lost from particulate matter	Proxy	Premature deaths, DAYLs, and YLLs from PM25 and O3	DALYs/yr
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
	SDG11	11.6.2. Share of people exposed to annual average PM2.5>25 μg/m3	Proxy	Level of regional exposure	%
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
		Global Mean Temperature (GMT) increase according to Paris Goals	Directly	-	ºC
		Cumulative CO2 emissions, counted from 2011	Directly	-	Gt CO_2/yr
		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr

		Cumulative land-use change emissions	Directly	-	Gt CO_2 eq/yr
	SDG14	14.3.1: Average marine acidity (pH) measured at the surface	Proxy	Ocean pH	dmnl
	SDG15	Biodiversity Intactness Index	Directly	-	dmnl
		15.1.1: Forest area as a proportion of total land area	Directly	-	%
		Primary forests as share of total terrestrial land area (excluding surface water)	Directly	-	%
		Percentage of land that is non-agricultural	Directly	-	%
		Land area afforested	Directly	-	km^2
		Global area of forested land as % of original forest cover	Directly	-	%
		Other natural land as share of total land area	Directly	-	%
Sustainable Resources	SDG2	Agricultural commodity price index	Directly	-	dmnl
	SDG6	Agricultural water use	Directly	-	km^3/yr
		Fertilizer use	Directly	-	Mt/yr
		Water consumption for electricity	Directly	-	km^3/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Directly	-	GJ/cap·yr
		Useful energy per capita for passenger transport.	Directly	-	GJ/cap·yr
		Useful energy per capita for buildings	Directly	-	GJ/cap·yr
		7.1.2. Energy obtained from traditional biomass combustion in buildings	Directly	-	%

		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP
	SDG12	12.2.1. Agricultural material footprint (biomass usage per capita)	Directly	-	t/cap or kg/$
Other Indicators	SDG2	Micronutrients and Macronutrients	Proxy	-	-
	SDG6	Groundwater depletion by river basin	Directly	-	%

Table 33. SDG indicators covered by IMACLIM-CHINA

IMACLIM-CHINA					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
People	SDG1	Food expenditure share	Directly	-	%
Prosperity	SDG8	8.1.1: Annual growth rate of real GDP per capita	Directly	-	%
		8.5.2. Unemployment rate	Directly	-	%
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
		9.4.1. Private and government-financed gross domestic	Directly	-	%

Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
		Cumulative CO2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO2/yr
Sustainable Resources	SDG7	7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP

Table 34. SDG indicators covered by MENA-EDS

MENA-EDS					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita	Directly	-	%
		8.1.1: Annual growth rate of real GDP per capita	Directly	-	%
		8.5.2. Unemployment rate	Directly	-	%
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
		Cumulative CO_2 emissions, counted from 2011	Directly	-	Gt CO_2/yr

Funded by the European Union

		Cumulative CO2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr
		Cumulative land-use change emissions	No, but will be added	-	-
Sustainable Resources	SDG6	Water consumption for electricity	Directly	-	km^3/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Directly		GJ/cap·yr
		Useful energy per capita for passenger transport.	Directly		MJ/$ GDP
		Useful energy per capita for buildings	Directly		GJ/cap·yr
		7.1.2. Energy obtained from traditional biomass combustion in buildings	Directly		%
		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP

Table 35. SDG indicators covered by MUSE

MUSE					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO2 emissions from industry	Directly	-	Gt CO_2/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Directly	-	GJ/cap·yr

Sustainable Resources		Useful energy per capita for passenger transport.	Directly	-	GJ/cap·yr
		Useful energy per capita for buildings	Directly	-	GJ/cap·yr
Other Indicators	SDG5	Exogenous GDP, modelled as in SSPs	Proxy	-	M$/yr
	SDG9	Investment costs for mitigation	Directly	-	M$/yr

Table 36. SDG indicators covered by OSEMOSYS-GR

OSEMOSYS-GR					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Planet Integrity	SDG9	Cumulative CO2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr
Other Indicators	SDG7	Share of renewable electricity generation	Directly	-	%
		Electricity system costs and investment	Directly	-	$/yr
		Use of traditional biomass	Directly	-	GJ/yr
	SDG12	Installed renewable energy-generating capacity	Directly	-	W/cap
	SDG13	Decarbonisation pathways in the power sector	Directly	-	Gt CO_2 eq/yr

Table 37. SDG indicators covered by PROMETHEUS

PROMETHEUS

Funded by the European Union

Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita	Directly	-	%
		8.1.1: Annual growth rate of real GDP per capita	Directly	-	%
		8.5.2. Unemployment rate	Directly	-	%
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG13	13.2.2. GHG emissions (Kyoto gases, AR5 global warming potentials)	Directly	-	Gt CO_2 eq/yr
		Cumulative CO_2 emissions, counted from 2011	Directly	-	Gt CO_2/yr
		Cumulative CO2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr
		Cumulative land-use change emissions	No, but will be added	-	-
Sustainable Resources	SDG6	Water consumption for electricity	Directly	-	km^3/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Directly		GJ/cap·yr
		Useful energy per capita for passenger transport.	Directly		MJ/$ GDP
		Useful energy per capita for buildings	Directly		GJ/cap·yr
		7.1.2. Energy obtained from traditional biomass combustion in buildings	Directly		%

Funded by
the European Union

		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP

Table 38. SDG indicators covered by TIAM

TIAM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG13	Cumulative CO2 emissions, counted from 2011	Directly	-	Gt CO_2/yr
		Cumulative CO_2 removal by means of bioenergy with carbon capture and storage	Directly	-	Gt CO_2/yr
Sustainable Resources	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Directly	-	GJ/cap·yr
		Useful energy per capita for passenger transport.	Directly	-	GJ/cap·yr
		Useful energy per capita for buildings	Directly	-	GJ/cap·yr
		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	-	%

		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP

Table 39. SDG indicators covered by WISEE-EDM

WISEE-EDM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly EU only; energy-intensive industry sectors only	-	%
		Direct CO2 emissions from industry		-	Gt CO_2/yr

Table 40. SDG indicators covered by WISEE-GSM

WISEE-GSM					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly Steel only	-	%
		Direct CO2 emissions from industry	Directly Steel only	-	Gt CO_2/yr

Table 41. SDG indicators covered by WTMBT

WTMBT					
Clusters	SDG	Indicator	How is it modelled	Proxy Name/Comment	Units
Prosperity	SDG8	GDP/capita compared to average OECD GDP/capita	Directly	-	%
		8.5.2. Unemployment rate	Proxy	Employed people by country	%
	SDG9	Industry Clean Energy (Share of FE provided by hydrogen/electricity in industry)	Directly	-	%
		Direct CO_2 emissions from industry	Directly	-	Gt CO_2/yr
Planet Integrity	SDG15	15.1.1: Forest area as a proportion of total land area	Directly	-	%
		Other natural land as share of total land area	Directly	-	%
Sustainable Resources	SDG2	Agricultural commodity price index	Directly	-	dmnl
	SDG6	Agricultural water use	Directly	-	km^3/yr
		Fertilizer use	Directly	-	Mt/yr
		Water consumption for electricity	Directly	-	km^3/yr
	SDG7	Useful energy buildings & mobility (useful energy consumption per capita)	Proxy	Residential energy consumption by country (population must	GJ/cap·yr

				be given exogenously)	
		Useful energy per capita for passenger transport.	Proxy	Energy consumption by transport by country (population must be given exogenously)	GJ/cap·yr
		Useful energy per capita for buildings	Directly	-	GJ/cap·yr
		7.2.1. Share of electrified Final Energy	Directly	-	%
		7.2.1. Share of Electricity and Hydrogen in passenger transport	Directly	Just Electricity	%
		Final energy intensity in MJ/ $ GDP	Directly	-	MJ/$ GDP
Other Indicators	SDG8	Employed people by skill level	Directly	-	ppl
	SDG2	Food production by commodity\and country	Directly	-	-
	SDG12	Raw materials extraction	Directly	-	-

Funded by
the European Union