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Integrated Assessment of the UN Sustainable Development Goals (SDGs) in Transformation Pathways towards a Resource-Efficient and Greenhouse-Gas-Neutral Germany

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Abstract: Integrated Assessment of the UN Sustainable Development Goals (SDGs) in Transformation Pathways towards a Resource-Efficient and Greenhouse-Gas-Neutral Germany

The research and development project "Integrated Assessment of the UN Sustainable Development Goals (SDGs) in Transformation Pathways towards a Resource-Efficient and Greenhouse-Gas-Neutral Germany" was carried out by GWS mbH (GWS; Osnabrück, Germany), the Millennium Institute (MI; Washington DC, USA & Geneva, Switzerland) and ERASME (Aubière, France). The project task was to develop and apply a modeling and evaluation approach for Germany to take an integrated view on various sustainability aspects in ambitious climate and resource protection scenarios. The United Nations Sustainable Development Goals (SDGs) were defined as the sustainability aspects to be assessed. This final report documents the main research and development services provided in the course of the project.

Since the official adoption of the SDGs, a variety of assessment methods have already been applied by researchers studying SDG-relevant nexus developments. The project therefore began with a thorough stocktaking by means of a comprehensive meta-study. The findings from this meta-study illustrate that research interest in SDG analyses has increased significantly over the past decade. Well-recognised methods for ex ante macroeconomic assessments of the climate and resource protection nexus are Integrated Assessment Models (IAMs), macroeconomic models and system dynamics models.

Considering applications of system dynamics models for resource conservation policy assessments UNEP (2017), for example, refers to initial applications of the Threshold 21 model on behalf of the United Nations. The system-dynamic iSDG model represents a further development of the Threshold 21 model, which has already been frequently used in the past for national analyses of SDG interactions (Allen et al. 2019b, 2021). Based on an in-depth structure that has been improved over several decades, its reporting aim is to capture a wide range of interactions between individual SDGs and associated sub-goals. The iSDG model simulates the fundamental trends for the SDGs under a business-as-usual scenario and supports the analysis of relevant alternative scenarios. As the research consortium was also able to draw on the iSDG model, the iSDG assessment approach has been calibrated and adapted to German development paths in the further course of the project.

To calibrate the structures of the iSDG model on German development dynamics, historical time series observations for around 200 social, economic and ecological indicators were integrated into the model database. In addition, further changes were made to the model structure in order to be able to take into account relevant development contexts of the Green-Supreme scenario of the RESCUE study (Dittrich et al. 2020b). Hence, the model version developed for Germany by the project team has been significantly expanded compared to previous applications of the iSDG model. At the end of the project, this extended model version for Germany was handed over to the researchers at the German Environment Agency (UBA). It can therefore be used by UBA in own follow-up analyses. It is also possible to publicly present the model and the results of the project on the internet. The model simulator can be accessed via https://exchange.iseesystems.com/public/millenniuminstitute/isdg-germany/.

Three central environmental dimensions are addressed by the parameterized transformations: Domestic greenhouse gas emissions, domestic material consumption and soil quality. Using the iSDG model structure extended for this project, the effects of sustainability transformations in the following fields of action were analyzed: Energy system, industry (incl. circular economy), construction and housing, mobility, and food and agriculture.

From a climate policy perspective, out modelled transformation scenario meets the original German policy objective for national development in line with the global 2°C target. In the

RESCUE study, a 97 % reduction in German greenhouse gas emissions compared to 1990 was modelled in the "Green Supreme" scenario. Not taking carbon capture and storage technologies into account, our transformation scenario simulates a reduction of domestic greenhouse gas emissions by 84 % until 2050 compared to 1990 levels. To some extent, this comparison reveals that not all details of the RESCUE study could be parametrized one-to-one in the iSDG model. However, comparing our results with related details from the RESCUE study, it should also be noted that no dynamic modelling was carried out for the RESCUE study. One important finding of the present project is therefore that the projection paths of dynamic simulations can deviate significantly from the findings of thematically comparable static modelling (which does not take into account the relevant feedback loops in central scenario details).

Our simulation results for Germany do not hint at any apparent trade-offs across individual SDG dimensions: Starting from already high SDG target achievement levels, the additional transformations assumed in the simulations generally lead to an increase in SDG target achievement levels. In 2050, compared to the baseline, the climate and resource policy scenario is characterized by the fact that no significant negative effects on individual SDG target achievement levels are simulated.

In political terms, these findings can be summarised like this: ambitious environmental policy transformations do not have to jeopardise achievements of other SDG target dimensions. Yet, as this far-reaching political conclusion is derived from an application of a specific simulation model, the boundaries of the applied modelling approach must also be considered seriously. What seems most notable in this regard is the fact that the model only maps developments in Germany. As the iSDG model has already been previously applied for SDG-specific assessments of alternative development pathways in other countries, we deliberately accepted this limitation in this initial SDG pathway assessment for Germany. As a matter of fact, this ensures the direct comparability of our results with published findings from related SDG-assessments for other world regions by means of the iSDG model. However, we are also aware that the German economy is closely linked to foreign markets, which is why (among other things) key indicators and targets from the resource policy domain were actually designed to capture global developments in detail. Given that no global interactions were modelled in our project, it remains for future projects to further deepen our research work documented here in this regard.

Kurzbeschreibung: Integrierte Betrachtung der UN-Nachhaltigkeitsziele (SDGs) in Transformationspfaden hin zu einem ressourcenschonenden und treibhausgasneutralen Deutschland

Das Forschungs- und Entwicklungsprojekt "Integrierte Betrachtung der UN-Nachhaltigkeitsziele (SDGs) in Transformationspfaden hin zu einem ressourcenschonenden und treibhausgasneutralen Deutschland" wurde von der GWS mbH (GWS; Osnabrück, Deutschland), dem Millennium Institute (MI; Washington DC, USA & Genf, Schweiz) und ERASME (Aubière, Frankreich) durchgeführt. Projektauftrag war, für Deutschland einen Modellierungs- und Bewertungsansatz zur integrierten Betrachtung verschiedener Nachhaltigkeitsaspekte in ambitionierten Klima- und Ressourcenschutz-Szenarien zu entwickeln und anzuwenden. Als zu bewertende Nachhaltigkeitsaspekte wurden dabei die Nachhaltigkeitsziele der Vereinten Nationen (engl. UN Sustainable Development Goals, SDGs) vorgegeben. Der vorliegende Abschlussbericht dokumentiert die bis zum Projektabschluss erbrachten Forschungs- und Entwicklungsarbeiten.

Seit offizieller Verabschiedung der SDGs wurden im Bereich der Nachhaltigkeitsforschung bereits eine Vielzahl von Methoden angewandt, um SDG-relevante Entwicklungen und dabei relevante Wechselwirkungen zu analysieren. Zur systematischen Erfassung dieses Forschungsstandes hat das Konsortium zu Beginn des Vorhabens eine umfassende internationale Metastudie durchgeführt. Diese Metastudie verdeutlicht, dass das Forschungsinteresse an SDG-Analysen im vergangenen Jahrzehnt deutlich gestiegen ist. Dabei wurden insbesondere Integrierte Assessment Modelle (IAM), makroökonomische Modelle und systemdynamische Modelle als grundsätzlich für gesamtwirtschaftliche ex ante Bewertungen des Klima- und Ressourcenschutz-Nexus verfügbare Methoden identifiziert.

Im Bereich der Ressourcenschonungspolitk verweist der IRP-Bericht „Resource Efficiency: Potential and Economic Implications“ (UNEP 2017) auf frühere Anwendungen des systemdynamischen Modells Threshold 21 für Nachhaltigkeitsanalysen im Auftrag der Vereinten Nationen. Das systemdynamische iSDG-Modell repräsentiert eine Weiterentwicklung des Threshold 21 Modells, welche in der Vergangenheit bereits mehrmals für nationale Analysen von SDG-Wechselwirkungen angewandt wurde (Allen et al. 2019b, 2021). Auf einer tiefgreifenden und mittlerweile über mehrere Jahrzehnte hinweg verbesserten Struktur basierend, zielt es in seiner Berichterstattung auf eine weitreichende Erfassung von Wechselwirkungen zwischen einzelnen SDGs und zugehörigen Unterzielen ab. Das iSDG-Modell simuliert die grundlegenden Trends für die SDGs unter einem Business-as-usual-Szenario und ermöglicht die Analyse von flexibel parametrisierbaren Alternativszenarien. Da das Forschungs-konsortium zur Durchführung dieses Vorhabens auf das iSDG-Modell zurückgreifen konnte, wurde im weiteren Projektverlauf der iSDG-Bewertungsansatz für entsprechende Analysen deutscher Entwicklungspfade verwendet.

Um die Strukturen des iSDG-Modells für eine Analyse der deutschen Verflechtungen anzupassen, mussten zunächst Datensätze zur Abbildung der historischen Entwicklung in Deutschland von ca. 200 sozialen, ökonomischen und ökologischen Indikatoren in die Modelldatenbank integriert werden. Darüber hinaus wurden weitergehende Änderungen der Modellstruktur durchgeführt, um relevante Entwicklungszusammenhänge des Green-Supreme-Szenarios der RESCUE-Studie (Dittrich et al. 2020b) berücksichtigen zu können.

Die in den eigenen Analysen parametrisierten Umstellungen behandeln drei zentrale Umweltdimensionen: Treibhausgasemissionen, inländischer Materialverbrauch (engl. Domestic Material Consumption) und Bodenqualität. Unter Nutzung der für dieses Vorhaben erweiterten iSDG-Modellstruktur konnten dabei die Auswirkungen von Umstellungen in folgenden Handlungsfeldern analysiert werden: Energiesystem, Industrie (inkl. Kreislaufwirtschaft), Bauen und Wohnen, Mobilität, Ernährung und Landwirtschaft.

Bei der Auswertung der Simulationsergebnisse zeigt sich, dass keine offensichtlichen Zielkonflikte auf die SDG-Zielerreichung identifiziert werden: Von bereits hohen SDG-Zielerreichungsgraden ausgehend, führen die in den Simulationen unterstellten zusätzlichen Umstellungen in der Regel zu einer Steigerung der SDG-Zielerreichungsgrade. Im Jahr 2050 ist das klima- und ressourcenpolitische Politikszenario im Vergleich zur Baseline dadurch geprägt, dass keine signifikant negativen Auswirkungen auf einzelne SDG-Zielerreichungsgrade simuliert werden.

In der RESCUE Studie wurde im „GreenSupreme“-Szenario durch sämtliche unterstellten Umstellungen eine Reduktion der deutschen Treibhausgasemissionen im Vergleich zu 1990 um 97 % erreicht. Die im Vergleich hierzu simulierten geringeren Treibhausgas-Reduktionen (84 % bis 2050 im Vergleich zu 1990 im Policy-Scenario) der eigenen Modellrechnungen verdeutlichen einerseits, dass auch der in diesem Vorhaben erweiterte iSDG-Bewertungsansatz nicht sämtliche Detailannahmen der RESCUE-Studie abbildet. Beim Ergebnisvergleich mit der RESCUE-Studie muss allerdings auch berücksichtigt werden, dass für die RESCUE-Studie keine dynamischen Modellierungen vorgenommen wurden. Als eine wichtige Erkenntnis des gegenständigen Vorhabens ist daher unter anderem festzuhalten, dass die Projektionspfade dynamischer Simulationen durch die Berücksichtigung relevanter Rückkopplungsschleifen in zentralen Szenariodetails deutlich von den Befunden thematisch vergleichbarer (entsprechende Rückkopplungsschleifen aber nicht berücksichtigender) statischer Modellierungen abweichen können.

Bei politischen Schlussfolgerungen ist zu beachten, dass das iSDG-Modell lediglich Entwicklungen in Deutschland simuliert. Da das iSDG-Modell bereits zuvor für SDG-spezifische Bewertungen alternativer Entwicklungspfade in anderen Ländern eingesetzt wurde, haben wir diese Einschränkung für unsere erste deutsche Transformationsanalyse von SDG-Entwicklungen bewusst in Kauf genommen, um damit die Vergleichbarkeit unserer Ergebnisse mit veröffentlichten Ergebnissen aus vergleichbaren Anwendungen des iSDG-Modells für andere Weltregionen ermöglichen zu können. Da in unserem Projekt keine globalen Wechselwirkungen modelliert wurden, bleibt es zukünftigen Forschungs- und Entwicklungsvorhaben vorbehalten, auch die aus globalen Wirkungszusammenhängen resultierenden Einflüsse auf SDG-Indikatoren wie spw. dem Materialfußabdruck unter Anwendung erweiterter Bewertungsansätze zu analysieren.

Dank der in diesem Bericht dokumentierten Entwicklungsarbeiten liegt nun eine vollständig parametrisierte iSDG-Version für Deutschland vor, die im Vergleich zu bisherigen Modellversionen deutlich erweitert wurde. Diese erweiterte Modellversion wurde am Ende des Projekts an die wissenschaftlichen Mitarbeitenden das Umweltbundesamts (UBA) übergeben. Sie kann daher vom UBA in eigenen Folgeanalysen eingesetzt werden. Auch eine öffentliche Präsentation des Modells und der im Rahmen des Projekts erarbeiteten Ergebnisse im Internet ist möglich. Der Modell Simulator kann über den Link https://exchange.iseesystems.com/public/millenniuminstitute/isdg-germany/ aufgerufen werden.

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List of abbreviations

Abbreviation	Full label
ADF	Augmented Dickey-Fuller
AIM-CGE	Asia-Pacific Integrated Model - Computable General Equilibrium
ALMOD	Agriculture and LULUCF Model
ATM	Automated teller machines
BAU	Business as usual
BC	Benefit-cost
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung
bn	Billion
BRICS	Brazil, Russia, India, China, and South Africa
bspw	beispielsweise
CCS	Carbon capture and storage
CD	Cobb-Douglas
CES	Constant Elasticities of Substitution
CGE	Computable General Equilibrium
CH_4	Methane
CLD	Causal Loop Diagram
CO_2	Carbon dioxide
COFOG	Classification Of the Functions Of Government
DGE	German Nutrition Society
DIN	Deutsches Institut für Normung
DMC	Domestic Material Consumption
DNE21+	Dynamic New Earth 21
DNS	German Sustainable Development Strategy
DP IAM	Detailed Process IAM
E3ME	Energy-Environment-Economy Macro-Econometric Model
EMAS	Eco-Management and Audit Scheme
ENGAGE	Environmental Global Applied General Equilibrium
ENV	Environmental
EPC	Energy Performance Certificate
ERASME	Jean Monnet Center of Excellence on Sustainable Development
ETR	Environmental Tax Reform
ETS	Emissions Trading Scheme
EU	European Union
EXIOBASE	A global multi-regional input-output database (https://www.exiobase.eu/)
EXIOMOD	Extended Input-Output Model
FAO	World Food Organisation

Abbreviation	Full label
FIES	Food Insecurity Experience Scale
FKZ	Forschungskennzahl
GCAM	Global Change Analysis Model
GDP	Gross Domestic Product
GEM-E3	General equilibrium model – Energy, Economy, Environment
GEMOD	Gebäudemodell (Building model)
GHG	Greenhouse gas
GIAM	Global Integrated Assessment Model
GINFORS	Global Interindustry Forecasting System
GLOBIOM	Global Biosphere Management Model
GNI	Gross national income
Green-X	Green electricity model (https://www.green-x.at/)
GTAP	Global Trade Analysis Project
GTEM	Global Trade and Environment Model
GW	Gigawatts
GWS	Gesellschaft für Wirtschaftliche Strukturforschung mbH
HIV	Human Immunodeficiency Virus
i.e.	id est (that is)
IAM	Integrated Assessment Model
IAMC	Integrated Assessment Modelling Consortium
ICES	Intertemporal Computable Equilibrium System model
ICSU	International Council for Science
IDEAS	Bibliographic database
IEA	International Energy Agency
IEE	Institute for Energy Economics and Energy System Technology
ifeu	Institut für Energie- und Umweltforschung (Institute for Energy and Environmental Research)
IGES	(Japanese) Institute for Global Environmental Strategies
IHR	International Health Regulations
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IO	Input-Output
IPAC	Integrated Policy Assessment Model for China
IPCC	Intergovernmental Panel on Climate Change
IRP	International Resource Panel
iSDG	Integrated Sustainable Development Goals Model
ISIC	International Standard Industrial Classification of All Economic Activities
JRC	Joint Research Centre

Abbreviation	Full label
K	Potassium
km	Kilometer
KPI	Key Performance Indicator
LDC	Least Developed Countries
LES	Linear Expenditure System
LPJmL	Lund-Potsdam-Jena managed Land (model)
LtG	Limits to Growth
LULUCF	Land Use, Land-Use Change and Forestry
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MDG	United Nations Millenium Development Goals
MEDEAS	Modelling sustainable energy system development under environmental and socioeconomic constraints
MEMO	A macro-economic model
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MEWA	Material Energy Waste and Agriculture
MF	Material footprint
MI	Millennium Institute
MIT	Massachusetts Institute of Technology
Mp	Market price
N	Nitrogen
N_2O	Nitrous oxide
NDC	Nationally Determined Contributions
NEMESIS	New Econometric Model of Evaluation by Sectoral Interdependency and Supply
NewERA	A dynamic computable general equilibrium model
ODA	Official development assistance
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PBL	Netherlands Environmental Assessment Agency
PIK	Potsdam Institute for Climate Impact Research
PM	Particulate matter
POLES	Prospective Outlook on Long-term Energy Systems
POLFREE	Policy options for a resource efficient economy
PRIMES	Price-induced market equilibrium system
ProgRess	Deutsches Ressourceneffizienzprogramm
PV	Photovoltaic
R&D	Research and Development

Abbreviation	Full label
REMIND	Regional Model of Investment and Development
RESCUE	Resource-Efficient Pathways to Greenhouse-Gas-Neutrality
RMC	Raw material consumption
RMI	Raw material input
RMSPE	Root Mean Squared Percent Error
RoW	Rest of World
SCOPE	Cross-Sectoral Deployment and Expansion Optimisation for Analyses of the Future Energy Supply System
SD	System dynamics
SDG	Sustainable Development Goals
SDi	SDG Indicator
SEM	Structural Equation Model
SFD	Stock-flow diagram
SR15	Special Report on Global Warming of 1.5°C
SSP	Shared Socio-Economic Pathway
SUR	Seemingly Unrelated Regressions
T21	Threshold21 model
TFP	Total Factor Productivity
TIMES	The Integrated MARKAL–EFOM System
TIMES-PanEu	Pan-European TIMES energy system mode
TREMOD	Transport Emission Model
TRIPS	Trade-Related Aspects of Intellectual Property Rights
TWh	Terawatt hours
UBA	German Environment Agency
UN	United Nations
UNEP	United Nations Environment Programme
URMOD	Environmental and Economic raw Materials Model
VAR	Vector Autoregressive
VTT	Valtion teknillinen tutkimuskeskus (Technical Research Centre of Finland)
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization
WIOD	World Input-Output Database
WITCH	World Induced Technical Change Hybrid
WP	Work Package

Summary

Introduction

The research and development project "Integrated Assessment of the UN Sustainable Development Goals (SDGs) in Transformation Pathways towards a Resource-Efficient and Greenhouse-Gas-Neutral Germany" was carried out by GWS mbH (GWS; Osnabrück, Germany), the Millennium Institute (MI; Washington DC, USA & Geneva, Switzerland) and ERASME (Aubière, France). These research institutions were commissioned by the German Federal Environment Agency (UBA) in July 2021. This final report documents all main research and development services provided by this consortium in the course of the project.

The project task was to develop and apply a modeling and evaluation approach for Germany to take an integrated view on various sustainability aspects in ambitious climate and resource protection scenarios. The assessed transformation pathway had to be aligned to key environmental objectives from the "GreenSupreme scenario" of the RESCUE study (Dittrich et al. 2020b). Therefore, all resource policy transformations considered in this study are oriented towards a reduction in the use of primary raw materials.[1] Concerning sustainability aspects, the United Nations Sustainable Development Goals (SDGs) were given as key reporting subjects.

In the year 2000, the United Nations defined eight global development goals with a predominantly development policy focus, which were to be achieved by 2015 (Millennium Development Goals, MDGs). These goals included, for example, providing primary education for all children, improving environmental protection, combating communicable diseases (such as malaria and HIV), establishing a global partnership for development and combating poverty and hunger (BMZ 2024). The SDGs were then negotiated with an expanded focus over several years of intergovernmental negotiations. In addition to "traditional development goals", the SDGs also address the protection of natural resources through sustainable environmental use (such as the use of land or water resources), social and health development goals, peace and security and the shared responsibility of states to achieve these goals. The SDGs therefore now form a normative frame of reference for "global goals and targets that the international community sets for itself" (Le Blanc 2015, p. 11).

Due to the development work documented in this report, a model version for Germany that has been significantly expanded compared to previous applications of the iSDG model is now available. This extended model version for Germany was handed over to the researchers at the German Environment Agency (UBA) at the end of the project. It can therefore be used by UBA in their own follow-up analyses. It is also possible to present the model and the results of the project publicly on the internet. The model simulator can be accessed via https://exchange.iseesystems.com/public/millenniuminstitute/isdg-germany/.

SDG modeling approaches

Since the official adoption of the SDGs, a variety of assessment methods have already been applied by researchers studying SDG-relevant nexus developments. The project therefore began with a thorough stocktaking by means of a **comprehensive meta-study (Chapter 2)**. In order to determine the current state of research on methods for and findings from applications of numerical assessment of SDG interactions and their development in future development paths,

[1] Thus, compared to the rather broad definition of "resources" in the 2030 Agenda, this report refers to "resources" in the narrower definition of the German Resource Efficiency Programme "ProgRess". Overarching goals of ProgRess are the long-term conservation of natural resources by the promotion of more sustainable raw material extraction activities as well as the implementation of more sustainable modes of raw material utilisation. To this end, ProgRess sets out measures to increase resource efficiency along the entire value chain - from raw material extraction and product development to production, consumption and the circular economy (https://www.bmuv.de/en/topics/water-management/overview-resource-efficiency/overview-of-german-resource-efficiency-programme-progress, retrieved on October 8, 2024).

1701 publications were first recorded in an electronic database and statistically evaluated in a systematic literature analysis. Based on the statistical evaluations, 275 publications were selected for a content review of their abstracts. 40 of these 275 publications were then scrutinised in a full-text analysis.

The findings from this meta-study illustrate that research interest in SDG analyses has increased significantly over the past decade: While the earliest recorded research articles were published in 1993 (one database entry), the total number of annual publications identified in the meta-study rarely exceeds 10 by the end of the 2000s. Starting from 21 articles in the publication year 2010, this number increases monotonically to a total of 293 thematically relevant publications in the publication year 2021.

The meta-study identified Integrated Assessment Models (IAMs), macroeconomic models and system dynamics models as methods that are generally available for ex ante macroeconomic assessments of the climate and resource protection nexus. This finding can be interpreted as an extension and consolidation of comparable earlier literature studies as published by Aguilar-Hernandez et al. (2021), van Soest et al. (2019) and UNEP (2017) , for example.

IAMs have generally been developed and applied to assess climate policy measures. Based on a detailed mapping of biophysical systems, SDG indicators of the water-energy-land use-climate nexus and associated interactions are generally mapped very well. With this analytical focus, however, relevant socio-economic SDG dimensions (such as demographic developments or developments in global and national poverty patterns) are generally not sufficiently taken into account. For comprehensive SDG assessments, more extensive social science modeling should therefore also be applied (van Soest et al. 2019).

The development and application of dynamic models to analyze economic systems has been established in the social sciences for over 50 years.[2] Macroeconomic Input-Output models (IO models) are characterised by a high level of detail in the mapping of macroeconomic demand structures, associated macroeconomic supply chains and the direct and indirect environmental pressures associated with the production of the analysed goods and services. See Aguilar-Hernandez et al. (2021) for a detailed overview of previous applications of (in particular) macroeconomic models to assess societal circular economy development paths in terms of their implied economic, social and environmental impacts.

System dynamics modeling approaches are not rooted in either natural science or social science theories. Instead, they are based on a generalized approach for the structured recording of the developmental dynamics of complex systems over time (Hardt and O'Neill 2017). Basic concepts for system dynamics modeling were developed in the 1960s (Forrester 1958). Following Hafner et al. (2020), key features of SD models result from the application of general principles from engineering and the theory of feedback control. Having initially been applied in industrial engineering, this modelling approach has meanwhile been used in a large number of applications. Compared to IAMs and macroeconomic models, system dynamics models are therefore often attributed a remarkable flexibility regarding the type and scope of the system interrelationships represented by them.

Considering applications of system dynamics models for resource conservation policy assessments UNEP (2017), for example, refers to initial applications of the Threshold 21 model on behalf of the United Nations. The system-dynamic iSDG model represents a further

[2] The first Nobel Prize in Economics was awarded in 1969 to Ragnar Frisch and Jan Tinbergen for the development and application of dynamic models to analyze economic systems. (https://www.ardalpha.de/wissen/nobelpreis/nobelpreis-geschichte-alfred-nobel-100.html, retrieved on March 6, 2024).

development of the Threshold 21 model, which has already been frequently used in the past for national analyses of SDG interactions (Allen et al. 2019b, 2021). Based on an in-depth structure that has been improved over several decades, it captures a wide range of interactions between individual SDGs and associated sub-goals. The iSDG model simulates the fundamental trends for the SDGs under a business-as-usual scenario and supports the analysis of relevant alternative scenarios. Corresponding scenario analyses can also be carried out beyond the time span of the SDGs (year 2030).

Early iSDG applications studied economies of the Global South in the context of traditional development work (Collste et al. 2017; Pedercini et al. 2019; Allen et al. 2020). However, the iSDG model was recently also applied in simulation studies on SDG interactions for the Australian economy (Allen et al. 2019b). Furthermore, the iSDG model has also been applied for Austria most recently (Spittler and Kirchner 2022).[3] As the research consortium was also able to draw on the **iSDG model**, the iSDG assessment approach has been calibrated and adapted to German development paths in the further course of the project.[4] This ensured that the project's own activities were linked to previous and ongoing, thematically relevant and internationally visible research and development work.

iSDG model adaptations for Germany

In order to adapt the structures of the iSDG model for an analysis of German interdependencies, around 200 social, economic and ecological German indicator time series had to be integrated into the model database. In order to ensure that the iSDG model correctly reflects the German system structure, some specific adjustments were made to the general assessment approach.

In addition, further changes were made to the model structure in order to be able to take into account relevant development contexts of the Green-Supreme scenario of the RESCUE study: With regard to the environmental policy transformation paths to be considered in our own SDG analyses, the terms of reference specified that assumptions of the "GreenSupreme" scenario of the RESCUE study (Dittrich et al. 2020b) should be taken into account. In the RESCUE study, the German Environment Agency (UBA) analyzed macroeconomic transformation options for establishing resource-conserving and greenhouse gas-neutral lifestyles, consumption and production methods in Germany by 2050. The relevant adjustments considered in the RESCUE study focused on the areas of energy supply, mobility, industrial production, agriculture and land use, construction and housing as well as waste and wastewater.

In order to implement this assignment, the usual iSDG assessment approach not only had to be calibrated to German impact relationships, but also had to be significantly adapted, in particular to reflect different resource policy fields of action in the "GreenSupreme" scenario. Corresponding changes were made in the core of the economic modeling as well as in other modules of the iSDG model describing central interdependencies of selected fields of action of the RESCUE study.

Supply-side modeling approaches using Cobb-Douglas (CD, Cobb and Douglas 1928) production functions are used in the iSDG model to depict economic developments. CD production functions derive changes in the overall economic production level from changes in the availability of the production factors labor and capital and the changes in their respective productivities (which are also derived endogenously in the model). Demand factors are not considered. When projecting macroeconomic production activities, the standard iSDG assessment approach

[3] More information can be found at the following link: startclim.at.

[4] The models suitable for macroeconomic assessments of transformation paths were developed over many years by independent institutions and are therefore usually not freely accessible. This applies to Integrated Assessment Models as well as to macroeconomic and system-dynamic models.

distinguishes between three different economic sectors (agriculture, industry and services). But this highly aggregated representation proved to be insufficient for the modelling of key assumptions of the RESCUE. For the model used in this project, an extension of the usual iSDG industry modeling was therefore developed based on international economic classifications.

The model developed for Germany is therefore capable to derive individual material flows from production activities in the following industries:

1) Mining and quarrying;

2) Water supply, wastewater disposal, waste disposal and removal of environmental pollution;

3) Building trade;

4) Manufacture of food, beverages and tobacco products;

5) Manufacture of wood and paper products, printing works;

6) Manufacture of chemicals and chemical products;

7) Other industry.

In addition to this very far-reaching expansion of the previous projection of industrial production levels for the entire iSDG modeling approach, individual adjustments were also made to existing sub-modules and an explicit expansion of the usual scope of the report was carried out through the additional integration of residential building modeling. Further details on all **model adaptations** implemented in this project phase, as well as the procedure for calibrating the adapted model framework in preparation for the subsequent scenario simulations, are summarized in **Chapter 3** of this report.

SDG modeling for Germany

The **applications of the adapted iSDG model for Germany** are summarized in **Chapter 4**. Various scenario parameterizations were carried out in order to identify potential synergies and conflicting goals in climate and resource policy transformation paths. These parameterizations reflect impacts of already established policy measures as well as more extensive transformation assumptions. Three central environmental dimensions were addressed by the parameterized transformations: domestic greenhouse gas emissions, domestic material consumption and soil quality. Analyzed action areas were given as follows: Energy system, industry (incl. circular economy), construction and housing, mobility, food and agriculture.

Our simulation results for Germany do not hint at any apparent trade-offs across individual SDG dimensions: Starting from already high SDG target achievement levels,[5] the additional transformations assumed in the simulations tend to increase SDG target achievement levels across individual target dimensions. Compared to baseline projections for the year 2050, the climate and resource policy scenario is characterized by the fact that no significant negative effects on individual SDG target achievement levels are simulated. However, particularly with regard to SDG 2 (zero hunger), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 12 (sustainable consumption and production) and SDG 13 (climate action), significant improvements in SDG target achievement in Germany are simulated. Further,

[5] For individual SDG indicators, the model calculates target achievement levels as the ratio between

- the deviation of the current indicator performance from an international "worst performance" reference value (zero level),

- and the difference between the specified target value and the international "worst performance" reference value (zero level).

A 100% target achievement rate would mean that all targets defined in the iSDG have been achieved. It should be noted that the iSDG model was originally designed to assess the development prospects of low-income countries. Many of the SDG indicators modeled are therefore particularly relevant for low-income country groups.

albeit less pronounced, improvements in target achievement are also evident for SDG 6 (clean water and sanitation), and SDG 8 (decent work and economic growth). Virtually no changes are simulated for SDGs 1 (no poverty), 3 (good health and wellbeing), 4 (quality education), 5 (gender equality), 10 (reduced inequalities), 11 (sustainable cities and comunities), 14 (life below water), 15 (life on land), 16 (peace and justice and strong institutions) and 17 (partnership for the goals).

The policy simulation is characterized by its green growth character: While the simulated climate policy changes tend to have a dampening effect on economic growth, these dampening economic effects are overcompensated by significant expansionary economic effects of the assumed circular economy transformations. These expansionary effects are triggered by massive increases in productivity.[6] Despite these expansionary economic effects, the assumed economy-wide increases in material efficiency result in a 40 % decrease in domestic material consumption (DMC) by 2050 compared to the baseline. The climate policy assumptions of the policy scenario imply an 84 % reduction in German greenhouse gas emissions by 2050 compared to 1990 baseline levels. These reductions, which are compatible with original German policy targets to enable global compliance with the 2°C target, are simulated without modeling carbon capture and storage technologies.

However, the greenhouse gas neutrality that Germany is politically aiming for by 2050 is not achieved in the iSDG simulations. In the RESCUE study, a 97 % reduction in German greenhouse gas emissions compared to 1990 was achieved in the "Green Supreme" scenario through all assumed changes. The lower greenhouse gas reduction simulated by us illustrates on the one hand that not all detailed assumptions of the RESCUE study could be mapped even with the extended iSDG assessment approach. As explained in more detail in the introductory chapter 1, the RESCUE study simulated very detailed assumptions on the development of production technologies, sector-specific intermediate and final demand structures and the resulting production levels in a multi-model simulation framework, which facilitated deeply disaggregated analyses of material- and emission-intensive sectors (energy production, transport, agriculture). To map detailed developments that are not projected in stand-alone applications of the iSDG model, respective soft link modeling approaches could also be sought in further research projects. However, an application of such a multi-model simulation framework was not considered necessary for this initial SDG-assessment of German transformation pathways.

When comparing the results with the RESCUE study, it should also be noted that no dynamic modelling was carried out for the RESCUE study. This means that the expansive economic effects of the assumed circular economy transformations that are clearly observable in our simulations were not captured in the RESCUE study: The "GreenSupreme" scenario of the RESCUE study actually assumes zero growth in Germany's economic output from 2030 onwards. The findings of our dynamic model simulations therefore deviate from the RESCUE study. One important finding of the present project is therefore that the projection paths of dynamic simulations can deviate significantly from the findings of thematically comparable static modelling (which does not consider relevant feedback loops).

[6] The increases in efficiency boost productivity. This stimulates economic growth in the short and long term.

The effect that resource-importing industrialized nations such as Germany benefit from ambitious increases in resource efficiency in macroeconomic terms has already been demonstrated in multi-regional simulation studies in the past (Hatfield-Dodds et al. 2017; Distelkamp and Meyer 2019).

Conclusions and limitations of the study

The simulations documented in this report do not reveal any fundamental trade-offs between ambitious climate and resource protection and further SDG-relevant developments for Germany. However, this does not generally guarantee that respective trade-offs will never occur. In the **final conclusions of Chapter 5**, it is first noted that our own literature review revealed a general consensus in sustainability research regarding the relevance of interdependencies across individual SDG dimensions. A complete consideration of all these interactions can never be the goal of modelling. However, the report concludes by naming central impact channels that are not represented by the current iSDG parameterisation. For future assessments of synergies and trade-offs between climate and resource protection and the SDGs, the comprehensive mapping of these impact channels is recommended.

Zusammenfassung

Einleitung

Das Forschungs- und Entwicklungsprojekt "Integrierte Betrachtung der UN-Nachhaltigkeitsziele (SDGs) in Transformationspfaden hin zu einem ressourcenschonenden und treibhausgasneutralen Deutschland" wurde von der GWS mbH (GWS; Osnabrück, Deutschland), dem Millennium Institute (MI; Washington DC, USA & Genf, Schweiz) und ERASME (Aubière, Frankreich) durchgeführt. Nachdem diese Institutionen vom Umweltbundesamt (UBA) im Juli 2021 mit der Durchführung des Vorhabens beauftragt wurden, dokumentiert der vorliegende Abschlussbericht die wesentlichen bis zum Projektabschluss im Jahr 2024 erbrachten Forschungs- und Entwicklungsarbeiten.

Projektauftrag war, für Deutschland einen Modellierungs- und Bewertungsansatz zur integrierten Betrachtung verschiedener Nachhaltigkeitsaspekte in ambitionierten Klima- und Ressourcenschutz-Szenarien zu entwickeln und anzuwenden. Die eigenen Szenarioanalysen waren dabei in ihren ökologischen Transformationsannahmen an entsprechende Vorarbeiten des "GreenSupreme"-Szenarios der RESCUE-Studie (Dittrich et al. 2020b) anzulehnen.[7] Als zu bewertende Nachhaltigkeitsaspekte wurden die Nachhaltigkeitsziele der Vereinten Nationen (engl. UN Sustainable Development Goals, SDGs) vorgegeben: Die Vereinten Nationen haben im Jahr 2000 acht bis zum Jahr 2015 global zu erreichende Entwicklungsziele (Millenium Development Goals, MDG) mit überwiegend entwicklungspolitischem Schwerpunkt definiert. Zu diesen Zielen zählten bspw. die Ermöglichung einer Grundschulausbildung für alle Kinder, die Verbesserung des Umweltschutzes, die Bekämpfung übertragbarer Krankheiten (wie bspw. Malaria und HIV), der Aufbau weltweiter Entwicklungspartnerschaften sowie die Bekämpfung von Armut und Hunger (BMZ 2024). Anschließend wurden in mehrjährigen zwischenstaatlicher Verhandlungen die SDGs mit einem erweiterten Fokus ausgehandelt. Neben „klassischen Entwicklungszielen" adressieren die SDGs auch die Sicherung der natürlichen Lebensgrundlagen durch nachhaltige Umweltinanspruchnahmen (wie der Nutzung von Land- oder Wasserressourcen), soziale und gesundheitliche Entwicklungsziele sowie Frieden und Sicherheit und die gemeinsame Verantwortung der Staaten zur Erreichung dieser Ziele. Damit bilden die SDGs heute einen normativen Referenzrahmen für "global goals and targets that the international community sets for itself" (Le Blanc 2015, p. 11).

Dank der in diesem Bericht dokumentierten Entwicklungsarbeiten liegt nun eine vollständig parametrisierte Modellversion für Deutschland vor, die im Vergleich zu bisherigen Anwendungen des iSDG-Modells deutlich erweitert wurde. Diese erweiterte Modellversion für Deutschland wurde am Ende des Projekts an die wissenschaftlich Mitarbeitenden im Umweltbundesamt (UBA) übergeben. Sie kann daher vom UBA in eigenen Folgeanalysen eingesetzt werden. Auch eine öffentliche Präsentation des Modells und der im Rahmen des Projekts erarbeiteten Ergebnisse im Internet ist möglich. Der Modell Simulator kann über den Link https://exchange.iseesystems.com/public/millenniuminstitute/isdg-germany/ aufgerufen werden.

SDG-Modellierungsansätze

Seit offizieller Verabschiedung der SDGs wurden im Bereich der Nachhaltigkeitsforschung bereits eine Vielzahl von Methoden angewandt, um SDG-relevante Entwicklungen und dabei

[7] Im Vergleich zu der eher breit gefassten Verwendung des "Ressourcen"-Begriffs im Kontext der Agenda 2030 wird in diesem Bericht der "Ressourcen"-Begriff daher durchgehend in der engeren Abgrenzung des Deutschen Ressourceneffizienzprogramms "ProgRess" verwendet. Siehe https://www.bmuv.de/themen/ressourcen/deutsches-ressourceneffizienzprogramm (abgerufen am 8. Oktober 2024) für diesbezüglich weitergehende Informationen.

relevante Wechselwirkungen zu analysieren. Zu Beginn des Vorhabens hat das Konsortium daher den internationalen Forschungsstand im Rahmen einer **umfassenden Metastudie (Kapitel 2)** systematischen analysiert. Hierzu wurden zunächst 1701 Publikationen in einer elek-tronischen Datenbank erfasst und in einer systematischen Literaturanalyse statistisch ausge-wertet. Auf Grundlage der statistischen Auswertungen wurden 275 Publikationen für eine inhaltliche Überprüfung ihrer Abstracts ausgewählt. Von diesen 275 Publikationen wurden abschließend 40 Publikationen einer Volltextanalyse unterzogen.

Diese Metastudie verdeutlicht, dass das Forschungsinteresse an SDG-Analysen im vergangenen Jahrzehnt deutlich gestiegen ist: Während die frühesten erfassten Forschungsartikel im Jahr 1993 veröffentlicht wurden (ein Datenbankeintrag), wurden bis zum Ende der 2000er-Jahre selten mehr als 10 Jahrespublikationen in der Datenbank erfasst. Ausgehend von 21 Beiträgen im Erscheinungsjahr 2010 steigt diese Anzahl bis zum Erscheinungsjahr 2021 monoton auf insgesamt 293 thematisch einschlägige Publikationen an.

Die eigenen Volltextanalysen identifizieren insbesondere **Integrierte Assessment Modelle (IAM)**, **makroökonomische Modelle** und **systemdynamische Modelle** als grundsätzlich **für gesamtwirtschaftliche ex ante Bewertungen des Klima- und Ressourcenschutz-Nexus verfügbare Methoden**. Dieser Befund kann als eine erweiterte Fort- und Zusammenführung vergleichbarer früherer Literaturstudien zu Anwendungsmöglichkeiten dynamischer Simulationsmodelle interpretiert werden. Siehe hierzu bspw. Aguilar-Hernandez et al. (2021), van Soest et al. (2019) sowie UNEP (2017).

IAM wurden in der Regel zur Bewertung klimapolitischer Maßnahmen entwickelt und angewandt. Auf einer detaillierten Abbildung biophysikalischer Systeme basierend, werden SDG-Indikatoren des Wasser-Energie-Landnutzung-Klima Nexus und damit verbundene Wechselwirkungen im Allgemeinen sehr gut abgebildet. Bei diesem Analysefokus werden allerdings relevante sozioökonomische SDG-Dimensionen (wie bspw. demografische Entwicklungen oder Entwicklungen globaler und nationaler Armutsmuster) und daraus ableitbare Handlungsherausforderungen in der Regel nicht hinreichend beachtet. Für umfassende SDG-Bewertungen sollten daher auch weitergehende sozialwissenschaftliche Modellierungen angewandt werden (van Soest et al. 2019).

Im Forschungsgebiet der Sozialwissenschaften ist die Entwicklung und Anwendung dynamischer Modelle zur Analyse ökonomischer Systeme seit über 50 Jahren etabliert.[8] In Analysen und darauf aufbauenden Politikbewertungen des Ressourcen-Energie-Klima Nexus unter expliziter Berücksichtigung ökonomischer Wechselwirkungen zeichnen sich makroökonomische Input-Output-Modelle (IO-Modelle) durch einen hohen Detailgrad in der Abbildung volkswirtschaftlicher Nachfragestrukturen, damit verbundener gesamtwirtschaftlicher Lieferketten und den mit der Erzeugung der gehandelten Güter- und Dienstleistungen einhergehenden direkten und indirekten Umweltinanspruchnahmen aus. Siehe Aguilar-Hernandez et al. (2021) für eine ausführliche Übersicht bisheriger Anwendungen von (insbesondere) makroökonomischen Modellen zur Beurteilung gesellschaftlicher Circular Economy Entwicklungspfade.

Systemdynamische Modellierungsansätze sind weder in naturwissenschaftlichen noch in sozialwissenschaftlichen Theorien verwurzelt. Stattdessen basieren sie auf einer generalisierten Vorgehensweise zur strukturierten Erfassung der Entwicklungsdynamik komplexer Systeme im Zeitverlauf (Hardt and O'Neill 2017). Das entsprechende Grundkonzept für systemdynamische Modellierung wurde in den 1960er Jahren entwickelt (Forrester 1958). In enger Anlehnung an

[8] Der erste Nobelpreis für Wirtschaft wurde 1969 an Ragnar Frisch und Jan Tinbergen für die Entwicklung und Anwendung dynamischer Modelle zur Analyse ökonomischer Systeme vergeben. (https://www.ardalpha.de/wissen/nobelpreis/nobelpreis-geschichte-alfred-nobel-100.html, abgerufen am 6. März 2024).

Hafner et al. (2020) lassen sich dessen wesentliche Grundsätze folgendermaßen zusammenfassen: Wesentliche Merkmale von SD-Modellen ergeben sich aus der Anwendung allgemeiner Prinzipien aus dem Ingenieurwesen und der Theorie der Rückkopplungskontrolle. Ausgehend von ersten Anwendungen im Wirtschaftsingenieurwesen wurde dieser Modellierungsansatz seitdem in einer Vielzahl von Anwendungsfällen eingesetzt. Im Vergleich zu IAMs und makroökonomischen Modellen wird systemdynamischen Modellen daher oftmals eine bemerkenswerte Flexibilität in Bezug auf Art und Umfang der dargestellten Systemzusammenhänge zugeschrieben.

Im Bereich der Ressourcenschonungspolitk verweist bspw. der IRP-Bericht „Resource Efficiency: Potential and Economic Implications" (UNEP 2017) auf frühere Anwendungen des systemdynamischen Modells Threshold 21 für Nachhaltigkeitsanalysen im Auftrag der Vereinten Nationen. Das systemdynamische iSDG-Modell repräsentiert eine Weiterentwicklung des Threshold 21 Modells, welche in der Vergangenheit auch bereits für nationale Analysen von SDG-Wechselwirkungen angewandt wurde (Allen et al. 2019b, 2021). Auf einer tiefgreifenden und mittlerweile über mehrere Jahrzehnte hinweg verbesserten Struktur basierend, zielt es in seiner Berichterstattung auf eine weitreichende Erfassung von Wechselwirkungen zwischen einzelnen SDGs und zugehörigen Unterzielen ab. Das iSDG-Modell simuliert die grundlegenden Trends für die SDGs unter einem Business-as-usual-Szenario und ermöglicht die Analyse von flexibel parametrisierbaren Alternativszenarien. Entsprechende Szenarioanalysen können auch über die Zeitspanne der SDGs hinaus (Jahr 2030) erfolgen.

Während entsprechende Anwendungen traditionell insbesondere für Volkswirtschaften des Globalen Südens im Kontext der Entwicklungsarbeit vorgenommen wurden (Collste et al. 2017; Pedercini et al. 2019; Allen et al. 2020), wurde das iSDG-Modell in jüngerer Zeit auch bereits in Simulationsstudien zu SDG-Wechselwirkungen der australischen Volkswirtschaft eingesetzt (Allen et al. 2019b). Außerdem wurde ein SDG-Modell für Österreich entwickelt (Spittler und Kirchner 2022; Hoffmann et al. 2024). Da das Forschungskonsortium zur Durchführung dieses Vorhabens ebenfalls auf das **iSDG-Modell** zurückgreifen konnte,[9] wurde auf Basis des eigenen Literaturüberblicks entschieden, im weiteren Projektverlauf den langjährig etablierten iSDG-Bewertungsansatz für entsprechende Analysen deutscher Entwicklungspfade zu kalibrieren und anzupassen. Hier-durch konnte auch eine Anknüpfung der eigenen Projektaktivitäten an bisherige und laufende, thematisch relevante und international sichtbare, Forschungs- und Entwicklungsarbeiten umfassend sichergestellt werden.

iSDG-Modellanpassungen für Deutschland

Um die Strukturen des iSDG-Modells für eine Analyse der deutschen Verflechtungen anzupassen, mussten zunächst Datensätze zur Abbildung der historischen Entwicklung in Deutschland von ca. 200 sozialen, ökonomischen und ökologischen Indikatoren in die Modelldatenbank integriert werden. Um sicherzustellen, dass das iSDG-Modell die deutsche Systemstruktur korrekt abbildet, wurden dabei einige spezifische Anpassungen des generellen Bewertungsansatzes vorgenommen.

Darüber hinaus wurden weitergehende Änderungen der Modellstruktur durchgeführt, um relevante Entwicklungszusammenhänge des „GreenSupreme"-Szenarios der RESCUE-Studie berücksichtigen zu können: Bezüglich der in den eigenen SDG-Analysen zu berücksichtigenden umweltpolitischen Transformationspfade wurde durch die Leistungsbeschreibung eine Berücksichtigung von Annahmen des „GreenSupreme"-Szenarios der RESCUE Studie (Dittrich et al.

[9] Die für gesamtwirtschaftliche Bewertungen von Transformationspfaden geeigneten Modelle wurden in langjährigen Entwicklungsprozessen von eigenständigen Institutionen entwickelt und sind daher in der Regel nicht frei zugängig. Dies gilt sowohl für Integrierte Assessment Modelle als auch für makroökonomische sowie systemdynamische Modelle.

2020b) vorgegeben. In der RESCUE Studie hat das Umweltbundesamt gesamtwirtschaftliche Transformationsmöglichkeiten zur Etablierung ressourcenschonender wie auch treibhausgas-neutraler Lebensstile, Konsum- und Produktionsweisen in Deutschland bis zum Jahr 2050 analysiert. Die diesbezüglich in der RESCUE-Studie betrachteten Anpassungen konzentrierten sich auf die Handlungsfelder Energieversorgung, Mobilität, industrielle Produktion, Landwirtschaft und Landnutzung, Bauen und Wohnen sowie Abfall und Abwasser.

Zur Umsetzung dieses Arbeitsauftrags musste der übliche iSDG-Bewertungsansatz nicht nur auf deutsche Wirkungszusammenhänge kalibriert, sondern insbesondere zur Abbildung unterschiedlicher ressourcenpolitischer Handlungsfelder des GreenSupreme"-Szenarios deutlich angepasst werden. Entsprechende Änderungen wurden im Kern der ökonomischen Modellierung wie auch in weiteren, zentrale Wirkungszusammenhänge ausgewählter Handlungsfelder der RESCUE-Studie beschreibenden, Modulen des iSDG-Modells vorgenommen.

Zur Abbildung ökonomischer Entwicklungen werden im iSDG-Modell angebotsseitige Modellierungsansätze unter Anwendung von Cobb-Douglas (CD, Cobb and Douglas 1928)-Produktionsfunktionen genutzt. CD-Produktionsfunktionen leiten Veränderungen des gesamtwirtschaftlichen Produktionsniveaus aus Veränderungen der Verfügbarkeiten der Produktionsfaktoren Arbeit und Kapital sowie den Veränderungen ihrer jeweiligen Produktivitäten (welche ebenfalls modellendogen hergeleitet werden) ab. Nachfragefaktoren bleiben dabei unberücksichtigt.

Bei der Projektion gesamtwirtschaftlicher Produktionstätigkeiten unterscheidet der übliche iSDG-Bewertungsansatz drei unterschiedliche Wirtschaftsbereiche (Landwirtschaft, Industrie und Dienstleistungen). Diese hochaggregierte Darstellung erwies sich im weiteren Projektverlauf als nicht hinreichend, um zentrale Annahmen der RESCUE Studie zur Entwicklung produktionsseitiger Einflüsse auf gesamtwirtschaftliche Materialinanspruchnahmen zu modellieren. Für das in diesem Vorhaben angewandte Modell wurde daher in Anlehnung an internationale Wirtschaftsklassifikationen eine Erweiterung der üblichen iSDG-Industrie-Modellierung entwickelt. In den Modellanwendungen für Deutschland konnten infolge dieser Entwicklungsleistungen unterschiedliche Materialnachfragen aus der Entwicklung der Produktionstätigkeiten folgender Industriezweige hergeleitet werden:

1) Bergbau und Gewinnung von Steinen und Erden;

2) Wasserversorgung, Abwasserentsorgung, Abfallentsorgung und Beseitigung von Umweltverschmutzungen;

3) Baugewerbe;

4) Herstellung von Nahrungs- und Genussmitteln, Getränken und Tabakwaren;

5) Herstellung von Holz- und Papiererzeugnissen, Druckerei;

6) Herstellung von Chemikalien und chemischen Erzeugnissen;

7) Sonstige Industrie.

Neben dieser für den gesamten iSDG-Modellierungsansatz sehr weitreichenden Erweiterung der bisherigen Projektion industrieller Produktionsniveaus wurden zudem individuelle Anpassungen in bereits existierenden Teilmodulen vorgenommen sowie eine explizite Erweiterung des üblichen Berichtsumfangs durch zusätzliche Integration einer Wohngebäude-Modellierung durchgeführt. Weitergehende Details zu sämtlichen in dieser Projektphase umgesetzten **Modellanpassungen** werden, ebenso wie die Vorgehensweise bei der Kalibrierung des angepassten Modellrahmens zur Vorbereitung der nachfolgenden Szenariosimulationen in **Kapitel 3** dieses Berichts zusammengefasst.

SDG-Modellierungen für Deutschland

Die **Anwendungen des für Deutschland angepassten iSDG-Modells** zur Bewertung von SDG-Zielerreichungen[10] und -Wechselwirkungen unter zusätzlicher Berücksichtigung von im „Green-Supreme"-Szenario der RESCUE Studie unterstellten Umstellungen zur Erreichung umfassender klima- und ressourcenpolitischer Transformationen werden in **Kapitel 4** zusammengefasst.

Verschiedene Szenarioparametrisierungen wurden vorgenommen, um potenzielle Synergien und Zielkonflikte in klima- und ressourcenpolitischen Transformationspfaden identifizieren zu können. Diese Parametrisierungen dienen der Berücksichtigung von Effekten bereits etablierter Politikmaßnahmen sowie von weitergehenden Transformationsannahmen. Drei zentrale Umweltdimensionen werden durch die parametrisierten Umstellungen angesprochen: Inländische Treibhausgasemissionen, inländischer Materialverbrauch und Bodenqualität. Unter Nutzung der für dieses Vorhaben erweiterten iSDG-Modellstruktur konnten dabei die Auswirkungen von Umstellungen in folgenden Handlungsfeldern analysiert werden: Energiesystem, Industrie (inkl. Kreislaufwirtschaft), Bauen und Wohnen, Mobilität, Ernährung und Landwirtschaft.

Bei der Auswertung der Simulationsergebnisse zeigt sich, dass keine offensichtlichen Zielkonflikte auf die SDG-Zielerreichung identifiziert werden: Von bereits hohen SDG-Zielerreichungsgraden[11] ausgehend, führen die in den Simulationen unterstellten zusätzlichen Umstellungen in der Regel zu einer Steigerung der SDG-Zielerreichungsgrade. Im Jahr 2050 ist das klima- und ressourcenpolitische Politikszenario im Vergleich zur Baseline dadurch geprägt, dass keine signifikant negativen Auswirkungen auf einzelne SDG-Zielerreichungsgrade simuliert werden. Insbesondere im Hinblick auf SDG 2 (kein Hunger), SDG 7 (bezahlbare und saubere Energie), SDG 9 (Industrie, Innovation und Infrastruktur), SDG 12 (nachhaltiger Konsum und Produktion) und SDG 13 (Maßnahmen zum Klimaschutz) werden unter Berücksichtigung der zusätzlichen klima- und ressourcenpolitischen Umstellungen allerdings deutliche Verbesserungen der SDG-Zielerreichung in Deutschland simuliert. Weitere, wenn auch weniger prägnante Verbesserungen der Zielerreichung zeigen sich zudem für SDG 6 (sauberes Wasser und Sanitäreinrichtungen) sowie SDG 8 (menschenwürdige Arbeit und Wirtschaftswachstum). (Nahezu) keine Veränderungen zeigen sich bei den SDGs 1 (keine Armut), 3 (Gesundheit und Wohlergehen), 4 (hochwertige Bildung), 5 (Geschlechtergleichheit), 10 (weniger Ungleichheiten), 11 (nachhaltige Städte und Gemeinden), 14 (Leben unter Wasser), 15 (Leben an Land), 16 (Frieden, Gerechtigkeit und starke Institutionen) und 17 (Partnerschaften für die Ziele).

Für die Politiksimulation kennzeichnend ist ihr Green Growth-Charakter: Während die simulierten klimapolitischen Umstellungen tendenziell dämpfend auf das Wirtschaftswachstum wirken, werden diese dämpfenden ökonomischen Effekte in der integrierten klima- und ressourcenpolitischen Transformation durch deutliche expansive ökonomische Effekte der unterstellten Circular Economy-Umstellungen überkompensiert.[12] Diese expansiven Effekte werden

[10] Für die einzelnen Indikatoren werden die jeweiligen Zielerreichungsgrade stets als Verhältnis zwischen

- der Abweichung der aktuellen Indikatorausprägung von einem internationalen „worst performance" Referenzwert (zero level), sowie
- der Differenz zwischen dem vorgegebenen Zielwert und dem internationalen „worst performance" Referenzwert (zero level) berechnet.

[11] Ein 100 % Zielerreichungsgrad würde bedeuten, dass alle im iSDG mit Indikatoren hinterlegten Targets erreicht sind. Zu beachten ist, dass das iSDG-Modell ursprünglich für die Bewertung der Entwicklungs¬perspektiven von Ländern mit niedrigem Einkommen konzipiert wurde. Viele der modellierten SDG-Indikatoren sind daher insbesondere für Ländergruppen mit niedrigem Einkommen relevant.

[12] Durch die Effizienzsteigerungen, die den RESCUE Szenarien zugrunde liegen, steigt die Produktivität, was sich kurz- und langfristig, positiv auf das Wirtschaftswachstum auswirkt. Der Effekt, dass rohstoffimportierende Industrienationen wie Deutschland von ambitionierten Steigerungen der Ressourceneffizienz gesamtwirtschaftlich profitieren, wurde in der Vergangenheit auch bereits in multiregionalen Simulationsstudien aufgezeigt (Hatfield-Dodds et al. 2017; Distelkamp and Meyer 2019).

in den Simulationen durch massive Produktivitätssteigerungen ausgelöst. Trotz dieser positiven expansiven Effekte wird durch die in diesen Simulationen unterstellten Umstellungen (bspw. der angenommenen gesamtwirtschaftlichen Steigerung der Materialeffizienz) bis zum Jahr 2050 ein Rückgang des inländischen Rohstoffkonsums (Domestic Material Consumption, DMC) um 40 % im Vergleich zur Baseline erreicht. Die klimapolitischen Annahmen des Politikszenarios implizieren bis zum Jahr 2050 eine Reduktion der deutschen Treibhausgasemissionen um 84 % im Vergleich zu den Ausgangsniveaus des Jahres 1990. Diese, mit ursprünglichen Zielwerten der deutschen Politik zur Ermöglichung einer globalen Ein-haltung des 2°C-Ziels kompatiblen Reduktionen, werden ohne Modellierung von Technologien zur CO_2-Abscheidung und -Speicherung simuliert. Die inzwischen politisch bis zum Jahr 2050 für Deutschland angestrebte Treibhausgasneutralität wird damit in den iSDG-Simulationen allerdings nicht erreicht.

In der RESCUE Studie wurde im „GreenSupreme“-Szenario durch sämtliche unterstellten Umstellungen eine Reduktion der deutschen Treibhausgasemissionen im Vergleich zu 1990 um 97 % erreicht. Die im Vergleich hierzu geringere Treibhausgas-Reduktion der eigenen Modellrechnungen verdeutlicht einerseits, dass auch mit dem in diesem Vorhaben erweiterten iSDG-Bewertungsansatz nicht sämtliche Detailannahmen der RESCUE-Studie abgebildet werden konnten. Wie im einleitenden Kapitel 1 näher ausgeführt wird, wurden in der RESCUE-Studie sehr detaillierte Annahmen zur Entwicklung von Produktionstechnologien, sektorspezifischen Zwischen- und Endnachfragestrukturen sowie daraus resultierenden Produktionsniveaus in einem Modellverbund simuliert, welcher insbesondere auch tief disaggregierte Analysen material- und emissionsintensiver Sektoren (Energieerzeugung, Verkehr, Landwirtschaft) ermöglichte. Zur Abbildung von im iSDG-Modell nicht eigenständig abgebildeten Detailentwicklungen könnten in weiterführenden Forschungsvorhaben grundsätzlich ebenfalls entsprechende soft link Modellierungen angestrebt werden. Für die in diesem Vorhaben erstmals für Deutschland vorgenommene Bewertung von Transformationspfaden bezüglich Synergien und Zielkonflikten zwischen Klima- und Ressourcenschutz und den SDGs wurde die Nutzung eines entsprechenden Modellverbunds allerdings zunächst als nicht notwendig angesehen.

Beim Ergebnisvergleich mit der RESCUE-Studie muss zudem angemerkt werden, dass für die RESCUE-Studie keine dynamischen Modellierungen vorgenommen wurden. Dies bedeutet insbesondere, dass die in unseren Simulationen markant beobachtbaren expansiven ökonomischen Effekte der unterstellten Circular Economy-Umstellungen durch den Bewertungsansatz der RESCUE-Studie nicht erfasst wurden: Das „GreenSupreme“-Szenario der RESCUE Studie unterstellt ab dem Jahr 2030 ein Nullwachstum der Wirtschaftsleistung in Deutschland. Die Befunde unserer dynamischen Modellsimulationen weichen somit von der RESCUE Studie ab. Als eine wichtige Erkenntnis des gegenständigen Vorhabens kann daher unter anderem festgehalten werden, dass die Projektionspfade dynamischer Simulationen durch die Berücksichtigung relevanter Rückkopplungsschleifen in zentralen Szenariodetails deutlich von den Befunden thematisch vergleichbarer (entsprechende Rückkopplungsschleifen aber nicht berücksichtigender) statischer Modellierungen abweichen können.

Schlussfolgerungen und Limitationen der Studie

Während die in diesem Bericht dokumentierten Simulationsanwendungen keine grundsätzlichen Zielkonflikte zwischen Klima- und Ressourcenschutz und der Entwicklung der SDG-Zielerreichung in Deutschland aufdecken, wird damit selbstverständlich nicht demonstriert, dass diese niemals in Transformationsprozessen auftreten. In den abschließenden **Schlussfolgerungen des Kapitels 5** wird hierzu zunächst festgehalten, dass der eigene Literatur-

Anzumerken ist allerdings, dass eine exakte Bewertung der Größenordnung dieses Effekts ausgesprochen herausfordernd ist, da die direkten Kosten zur Realisierung der simulierten Effizienzsteigerungen in der Regel nur geschätzt werden können.

überblick zu Beginn des Vorhabens aufzeigte, dass in der Nachhaltigkeitsforschung als allgemeiner Konsens etabliert wurde, dass sich die SDG-Ziele in ihren jeweiligen Entwicklungen untereinander auf vielfältige Weise beeinflussen. Ob eine vollständige Berücksichtigung all dieser Wechselwirkungen Ziel einer Modellierung sein kann, ist eine wissenschafts-philosophische Frage, die in ihrer Reichweite weit über den Berichtsumfang dieses Vorhabens hinausweist. - Wie jedes andere Modell auch, zeigt das iSDG-Modell eine vereinfachte Abbildung der Realität, wodurch das simultane Zusammenspiel der durch das Modell abgebildeten Wirkunsgkanäle im Zeitverlauf analysiert werden kann.

Der Bericht schließt mit einer Benennung zentraler Wirkungskanäle, welche in der gegenwärtigen iSDG-Parametrisierung noch unberücksichtigt bleiben: Das Modell wurde entwickelt, um die Wechselwirkungen zwischen verschiedenen Politiken zu erfassen. Dabei betrachtet es ausschließlich Entwicklungen im Inland. Zudem erfolgt keine Abbildung sektoraler Details. Für zukünftige Bewertungen von Synergien und Zielkonflikten zwischen Klima- und Ressourcenschutz und den SDGs wird eine bessere und möglichst umfassende Berücksichtigung dieser Wirkungskanäle in den dann durchzuführenden Modellierungen empfohlen.

Außerdem wird auf identifizierte Limitationen der aktuellen Modellparametrisierungen eingegangen: Nicht alle potenziellen Spillover-Effekte[13], die in der iSDG-Modellstruktur dargestellt und in vorangegangenen Berichten skizziert wurden, waren in den quantitativen Ergebnissen im Fall von Deutschland zu erkennen. Hierfür gibt es mehrere Gründe. Aufgrund des Charakters der SDGs waren die meisten SDG-Werte bereits zu Beginn des Simulationszeitraums hoch, was Spillover-Effekte dämpft, da zusätzliche Verbesserungen schwerer zu erreichen sind. Einige der erwarteten Spillover-Effekte könnten auch durch zusätzliche Anpassungen der Modellstruktur besser abgebildet werden.

[13] Spillover-Effekte bezeichnen die indirekten Auswirkungen von Wirkungen auf primär beeinflusste Faktor, welche aus Interdependenzen zwischen den primär beeinflussten Faktoren und weiteren, ursprünglich nicht direkt beeinflussten Faktoren resultieren.

1 Background to the report

1.1 Sustainable Development Goals (SDGs): Origins, needs and opportunities for mapping trade-offs and synergies, and available datasets

1.1.1 Thematic introduction to the United Nations Sustainable Development Goals (SDGs)

Figure 1: The 17 Sustainable Development Goals

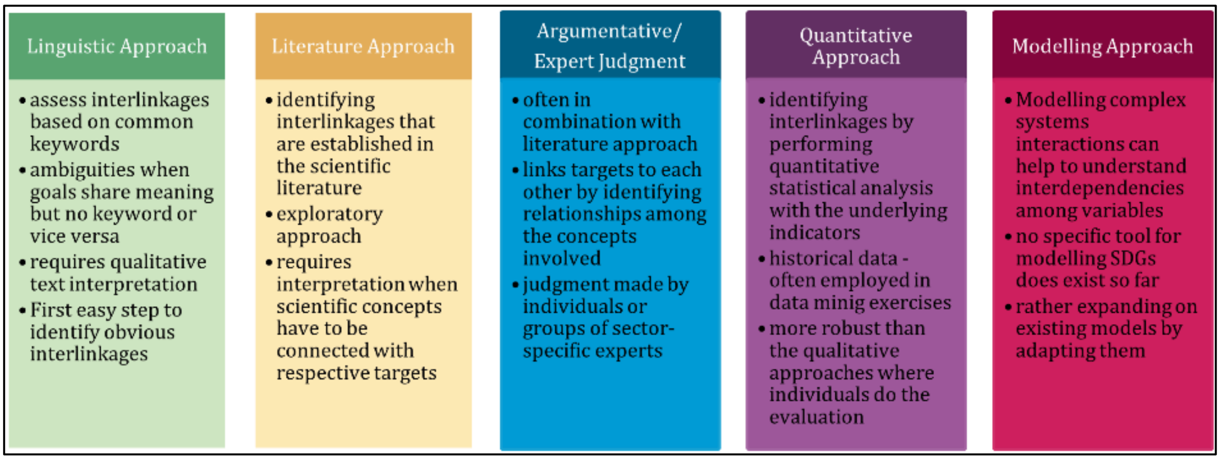
Source: Own representation of the contents of (Folke et al. 2016)

The Sustainable Development Goals (SDGs) have been stated in the so-called "2030 Agenda for Sustainable Development" (United Nations 2015b). After the United Nations had already defined eight global development goals for the year 2015 (Millenium Development Goals, MDG. See United Nations 2015a for the final MDG report), the SDGs currently define 17 global development goals for the year 2030. See Figure 1 for a visual overview of the SDGs.

It is important to realise that these goals represent the outcomes from intergovernmental negotiations. In normative terms they frame "global goals and targets that the international community sets for itself. As a compromise reflecting a multiplicity of concerns and interests, the set of SDGs taken as a whole is not based on any particular interpretation of the world; nor does it reflect a specific, coherent systemic view of how the socio-economic engine works and delivers outcomes along all the dimensions covered by the goals" (Le Blanc 2015, p. 11).

However, given that the individual goals refer to mutually interlinked economic, social and environmental development objectives, it seems evident that coherent policy approaches are needed to achieve these goals (Nilsson et al. 2016). From a policy consulting perspective, the SDG thus "highlight the need for more integrated research for sustainable development across natural, social, health sciences, economics and engineering. They also require a stronger drive towards transdisciplinary research" (ICSU 2017, p. 223).

Figure 2: Methodological approaches to SDG interlinkage analyses



Source: Own representation of the contents of (Miola et al. 2019)

Since their approval by all UN Member States in 2015, sustainability research therefore already applied a variety of methodologies to address the analytical challenges posed by the integrated, indivisible, and interlinked nature of the SDGs. A classification of respective approaches to SDG-interlinkage analyses made in Miola et al. (2019) is given in Figure 2. We reproduce this figure here to illustrate that all subsequent discussions in this report will focus closely on quantitative approaches and, especially, on modelling approaches. Whereas we are also aware of expert judgements, we merely consider these as general parameterisation options that could in principle be applied in case of insufficient data availabilities. To name a representative linguistic/literature study, we refer to Lim et al. (2018) as an example. Readers with further interests in linguistic and literature approaches are referred to Miola et al. (2019) and the corresponding literature references listed therein.

This focus on quantitative modelling of SDGs emerges from the research objectives of this project. The present report documents research and development work for the project "Integrated Assessment of the UN Sustainable Development Goals (SDGs) in Transformation Pathways towards a Resource-Efficient and Greenhouse-Gas-Neutral Germany" (FKZ 3721 31 101 0). Conceptually, this project was organized as follows: **Work package 1 (WP1)** targeted the identification of available methods and tools for ex ante SDG-assessments of integrated transformation pathways. Based on this initial work, follow-up project activities were targeted towards adapting and applying a specific model for SDG interlinkage assessments in integrated climate and resource protection pathways for Germany **(WP2)**, and to explore ex ante the impact of varied climate policy and resource policy measures on Germany's SDG achievements **(WP3)**. The focus on expert judgements, quantitative approaches and, especially, on modelling approaches therefore reflects the authors' fundamental understanding that quantitative approaches rather than qualitative tools are better suited to accomplish respective tasks.

1.1.2 Empirical outline of relevant SDG datasets

The "Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development" is comprehensively documented by the UN Statistics

Division. [14] The database currently reports about 231 unique indicators.[15] This number of indicators results from the fact that each of the 17 SDG has been subdivided into individual targets, for which more than one indicator is sometimes considered. The so-called SDG Tracker (https://sdg-tracker.org/) features very accessible interactive visualisations and access to the official SDG indicators. The open-access website tracks the latest data across all 17 SDG. It is an integrated project of the Our World in Data initiative (https://ourworldindata.org/).

On the UN homepage, respective data sets can be regarded and compared with each other as time series in an easily accessible format.[16] Basically, a differentiation of 197 geographic areas is possible. However, the number of available time series (as well as the covered reporting periods) varies considerably for individual indicators.

For comprehensive statistical reports and analyses, the World Bank offers an opportunity for bulk downloads of a large number of time series in a single Excel-based format.[17] Since the World Bank does not report on the original UN indicators exclusively, slightly more than 400 available World Bank time series are currently reporting about developments in Germany. However, observations are not available for all time series. The reporting period ranges from 1990 to 2019. Additional development data may also be retrieved from the World Bank's "World Development Indicators" database which, in case of Germany, provides access to around 1400 indicator time series which sometimes go back as far as 1960.[18]

In addition to these global databases, many regional and national monitoring systems have been installed by now. Due to this work, further sustainability indicators in addition to the globally accepted SDG indicators are now available for individual countries and regions. Therefore, to take differing development levels and growth options across countries and regions into account,[19] individually adapted indicators can be analysed. For respective summary information on the European SDG indicators see TextBox 1. Meanwhile, the European Commission also launched a comprehensive web platform to provide tools, organises knowledge and support the evidence-based implementation of the SDGs.[20]

The set of indicators published by the German Federal Statistical Office for the global SDG can be interactively accessed at https://sdg-indikatoren.de/en/. The national indicators of the German Sustainable Development Strategy (DNS) are published every two years by the Federal Statistical Office and can be interactively accessed at https://sustainabledevelopment-deutschland.github.io/. See Die Bundesregierung (2021) for the last published version of the DNS. Overall, it can be stated that, at the federal level, comprehensive statistical time series information is available for mapping SDG-relevant developments in Germany. Referring to the total set of globally adopted UN SDG indicators the Federal Statistical Office states that over 200 indicators are already being reported for Germany. A further set of 3 indicators is currently

[14] The complete indicator list can be accessed at https://unstats.un.org/sdgs/indicators/indicators-list/ (retrieved on April 24, 2024)

[15] A tabular overview of the official list of included indicators can be retrieved at the following address: https://unstats.un.org/sdgs/indicators/Global%20Indicator%20Framework%20after%202021%20refinement_English.xlsx (retrieved on July 24, 2024)

[16] https://unstats.un.org/sdgs/UNSDG/IndDatabasePage (retrieved on July 24, 2024)

[17] https://databank.worldbank.org/source/sustainable-development-goals-(sdgs)# (retrieved on April 24, 2024)

[18] See https://datatopics.worldbank.org/world-development-indicators/wdi-and-the-sustainable-development-goals.html for further details (retrieved on April 24, 2024)

[19] "In general, an indicator set needs to account for the specific context of the reality it is meant to measure" Miola et al. 2019, p. 6.

[20] The "KnowSDGs" platform (Knowledge base for the Sustainable Development Goals) can be accessed via https://knowsdgs.jrc.ec.europa.eu/ (retrieved on April 24, 2024)

classified as "in progress". This means that regular reporting is aimed for, but the necessary preparatory work in this regard has not yet been completed.[21]

TextBox 1: Indicators of the EU Commission

- To measure progress towards SDG achievement in the European Union, an SDG indicator set including roughly 100 existing EU indicators was developed under the leadership of Eurostat. The purpose of this set which is structured along the 17 global Sustainable Development Goals is to monitor progress towards the SDGs at the European level.
- The indicator set is regularly reviewed and limited to six indicators per SDG in order to attach the same importance to all goals and enable a well-balanced measurement of progress regarding all dimensions of sustainability. Besides, individual indicators, which are referred to as multi-purpose indicators, are used to monitor more than one goal.
- The EU SDG indicator set provides the basis for Eurostat's annual monitoring report on progress towards the SDGs. In June 2021 the fifth version of the Monitoring report on progress towards the SDGs in an EU context was published.
- The Eurostat publication "Sustainable development in the European Union - Overview of progress towards the SDGs in an EU context" is a shorter version which provides a statistical overview of the progress towards SDG achievement in the EU and its Member States. The Eurostat database provides time series of the selected indicators for all EU Member States. Including results for the individual EU Member States, the digital publication facilitates multi-nationalbase comparisons.

Source: Own representation of the contents of Statistisches Bundesamt (retrieved on December 15, 2021)

Thus, with reference to the sometimes much more restrictive data availabilities of model-based SDG assessments in other world regions (see, for example, Pedercini et al. 2018b or Pedercini et al. 2019 as respective references), all project activities documented in this report were primarily aimed at identifying available modelling frameworks (in the sense of Miola et al. 2019) and to present available methods for the numerical calibration of corresponding modelling approaches. Considering almost 1700 scientific contributions, we compiled an extensive literature review for this purpose. The implementation and results from this review are documented in detail in **chapter 2** of this report. All subsequent modelling activities are documented in chapters 3 and 4. **Chapter 3** introduces the model that was applied in our own SDG-assessments of German transformation pathways. Any necessary model adjustments and resulting simulation characteristics are summarised in this chapter. Given this conceptual methodological introduction to the model, policy parametrisations and resulting findings from respective policy simulations are presented in **chapter 4**. **Chapter 5** concludes and also discusses limitation of the study as well as future research needs.

For all policy scenarios analysed in our project, the RESCUE study (Günther et al. 2019) of the German Environment Agency (UBA) was considered as a central reference. Thus, to fully present all essential principles of our own research and development work, we firstly complete this introductory section by key references to the RESCUE study.

[21] The figures reported here were taken from the national SDG homepage (https://sdg-indikatoren.de/en/reporting-status/) (retrieved on April 24, 2024)

1.2 Introduction to the RESCUE study

1.2.1 Methodological summary

TextBox 2: Resource-Efficient Pathways towards Greenhouse Gas- Neutrality (RESCUE)[22]

- In the RESCUE study (Günther et al. 2019), the German Environment Agency (UBA) identified possible pathways for achieving greenhouse gas (GHG) neutrality in Germany in a resource-efficient manner by 2050.
- For this, a total of six scenarios were developed to examine possible technical / technological changes in individual action fields as well as lifestyle changes required for achieving GHG-neutrality by 2050. As an additional aspect, the associated raw material requirements (metals, biomass, construction minerals, and fossil energy carriers) were quantified.
- The results of RESCUE show that it is possible to achieve the current climate targets for Germany while reducing overall raw materials demand at the same time, but that this requires ambitious and economy-wide changes/transformations (across all action fields) within the next few years. The envisaged changes/transformation described in RESCUE are also of relevance in the context, e.g., of EU Green Deal.
- In RESCUE, the focus is on the necessary sectoral adjustments. However, the pathways described in RESCUE were not yet examined against the background of other sustainability and environmental goals.

Source: Adapted from the original terms of reference of this project.

A summary of the contextual framework of the RESCUE study is given in TextBox 2. The methodological framework that has been implemented for the RESCUE study applies the results of very detailed sectoral calculations as input variables for macroeconomic energy and material analyses. Details of this soft linked calculation approach are presented in Dittrich et al. (2020a).

The RESCUE study aimed to identify possible transformations in key action areas to achieve Germany's climate and resource policy goals. The action areas analysed were:

- energy supply,
- mobility,
- industrial production,
- agriculture and land use,
- construction and housing,
- waste and wastewater,
- consumption-side changes.

[22] https://www.umweltbundesamt.de/en/topics/climate-energy/climate-protection-energy-policy-in-germany/rescue-resource-efficient-pathways-to-greenhouse (retrieved on April 24, 2024)

For each of these action areas, detailed transformation scenarios were designed for the target year 2050. The effects of these transformative assumptions were then estimated by soft linked applications of the following calculation models (overview compiled from information provided in Dittrich et al. 2020a):

- TREMOD: An expert assessment tool for detailed calculations of energy consumption and GHG emission levels of all motorised means of transport in Germany. Direct GHG emissions of fuel combustion as well as the GHG emissions for the provision of all fossil and renewable energy sources used in transport are considered by the tool. Transport modes are recorded in a highly differentiated manner according to size, age, energy source used, exhaust emission standard and other vehicle characteristics. A detailed model documentation is provided by Knörr et al. (2016).
- GEMOD: The GEMOD module calculates heating and air-conditioning demand of the existing building stock in dependence on the insulation level, as well as the provision of the demand by heat generators, ventilation, and air-conditioning systems. The demands are calculated as annual heating demand, annual hot water demand, cooling demand and ventilation demand in close accordance with the DIN standards of the Energy Saving Ordinance. The building stock is represented by a building typology with 52 residential building types and 182 non-residential building types. Detailed documentation and applications of the model can be found in Mellwig et al. (2015).
- ALMOD: The Agriculture and LULUCF Model (ALMOD) was developed by ifeu to address the specific requirements of the project, in order to model in a detailed and consistent manner agricultural production (arable farming and livestock breeding), associated removals of biotic raw materials (especially food and feed), raw material inputs (such as fertilisers) and the greenhouse gases (carbon dioxide, methane and nitrous oxide) and land use (arable farming and grassland) associated with these activities. The base year of the model is 2010. It includes in detail all greenhouse gas emissions based on the methodology of the German greenhouse gas inventories.
- SCOPE: The SCOPE methodology (Cross-Sectoral Deployment and Expansion Optimisation for Analyses of the Future Energy Supply System) is based on a modular framework for the modelling and analysis of Cross-Country and Cross-Sectoral energy scenarios developed by Fraunhofer IEE. From a macroeconomic perspective, the model determines the minimum marginal cost utilisation of the mapped energy plants and simultaneously satisfies demand profiles from the electricity, heat and transport sectors. Optionally, investment decisions can be taken into account in the objective function via annuity technology costs in order to determine a minimum-cost technology mix for future scenarios. SCOPE is implemented in Matlab, a detailed description can be found in Fraunhofer IEE (2015).
- URMOD: The environmental economic commodity and GHG model (URMOD) is used in the context of the Green Scenarios to link both commodity expenditures and GHG emissions with the causative economic production and consumption activities at a detailed commodity group level. This makes it possible to convert the flows of goods in the national economy into raw material or greenhouse gas equivalents in order to express consumption footprints. The raw material and GHG equivalents describe the cumulative raw material input and the cumulative GHG emissions, respectively, that are generated in the production of the goods over the entire production chain. All economic activities, raw material expenditures and GHG emissions in the national economy are represented in a fully integrated approach. Among

other things, this model allows the GHG emissions associated with imports and exports to be estimated.

In this soft linked modelling framework, very detailed assumptions concerning the development of production technologies, sector-specific intermediate and final demand structures as well as resulting production levels were directly parameterised in the respective sector models for the material- and emission-intensive sectors (energy production: SCOPE, transport: TREMOD, buildings: GEMOD, agriculture: ALMOD). For the economy-wide estimation of all greenhouse gas emissions together with Germany's raw material consumption levels, the economic developments calculated in this way for key sectors were then transferred to the deeply disaggregated structures of the Input-Output table (mapping a total of 274 goods groups / production sectors for the base year 2010) of the URMOD tool. For the remaining sectors, a more general set of assumptions was parameterised in the URMOD-IO table. These hypotheses covered overall framework assumptions (like, for example, general efficiency improvements due to technical progress) as well as generic scenario assumptions (like the assumption of an economy-wide avoidance of food waste which was mapped by a general reduction of selected food inputs).

Once all respective structural assumptions were parameterised in the IO table, the macroeconomic production levels could then be determined for individual target years by corresponding variations of final demand components. In the case of the GreenSupreme scenario summarised in TextBox 3, final inland demand expenditures were adjusted for all production sectors which had not been initially pre-determined by individual sector modelling results. These adjustments were arranged in such a way that the implied average annual GDP growth rates equalled 0.7 % for the 2010 to 2020 period. This growth rate was then assumed to decline to zero by 2030 and stagnate (i.e., stay constant) until 2050.

As the RESCUE project focused on German transformation pathways, global socioeconomic development dynamics and their feedbacks to and from the German scenario assumptions were generally not mapped. However, for an integrated account of total greenhouse gas emissions and primary raw material use along international value chains for the provision of goods and services used in Germany, supplementary assumptions had to be included regarding the development of production technologies abroad. In addition to the national URMOD table mentioned above, two further IO tables (with corresponding environmental extensions) were therefore adopted to represent production structures in the European Union and, respectively, a Rest of World region. Through exogenous variation of the respective goods and raw material input coefficients as well as emission coefficients, the scenario assumption of a comprehensive global diffusion of strong efficiency improvement could then be parameterised in these tables.

As URMOD is not a dynamic model that could project variations in Input-Output structures autonomously over time, such detailed adjustments have to be implemented individually for each projected scenario year. To reduce respective workloads to reasonable levels, the RESCUE study applied this parameterisation method therefore only for reference years 2030, 2040 and 2050: Starting from calculations for the target year 2050, reference values for base years 2030 and 2040 have been subsequently added to mimic key characteristics of a prospective transformation path. For the presentation of results between these three reference years, all missing observations were then usually interpolated linearly.

TextBox 3: RESCUE scenario GreenSupreme

- In GreenSupreme, the most effective measures considered in the RESCUE study are combined to further reduce GHG emissions and raw material consumption up to 2050. In a nutshell, this includes a combination of material efficiency measures together with assumptions on sustainable and healthy lifestyles.
- Assuming a very rapid transformation, GreenSupreme thus represents, compared to other RESCUE scenarios, the scenario with the largest technically conceivable transformation and, at the same time, the broadest changes in German consumption patterns.
- In contrast to the other RESCUE-scenarios, which assume an average annual GDP growth of around 0.7 % for Germany, in GreenSupreme the annual GDP growth is assumed to be zero after 2030.
- The scenario succeeds in reducing GHG-emissions by 97 percent by 2050 compared to 1990. If natural sinks are considered through sustainable agriculture and forestry (LULUCF), reductions of up to 104 percent are possible. GHG-neutrality can thus be safely achieved without nuclear energy and technical sinks such as CCS. In total, a reduction in GHG-emissions of 69 percent in 2030 and 88 percent in 2040 compared to 1990 will be achieved (excluding LULUCF).
- The final energy demand (excluding the non-energy demand of the chemical industry) can be reduced from around 2,500 terawatt hours (TWh) in 2015 to less than 1,100 TWh by 2050. To achieve GHG-reductions quickly, coal-fired power generation is phased out by 2030 and coal use completely phased out by 2040.
- The share of renewable energies will rise to 86 percent by 2030 and to 97 percent by 2040. Innovations in fuel supply will be promoted and technologies developed at an early stage, so that by 2030 around 63 TWh of sustainable, electricity-based fuels will already be imported. The share of renewable energies in fuel supply is already 11 percent in 2030 and 40 percent in 2040. By 2050, fossil fuels will no longer be used in all areas.
- Primary raw material consumption is reduced by 70 percent by 2050 compared to 2010 in this scenario.

Source: Own representation adapted from https://www.umweltbundesamt.de/en/topics/climate-energy/climate-protection-energy-policy-in-germany/a-resource-efficient-greenhouse-gas-neutral-germany/rescue-scenario-greensupreme (retrieved on July 24, 2024)

1.2.2 Key distinctions between our study and the RESCUE study in terms of content and methodology

The RESCUE study followed a normative approach. Starting from predefined target values for the year 2050, it was shown that these can be achieved in Germany through rapid, comprehensive, and ambitious changes in selected key sectors (energy production, mobility, agriculture and land use, and housing) together with complementary more general changes in production and consumption patterns. To demonstrate this in detail, complex calculations were carried out under the application of an Input-Output based, static assessment procedure incorporating in-depth insights from partial sectoral modelling studies. Additional calculations for the base years 2030 and 2040 illustrate potential macroeconomic transformation steps towards achieving the desired target states.

From an ecological point of view, the parameterised scenarios are distinguished by the fact that the selected targets do not only prescribe the transformation to a greenhouse gas-neutral society. In contrast to many other climate scenarios, they also quantify very ambitious development milestones in terms of resource use (including land use) for the year 2050. See, inter alia, Wiese et al. (2022) for a respective review of the RESCUE scenarios as compared to other German energy scenarios. The results of the RESCUE study thus already provide scenario benchmark values for selected SDG indicators (namely greenhouse gas emissions and material footprint).

However, the RESCUE study did not intend to take a comprehensive look at all SDG indicators. Consequently, for some further SDG indicators, specific scenario values were exogenously predetermined and applied as a fixed prerequisite for subsequent analyses. Examples of this include assumptions on the development of GDP (SDG 8), on the assumed decrease in food waste (SDG 12) or on the assumed comprehensive international technology transfer (SDG 17). This implies, for instance, that all feedback effects of the assumed (comprehensive) transformation of the global industrial system on overall economic growth have been completely disregarded in all RESCUE scenarios. Furthermore, given that the methodology applied in the RESCUE study cannot provide any insights into labour market developments, apparently expectable interactions with SDG 8 remained completely unaddressed. In the manufacturing sector (explicitly listed as a target for SDG 9), aggregate economic developments were not endogenously determined through partial sector modelling, but rather residually adjusted to achieve assumed GDP target values. Furthermore, income distribution (SDG 10), fossil-fuel subsidies (SDG 12) and overall tax revenue and public budget dynamics (SDG 17) were not mapped by the applied calculation approaches.

It is therefore worth noting that, while RESCUE examined the question of *"what should happen"* to transform the German society in a greenhouse gas neutral and resource efficient way, our project addressed the rather complementary question of *"what can happen"* during respective adaptation processes within the SDG nexus.

2 Meta-analysis: International literature review on methods and tools for analysing SDG-interrelationships.

2.1 Context of the own literature review

2.1.1 Expert judgements and derived quantitative approaches

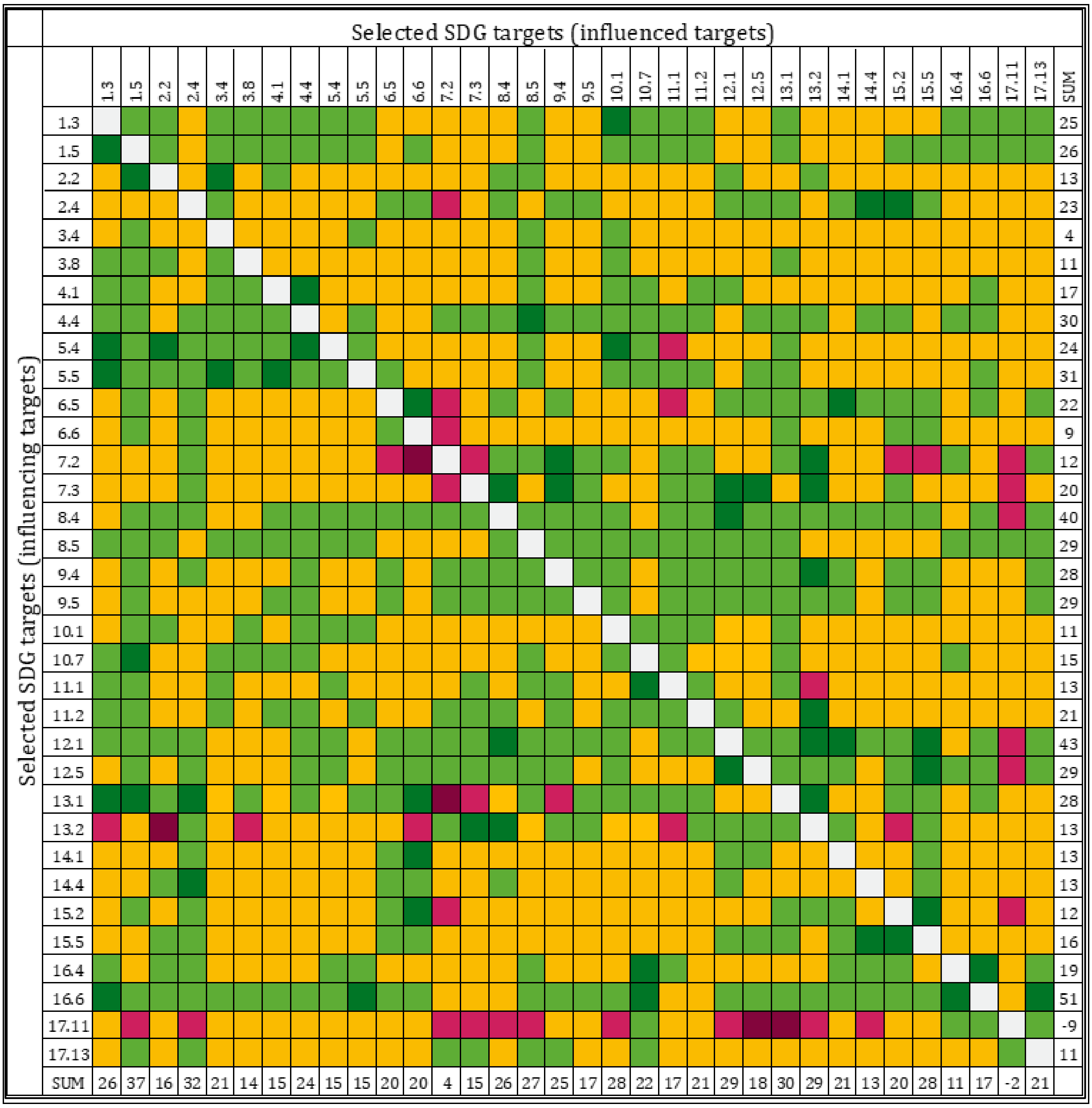
Since the adoption of the SDGs, the sustainability research community emphasises the need to develop coherent policy approaches that consider SDG-interactions explicitly. It is our understanding that this should be recognised to provide strong arguments for a thorough empirical foundation of respective policy approaches. Notably, dynamic top-down analyses can provide a broad account of evidence-based benefits, trade-offs and synergies at the national level. The following subchapter summarises the literature that we consider to be of central importance in this regard. However, to begin with, we will briefly also introduce other quantitative methods and tools that may eventually also be applied for the conceptual design of respective simulation models.

Thus, we first refer to the widespread use of Cross-Impact matrices (Le Blanc 2015; Nilsson et al. 2016; ICSU 2017). These approaches are used to quantify considered SDG-interactions on an ordinal scale. While different numerical evaluation criteria can be applied (see, for example, Weimer-Jehle 2006 or ICSU 2017 in this regard), the overall procedure can be briefly explained as follows: For a selected subset of targets or goals, all combinatorically feasible bivariate interactions are systematically arranged in a matrix representation. According to the selected scoring system, all direct interactions between individual targets or goals are then parameterised in the individual matrix cells. An example of a respective application is shown in Figure 3. In this application, the strength of each direct interaction was coded on a seven-point scale (ranging from -3 to +3), with negative values indicating trade-offs and positive values indicating synergies. For the graphical representation, the respective numerical values were mapped to coloured areas. After such a systematic assessment of direct interactions has been made, assorted network analysis techniques can be applied to identify implied indirect effect relationships, discern resulting network clusters, and present them in a descriptive visual manner.

While this method can apparently be implemented purely qualitatively, without considering available empirical data, an application based on historically observed correlations is naturally also possible. We consider the initiative of the Japanese Institute for Global Environmental Strategies (IGES), which has developed a very comprehensive SDG Interlinkages Analysis & Visualisation Tool (Zhou and Moinuddin 2017) noteworthy in this regard. As this tool is freely available and extensively documented on the internet,[23] we will not go into further detail here. But it seems important to us to emphasise that, beyond the original objective of this project, the scope of information made available via the IGES tool for monitoring sustainability developments exceeds by far that of the current national SDG monitoring in Germany.

[23] https://sdginterlinkages.iges.jp/ (retrieved on January 30, 2024)

Figure 3: Exemplary Cross-Impact matrix



The applied colour scheme ranges from dark red (-3, "cancelling interaction") to dark green (+3, "indivisible interaction").
Source: Own representation of the contents of Weitz et al. (2018)

Reconsidering own recent work in this domain (Meyer 2019), it therefore seems advisable to us that future projects explore similar possibilities for the further development of existing monitoring approaches. Thereby, the question of adequate measures and indicators for an appropriate evaluation of respective goals and targets should also be discussed in depth. In fact, current experience with corresponding evaluations indicates that it is difficult, if not even impossible, to establish universally accepted evaluation methods.[24]

[24] While our research project did not aim to elaborate any monitoring approaches, we would like to point out that different monitoring methods are currently in use. Unfortunately, this instance tends to produce conflicting findings: "We present the state of the art by comparing the three most prominent methods to measure SDGs performance at country level (…). We compare and contrast these methods. Our results suggest a strong discrepancy in existing methods. Depending on the chosen indicators and methods applied, countries can receive substantially different relative evaluations." Miola and Schiltz 2019, p. 1.

2.1.2 Dynamic modelling approaches for SDG interlinkage analysis

Table 1: The 17 Sustainable Development Goals positioned in their relation to ecological, social and economic dimensions of sustainability

Biosphere	Society	Economy
6 Clean Water and Sanitation	1 No Poverty	8 Decent Work and Economic Growth
13 Climate Action	2 Zero Hunger	9 Industry, Innovation and Infrastructure
14 Life Below Water	3 Good Health and Well-being	10 Reduced Inequalities
15 Life on Land	4 Quality Education	12 Responsible Consumption and Production
	5 Gender Equality	
	7 Affordable and Clean Energy	
	11 Sustainable Cities and Comunities	
	16 Peace and Justice and Strong Institutions	
	17 Partnership for the Goals	

Source: Own representation of the contents of (Folke et al. 2016)

Our conceptual understanding of general system structures that underpin individual SDG interactions is shown in Table 1. This Table was adapted from Folke et al. (2016) and illustrates that the SDGs refer in particular to three interdependently interacting subsystems (biosphere, society and economy). This underlying concept of social-ecological systems acknowledges that the economy and society are, as globally intertwined subsystems, embedded within the biophysical system (labelled as biosphere in the table). This is the basis of the planetary boundaries framework as applied in defining a safe operating space for humanity (Rockström et al. 2009; Steffen et al. 2015).

Taking this conceptual orientation, we conducted a systematic literature review of models and tools available for simulations of SDG interactions. This work is substantively close to previous literature reviews as published by, for example, Allen et al. (2016). However, whereas Allen et al. (2016) developed and applied a typology and inventory of 80 different models, including top-down 'macro framework' as well as bottom-up sectoral models, we did not aim to represent the entire set of currently available ex ante tools. Instead, our literature review aimed to identify those ex-ante assessment methods that are already capable for, or appear to be straightforward adaptable to, an integrated mapping of various SDG target interactions. Guided by this, we decided to focus the review of modelling approaches on macro frameworks, as "macro framework models are likely to be more useful for undertaking system-level or economy-wide scenario analysis driven by the national long-term goals and targets, and for exploring trade-offs and synergies among sectors" (Barbero Vignola et al. 2020, p. 10). Referring to recent literature reviews of related quantitative modelling (Bennich et al. 2020; Hafner et al. 2020), this implies that we refrain from any closer look at agent-based models.

Our review process is comparable to, inter alia, a related review conducted by Miola et al. (2019). However, whereas Miola et al. (2019) compiled a comprehensive review of identified SDG interactions on the Goals and Target levels, we acknowledge the specific thematic starting point of our review activities: **We compiled a literature review on SDG interactions, which address either the climate policy or the resource policy domain or integrate both domains.**

To this, it is interesting to note that key climate policy indicators (like greenhouse gas emissions) are notably assigned to SDG 9 and SDG 13. On the other hand, key indicators of resource policy (like the material footprint) are considered under SDG 8 and SDG 12. Looking back at Table 1 this means that our research focus moves different tiers of social-ecological systems into the spotlight of the analysis simultaneously: Whereas SDG 8, SDG 9 and SDG 12 consider economic developments (right-hand column of Table 1), SDG 13 is directly assigned to the biosphere (left-hand column of Table 1). Hence, our methodological literature review merges publications from three strands of literature which we consider to be particularly relevant for dynamic simulation studies of SDG-interactions:

Traditional **Integrated Assessment Models (IAM)** are usually characterised as macro approaches, which feature distinct advantages in the mapping of biophysical cause-effect relationships. Reviewing IAM-based studies of interactions among SDG, van Soest et al. (2019) document that a majority of their reviewed IAM applications dealt with SDG 13 (climate action). In these studies, interactions with other SDG were most often included via carbon pricing and mitigation costs and their impacts on SDG 8 (decent work and economic growth). However, as shown in previous publications by, among others, members of our research team (Meyer et al. 2021) the usually very detailed mapping of the energy system and derived biophysical indicators (such as emissions and radiative forcing levels) provided by IAM, come along with a rather rudimentary mapping of socioeconomic tiers. [25]

Environmental (or ecological) **Macroeconomic models** (Hafner et al. 2020), in contrast, are characterized by a very detailed representation of economic interactions. As most recently annotated in a systematic literature review by van Zanten and van Tulder (2021), this is a prerequisite at least for many SDG analyses.[26] However, whereas Macroeconomic models can capture a variety of economic sectors together with their mutually interdependent monetary transactions, lower levels of detail concerning physical and technological representations of individual sectors must usually be accepted. Especially for pathway analyses of a Circular Economy transition, respective models are regularly applied: A recent meta-analysis of the macroeconomic effects implied in ex ante Circular Economy scenario simulations identified 17 relevant studies based on macroeconomic modelling approaches, but only one study based on an IAM framework (Aguilar-Hernandez et al. 2021). See also McCarthy et al. (2018) in this regard.

The third class of macro framework models for economy-wide scenario analysis that we consider comprises **System Dynamics models**. As an essential reference in this regard, we refer to the most prominent acknowledgement of System dynamic models' capabilities for projecting SDG interactions given by Allen and colleagues (Allen et al. (2016). Besides this, we observe continuing interests in system dynamics modelling approaches in the field of resource conservation policy: UNEP (2017) explicitly features system dynamics models, as well as macro-

[25] On this subject, see also the following comment on the potential of future IAM applications for SDG impact analysis.: „IAMs will need to cooperate more closely with social sciences, as understanding biophysical processes is no longer sufficient while studying SDGs (e.g. demography, governance, and poverty research)“ van Soest et al. 2019, p. 218.

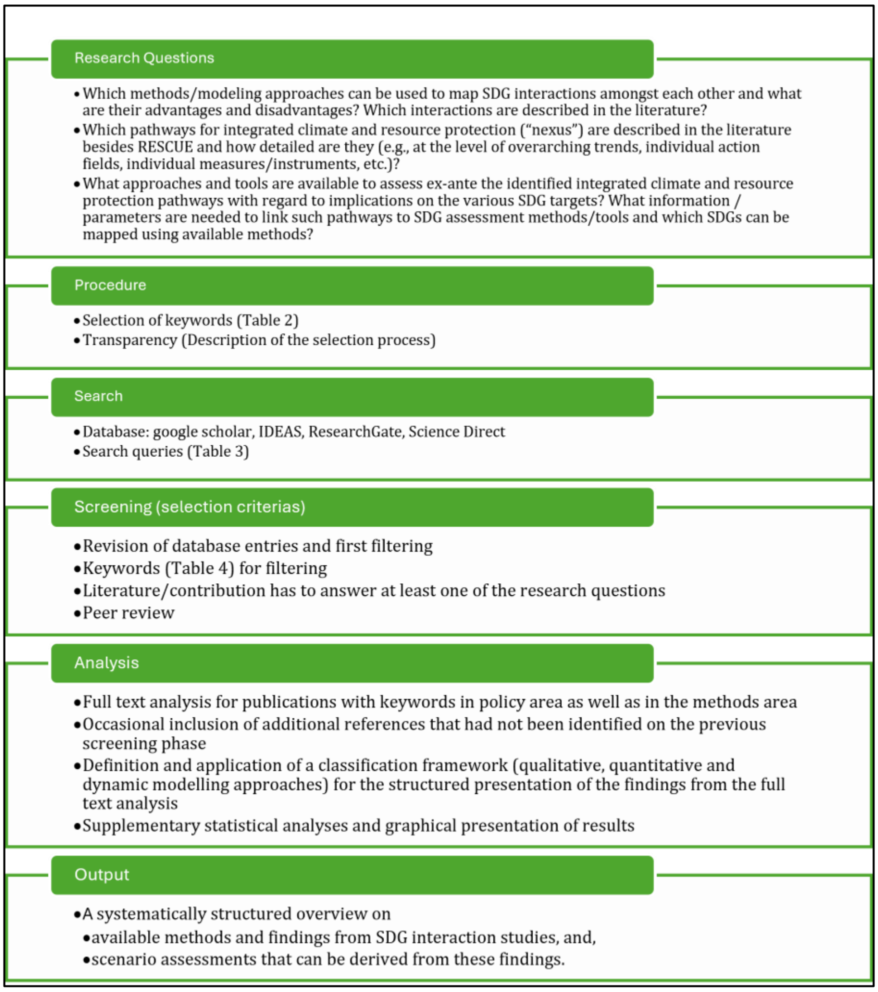
[26] “SDGs cannot be viewed in isolation of the economic structures in which they are to be achieved” van Zanten and van Tulder 2021, p. 219.

economic models, as methodologically appropriate tools for simulating the macroeconomic benefits of resource efficiency.

2.2 Methodological approach for the compilation of the literature review

2.2.1 Research questions, procedure, and search

Figure 4: Methodological approach of the systematic literature review



Source: Own representation

As stated before, our analysis is comparable to previous work, e.g., by Miola et al. (2019), van Zanten and van Tulder (2021) (who focused on economic activities), or McCollum et al. (2018) (who focused on energy-related studies). Also, our approach to the identification of dynamic simulation models is in substantial agreement with the conceptual structures applied by Aguilar-Hernandez et al. (2021) in their related meta- study on the macroeconomic effects of resource policy interventions.

The structure and methodological approach of our review was guided by the criteria of a systematic literature review as given by Haddaway et al. (2015) and Haddaway et al. (2018). It consisted of the steps depicted in Figure 4. The individual steps are explained in detail below.

Table 2: Relevant keywords for literature search

NO	Keyword I	NO	Keyword II
1	2030 Agenda	A	Trade-offs
2	national development	B	co-benefit
3	planetary boundaries	C	policy coherence
4	Sustainable Development Goals	D	Interaction
5	sustainable development	E	Integrated
6	sustainability	F	Nexus
7	sustainability goal	G	Relationships
8	sustainability science	H	Pathway
		I	Synergies

Source: Own representation

The first step in the systematic literature review was to identify relevant keywords for the search. Relevant keywords should identify publications that answer at least one of the following research questions:

1. Which methods/modelling approaches can be used to map SDG interactions amongst each other and what are their advantages and disadvantages? Which interactions are described in the literature?
2. Which pathways for integrated climate and resource protection ("nexus") are described in the literature besides RESCUE and how detailed are they (e.g., at the level of overarching trends, individual action fields, individual measures/instruments, etc.)?
3. What approaches and tools are available to assess ex-ante the identified integrated climate and resource protection pathways regarding implications on the various SDG targets? What information/parameters are needed to link such pathways to SDG assessment methods/tools and which SDGs can be mapped using available methods?

A first selection of keywords was derived from key literature references which were selected in joint agreement with the UBA (Le Blanc 2015; Weitz et al. 2018; Nilsson et al. 2016, 2016; Miola et al. 2019; Zhou and Moinuddin 2017; van Soest et al. 2019; Allen et al. 2019b; Ekins et al. 2019; TWI2050 - The World in 2050 2018; Philippidis et al. 2020; Bergöö et al. 2019). These keywords were complemented by keywords from highly cited publications as well as related key publications by the research team (Allen et al. 2016; Pedercini et al. 2020; Allen et al. 2021; Collste et al. 2017; Allen et al. 2017; Pedercini et al. 2018a; Pedercini et al. 2019).

The number of keywords was then reduced by removing (almost) identical entries and selecting only those entries deemed most relevant with respect to the overarching research questions. Whereas this reduction step resulted in 51 individual search terms, we finally decided to retain only keywords which could be directly associated with focal policy areas and related science keywords. This led to the final selection of 17 relevant search terms as summarised by Table 2.

Table 3: Queries applied in the literature search

NO	Query	NO	Query
1	(2030 Agenda) AND trade-offs	13	sustainability AND trade-offs
2	(2030 Agenda) AND co-benefit	14	sustainability AND co-benefit
3	(2030 Agenda) AND (Policy coherence)	15	sustainability AND (policy coherence)
4	(2030 Agenda) AND interaction	16	sustainability AND interaction
5	(2030 Agenda) AND integrated	17	(Sustainable Development Goals) AND relationships
6	(2030 Agenda) AND pathway	18	(Sustainable Development Goals) AND nexus
7	(Sustainable Development Goals) AND tradeoffs	19	(2030 Agenda) AND synergies
8	(Sustainable Development Goals) AND co-benefit	20	(2030 Agenda) AND relationships
9	(Sustainable Development Goals) AND (policy coherence)	21	(2030 Agenda) AND nexus
10	(Sustainable Development Goals) AND interaction	22	(Sustainable Development Goals) AND synergies
11	(Sustainable Development Goals) AND integrated	23	(Sustainable Development Goals) AND nexus
12	(Sustainable Development Goals) AND pathway	24	(Sustainable Development Goals) AND relationship

Source: Own representation

In the subsequent search process, various combinations of keywords I and keywords II were combined in systematic queries (e. g. Agenda 2030 + trade-offs, Agenda 2030 + co-benefit, Agenda 2030 + policy coherence, Agenda 2030 + interaction). The individual queries addressed the bibliographic databases of IDEAS (https://ideas.repec.org/), google scholar (https://scholar.google.de/), ResearchGate (https://www.researchgate.net/) and Science Direct (https://www.sciencedirect.com/).

In google scholar the research included all languages, that is the research was with no prior constraints. IDEAS is a large freely available database for literature dedicated to economics. ResearchGate is (one of) the largest academic networking platform for researchers. The bibliographic database Science Direct hosts over 18 million pieces of content from more than 4,000 academic journals and 30,000 e-books published by the Dutch publisher Elsevier. For IDEAS the terms had to be present in the record, that means either in the title, the abstract or the keywords. For google scholar the term was searched in the whole available document (title, abstract, keywords, table of contents, main text if freely available). The search results were sorted by relevance and the first six resulting pages were considered for the screening.

For a paper to be considered in our database, both terms of the query had to be present in the title or the abstract. Searches with queries or combinations of terms that did not yield new search results or relevant publications were aborted. Therefore, in total 24 out of 72 possible combinations have been used for the search.

To ensure that all key findings from the subsequent full-text analyses are reflected by our final database, individual contributions that had not previously identified by this initial search process were also supplemented to the database in the further course of the project. All published statistics in this report on the structure of the database therefore refer to this enhanced data set (including references from follow-up snowballing activities).
In essence, our meta-analysis is thus based on three elementary work steps: Initial database queries and statistical analyses, full text analysis I (of identified database entries), full text analysis II (of relevant literature references identified in full text analysis I). The full literature collection process was completed in March 2022. The oldest entries we considered refer to publications from the early 1990s.

2.2.2 Screening

For the following analyses, it was ensured that all (relevant) database entries were completely recorded. This concerned in particular abstracts and keywords. However, in this evaluation phase, all relevant database entries were thoroughly checked for completeness, including titles, author names, publication types, and publication years, and any missing information identified was subsequently filled in (where possible).[27] In addition, a final check was made to ensure that individual contributions would not accidentally be listed more than once in the database.

We then developed assessment criteria to select from the complete set of database entries those publications that feature a close thematic relationship to the subject matter of our project. The applied selection categories and queried attributes were developed iteratively by us. On this calibration stage, we checked selected references which appeared to be of central importance in light of previous literature reviews (Miola et al. 2019; van Soest et al. 2019; Aguilar-Hernandez et al. 2021; Allen et al. 2016) to see whether these references were also identified in our literature database when applying respective search parameters.

The final list of keywords considered in this evaluation is shown in Table 4. As can be seen, we organized our selection criteria along three dimensions. In the left column, all keywords are listed which, according to our observations, indicate specific references to the main topics of our research ("Science / Policy Domain"). The center column (“Kind of Interactions considered”) contains a variety of keywords aimed at identifying articles directly related to interaction-analyses. Finally, the right column (“Object of Analysis, applied Tools and Methods”) reflects our awareness of the range of methods available for quantitative SDG-interlinkage analyses.

[27] The reference to *relevant* publications acknowledges that, with due regard to the personnel capacities available to us, we decided to restrict this internal quality control to database entries that had been published after the year 2014. Furthermore, based on internal considerations, we decided at this processing stage to exclude all publications in the following journals from any further analyses: Midwifery, J Appl Biol Biotechnol, Joule, Journal of Applied Corporate Finance, Review of International Geographical Education Online, UCL Open: Environment, Discover Sustainability, Meridiano 47, NeoBiota, University of Oslo Faculty of Law Research Paper, Fire Safety Journal, BANCARIA, J Microbiol Exp, EVRODIJALOG Journal for European Issues, procedia-social and behavioral sciences, Frontiers in veterinary science, International Review for the Sociology of Sport, Bmj, Global Journal of Human Resource Management, International Migration, Journal of Management Studies, Nature Human Behaviour, Accounting and Business Research, Complexity, European Journal of Public Health, Journal of Business Logistics, Journal of Manufacturing Systems.

Table 4: Assessment criteria applied on screening phase I

Sciene / Policy Domains	Kind of Interactions considered	Object of Analysis, applied Tools and Methods
2030 Agenda	alternative development	assess pairwise interactions
carbon reduction	broader suite of policies	backcasting
Circular Economy	co-benefit	causal loop diagrams
climate action	coherence	conceptual mapping
climate and energy	comprehensive sustainable development pathway	dashboard
climate change	Correlation	decision-making
climate policy	cross-sector	dynamic stock model
decarbonisation		empirical evidence
decoupling	development network	evidence-based policy
emission reduction	driving forces	ex ante assessment
energy transition	feedback	forecasting
environmental assessment	governance gaps	foresight
global warming	holisitc approach	futures
industrial ecology	integrated policy	indicators of sustainability
material and energy use	integrated system	integrated assessment
material use	interaction	integrated methods
mitigation policy	interdependencies	integrated modelling
Nationally Determined Contributions	interlinkage	integrated scenario
natural resources	intersectoral	interlinkage management
planetary boundaries	links among goals	macroeconomic simulation
planetary operating space	modelling of linkages	meta-analysis
Resource efficiency	multi-causality	modeling system
resource policy	multi-criteria	modelling
resource pressure	multi-level	network analysis
resource use	multisector	numerical data

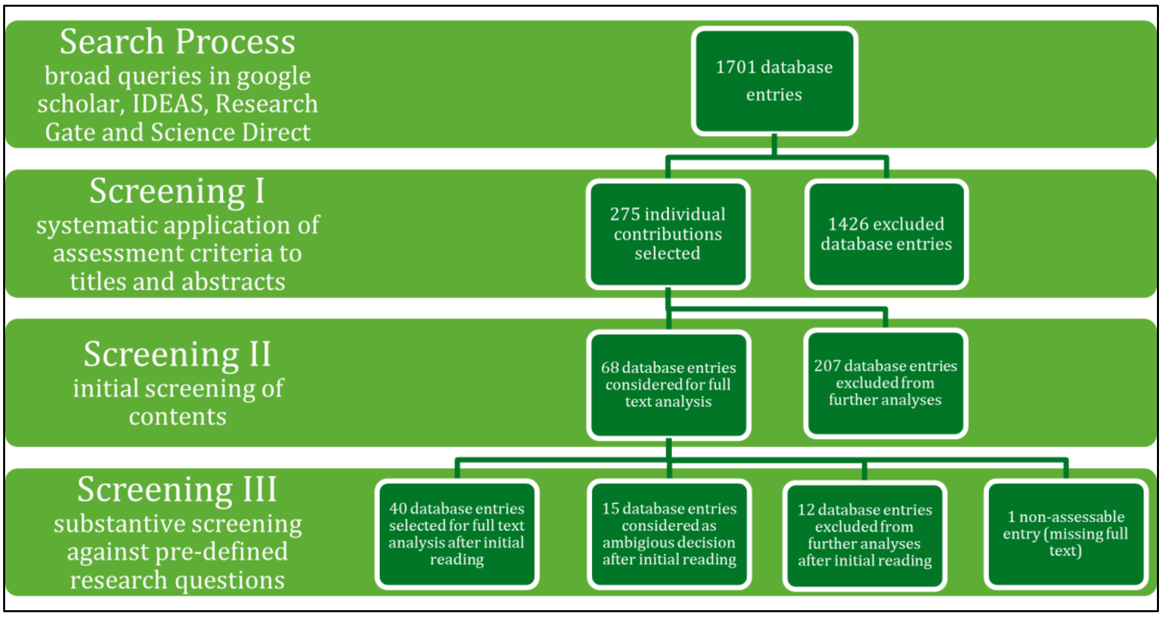
Sciene / Policy Domains	Kind of Interactions considered	Object of Analysis, applied Tools and Methods
science-policy interface	multi-sectoral	pathway
SDG metrics	nexus approach	qualitative analysis
SDG strategies	nexus concept	quantification
socio-technical transition	policy alignment	quantitative model
sustainability gaps	policy integration	quantitative research
Sustainability governance	policy mix	rank synergies and trade-offs
sustainability transition	synergies	regression analysis
Sustainable Development Goals	synergy	Scenario
UN SDG	conceptual integration	SDG attainment
wellbeing	cross-impact	dynamic assessment
	system dynamics	econometric modeling
	system thinking	socioeconomic scenario
	systems analysis	statistical analysis
	systems approach	statistics
	systems thinking	storyline development
	trade-off	sustainability assessment
	win-win	systematic review
		trajectories
		trajectory
		transformation

Source: Own representation

By means of the assessment criteria listed in Table 4, each database entry was checked in its respective titles, abstracts, and keywords to ensure that all the listed dimensions were covered by these entries. For this purpose, we programmed an evaluation routine in R, which reads in the complete database information as a structured Excel sheet to then check individually for each record whether at least one entry is found from each individual column of Table 4.[28]

[28] R is an open access general development environment for statistical data processing. For programming complex data analyses and statistical modelling, R provides a wide range of extremely powerful calculation routines. In addition, R is characterised by outstanding capabilities in the visualisation of data sets. See the R-project homepage for further details and software installation routines for UNIX, Windows or MacOS platforms (https://www.r-project.org/) (retrieved on April 24, 2024)

Figure 5: Selection process of systematic literature review



Source: Own calculations

The identification routines applied by this algorithm are not case sensitive. Keywords written in lower case are therefore also recognized if they were written in upper case in the publication (and vice versa). In addition, the algorithm was designed to also identify corresponding word stems.[29] These guidelines were deliberately set broadly, in a mutually exclusive format, by the GWS-project management. In order to ensure a broad coverage of related research activities and to facilitate continued improvements of our database through respective snowballing activities, identified literature reviews with strong relevance for our project activities were generally included in the full text analyses. Additionally, it was agreed that ex ante assessments and individual applications of tools for interlinkage analyses should generally be included in the full text analyses. For the remaining selection criteria, individual reviewers could apply their own weightings in their overall assessment. For the respective overall evaluations, the decision categories were given as follows: "Included in the full-text analysis", "unclear decision", "not included in the full-text analysis".

The algorithm then stores all identified literature entries as a well-structured Excel spreadsheet. As shown in Figure 5 (second row from above), we identified a total of 275 individual database entries by the application of this method. These shortlisted 275 entries were then evaluated in more detail by our research consortium: For each of the initially identified 275 database entries, the GWS research team pre-assessed, based on associated abstracts and titles and own scientific expertise, whether these entries should be explicitly considered in subsequent full-text analyses ("Screening II"). This preliminary shortlist was then presented to the entire project team as well as to UBA's project management for approval. At this stage, all research participants as well as UBA had the opportunity to make own requests for changes and to indicate further contributions that had not yet been adequately considered in previous analyses. Finally, a common list of 68 database entries was agreed to be tentatively considered for full-text analyses.

[29] The search term „pathway", for example, also identifies articles that report exclusively in the plural about „pathways".

TextBox 4: Key questions for the text analysis

Our individual decisions to include a paper in the literature review are guided in each case by a substantive assessment of the following key questions:

- Does the research contribution under consideration provide an overview on issues that appear strongly relevant for the project?
- Are methods applied which facilitate scenario analyses?
- Does the contribution report about ex ante assessments? Is it intended to report about quantified pathway projections?
- Does the research contribution cover a broad range of SDG?
- Does the research contribution feature a focus on the resources & climate nexus and implied SDG-interlinkages?
- Are presented analyses and results characterised by a high level of detail (for example in their consideration of individual regions, action areas, sectors or instruments)?
- Does the research contribution apply specific tools for interlinkage analysis?

Source: Own representation

In the final step (Screening III), each of the respective 68 database entries was individually screened for inclusion in the literature review. For this purpose, selected entries were assigned to individual members of the research consortium for evaluation on a work-sharing basis. These assignments were made by the GWS-project management, with consideration of the individual knowledge and experience of the respective research participants.

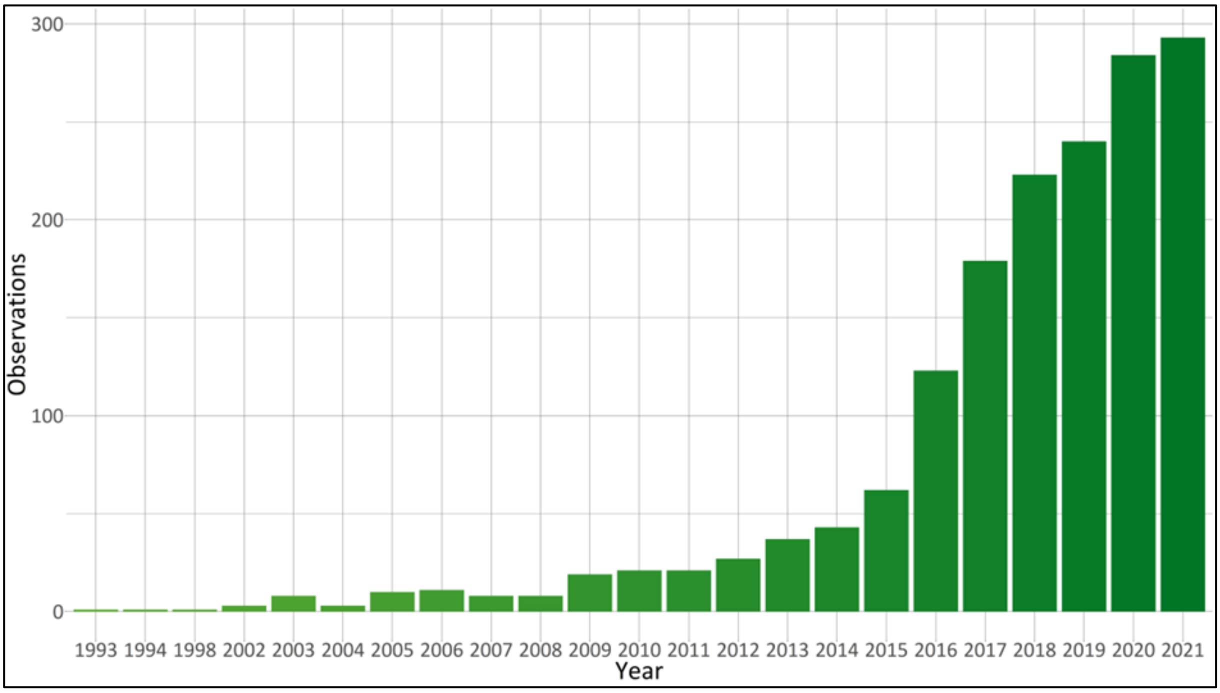
Since all evaluations of this work step were to be carried out with at least preliminary knowledge of the full texts, respective reviewers had to supplement any full texts not yet available by means of supplementary literature research or personal inquiries to the respective authors. This was not possible in all cases: Therefore, one database entry could not be conclusively assessed due to a missing full text.

In total, 40 entries were selected for individual full-text analysis and inclusion in our literature review. In their respective decisions, the individual reviewers were guided by the seven key questions as shown by TextBox 4.

2.3 Statistical summary of the analysed database

2.3.1 Full database

Figure 6: Total number of all recorded database entries by publication year



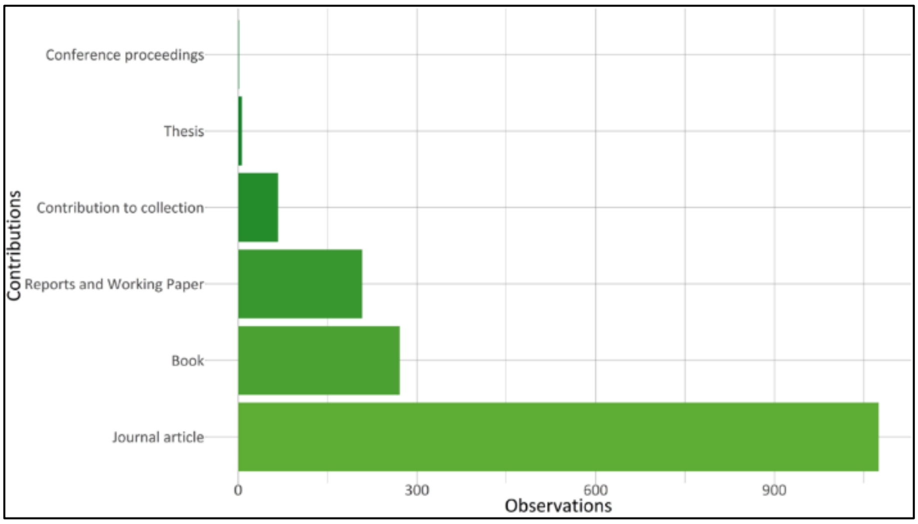
Source: Own calculations

Overall, 1701 individual entries have been coded in our database. As shown by the histogram in Figure 6, the research interest in interaction analyses for sustainable development has grown continuously over the past decade. While the earliest research articles we recorded were published in 1993 (one database entry), the number of corresponding annual publications identified by us until the end of the 2000s rarely exceeds 10. After that, however, this research topic clearly gets into vogue: Starting from 21 contributions in the publication year 2010, the number of thematically relevant publications identified by us rises monotonically to a total of 293 publications in the publication year 2021.

Figure 7 illustrates that most recorded database items refer to journal articles. Slightly more than 66 % of all database entries belong to this publication category. This is followed by books (slightly less than 17 % of all database entries) and the group of reports and working papers not published by a publishing house (almost 13 % of all database entries). Slightly more than 4 % of all database entries were categorized as individual contributions in edited volumes. Other forms of publication (university publications and conference proceedings) were rarely recorded. Together, they represent less than 0.5 % of all database entries.

Given the high share of publications from academic journals in our database, it is interesting to see in which journals the respective articles have been published. In total, we recorded 424 different journal titles. This high number of different journal titles can be explained by the fact that most journals (295 titles) are only listed with a single publication in our database. At the same time, a total of 182 of the journal articles recorded by us refer to an identical journal (Sustainability). Thus, Sustainability clearly dominates the set of academic articles recorded by us.

Figure 7: Breakdown of coded database entries by publication types



Empirical distribution of all recorded database entries.
Source: Own calculations

The journal with the second most publications (Journal of Cleaner Production) contributed 29 articles. The journal with the third most recorded publications (Sustainability Science) published 28 publications. Table 5 shows an overview of those journals that were most frequently considered in our meta analysis. The next ranked journals contribute less than 20 articles each (Sustainable Development: 18, Environment, Development and Sustainability: 17, Nature Sustainability: 17, Current Opinion in Environmental Sustainability: 14, World Development: 14, Climate Policy: 13, Ecological Economics: 13, Environmental Research Letters: 13).

Figure 8 illustrates the broad range of topics covered by the publications analysed. For the wordcloud shown, all titles and (where available) abstracts and keywords were broken down into individual words so that their respective frequencies of use could be analysed. In the visual representation, these frequencies have been represented by different colours (from yellow to orange, green, blue and violet to red (low to high frequency) and font sizes (with larger font sizes representing higher frequency of word occurrence).

As expected, the overarching "SDGs"-term is identified most frequently in this analysis.[30] Apart from that, with the "environmental" items being coloured in violet and the "economics" as well as "agenda" items being coloured in dark blue, many of the recorded publications can be classified as economic-environmental Agenda 2030 analyses. With "energy" being coloured in dark blue and "climate change" being highlighted in light blue, climate policy contributions represent a significant proportion of the contributions we captured. However, the social dimension of the SDGs appears to be discussed with similar frequency as it has also been coloured in dark blue. Resource issues are particularly captured under "food" and "water" keywords (both shown in dark green), as well as under "land" use aspects (light green). Overall, trade-offs (shaded in dark green) appear to be mentioned more frequently than synergies (shaded in light green).

[30] The most frequent overarching terms (like goals, policy, or sustainability) are not shown in this illustration as they would strongly dominate the resulting figure.

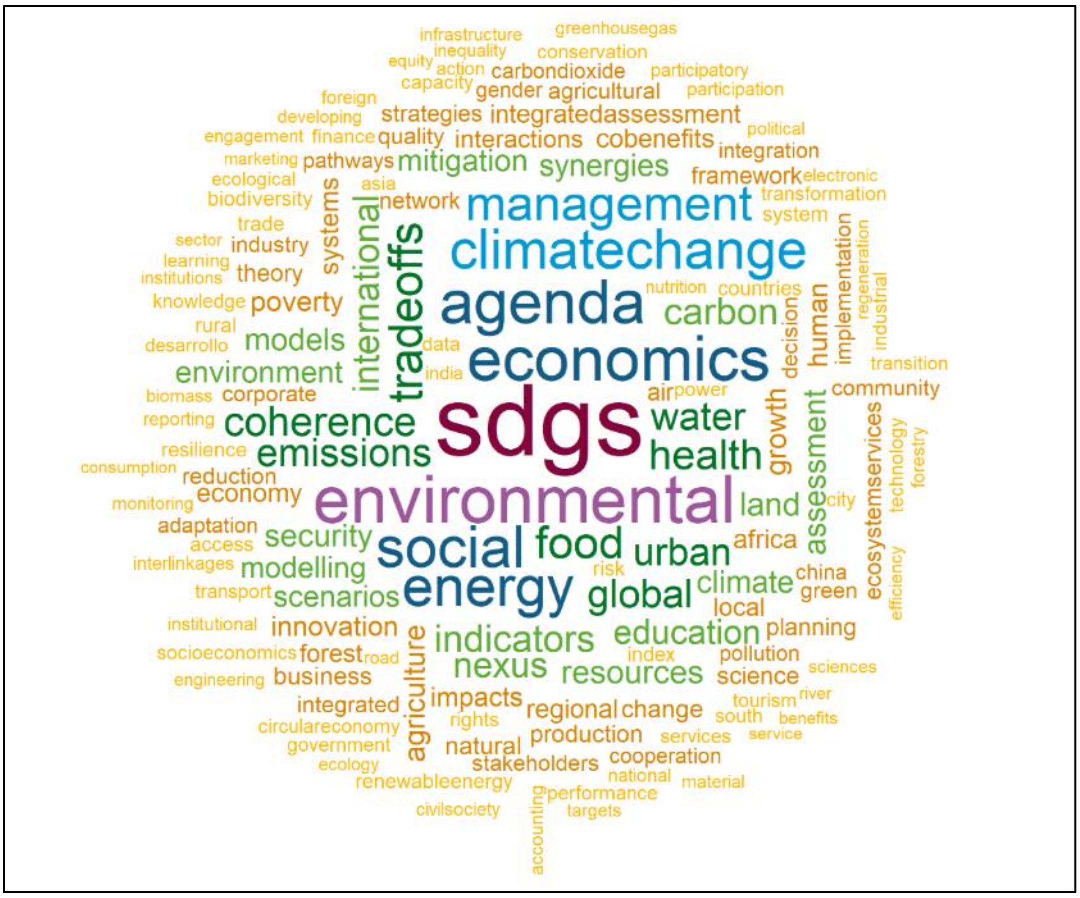
Table 5: Systematic literature review: most frequently considered journal titles

Seq. Number	Journal	Number of Publications
1	Sustainability	182
2	Journal of Cleaner Production	29
3	Sustainability Science	28
4	Sustainable Development	18
5	Environment, Development and Sustainability	17
6	Nature Sustainability	16
7	Current Opinion in Environmental Sustainability	14
8	World Development	14
9	Climate Policy	13
10	Ecological Economics	13
11	Environmental Research Letters	13
12	Business Strategy and the Environment	12
13	Energies	11
14	Environmental science & policy	11
15	Renewable and Sustainable Energy Reviews	11
16	International Environmental Agreements: Politics, Law and Economics	10
17	Nature Climate Change	9
18	Technological Forecasting and Social Change	9
19	Politics and Governance	8
20	Science of The Total Environment	8
21	Ecosystem Services	7
22	Global Environmental Change	7
23	Economies	6
24	Energy Policy	6
25	Global Environmental Change - Human and Policy Dimensions	6
26	Land Use Policy	6
27	Applied Energy	5
28	Ecology and Society	5

Seq. Number	Journal	Number of Publications
29	Environmental Policy and Governance	5
30	International Journal of Sustainable Development & World Ecology	5
31	Land	5
32	Marine Policy	5
33	Water	5
34	Administrative Sciences	4
35	Agricultural Systems	4
36	Corporate Social Responsibility and Environmental Management	4
37	Development Policy Review	4
38	Frontiers in Environmental Science	4
39	International Journal of Energy Economics and Policy	4
40	Journal of Environmental Management	4
41	Journal of Sustainable Tourism	4
42	Nature	4
43	One Earth	4
44	Plos one	4
45	Regional Environmental Change	4
46	Renewable Energy	4
47	Resources, Conservation & Recycling	4
48	Sustainable Cities and Society	4

Empirical distribution of journal titles for journals that are referenced at least four times in our database.
Source: Own calculations

Figure 8: Wordcloud based on SDG publication titles, abstracts, and keywords



Focal topics emerging from all research items included in our database, derived from individual publication titles, abstracts and keywords.

Source: Own calculations

2.3.2 Screening results

A detailed list of researchers who contributed to at least two of these 275 candidate publications of Screening Phase II is given in the Appendix: Detailed findings from the literature review (Table 53). Here, we only provide a brief introduction to those authors who contributed to five or more of the identified publications.

Cameron Allen, Graciela Metternicht and Thomas Wiedmann from the University of New South Wales in Sydney (Australia) contributed a methodological and a policy implementation review (Allen et al. 2016; Allen et al. 2018) as well as a case study application based on **Trend assessments, Cross-Impact matrix analysis and Network analysis** (Allen et al. 2019a). It is interesting to note that with Wiedmann, a well-known expert in macroeconomic Input-Output analyses and derived macroeconomic footprint assessments was involved in this work. However, most of his research identified by our review approach focuses primarily on applications of system dynamics models for SDG-interaction studies: Together with Matteo Pedercini, Allen, Metternicht and Wiedmann published findings from applications of the iSDG model to Australia and, respectively, Fiji (Allen et al. 2019b, 2021).[31] As head of the research and modelling activities at MI, additional iSDG model applications that are also included in our database have also been co-authored by Matteo Pedercini (Pedercini et al. 2018b; Pedercini et al.

[31] For the sake of completeness, we would like to mention that one additional publication co-authored by Metternicht Bizikova et al. 2018 was only identified on a later evaluation stage and has thus not been included into the literature review.

2020; Collste et al. 2017). With his proven methodological expertise, Pedercini also co-authored the iSDG developments and applications documented in this report.

Regarding our recorded IAM contributions, individual PIK members can be identified as frequently involved co-authors of individual model applications as well as inter-model comparison studies as follows: Alexander Popp coordinates the development of the global multi-regional land-use optimization model MAgPIE (Model of Agricultural Production and its Impacts on the Environment).[32] See (Humpenöder et al. 2018) for a selected reference publication. Gunnar Luderer is the Lead Scientist for the REMIND Integrated Energy Economy Climate Model.[33] Luderer and Popp jointly contributed to selected applications of the REMIND–MAgPIE framework (Soergel et al. 2021; Bertram et al. 2018). The Soergel et al. (2021) as well as the Humpenöder et al. (2018) studies were inter alia also co-authored by Benjamin Leon Bodirsky, another MAgPIE expert from the PIK research team. See Herrero et al. (2021) as well as Valin et al. (2021) for additional references to the work of Bodirsky from our database. Based on findings from the AMPERE model inter-comparison database,[34] Luderer also contributed to a comparison study of four IAMs (GCAM, MESSAGE, POLES, REMIND) (Stechow et al. 2016). Additionally, Luderer also contributed to a multi-model study which included eleven IAMs that was (amongst others) co-authored by Detlef van Vuuren (Kriegler et al. 2015).

Detlef van Vuuren is senior researcher at PBL (Netherlands Environmental Agency) and professor at Utrecht University (The Netherlands). As a member of the IMAGE integrated assessment modelling team,[35] he co-authored IMAGE modelling studies (van den Berg et al. 2016; van Vuuren et al. 2015) just as a GLOBIOM application included in our database (Obersteiner et al. 2016). Additionally, our database also lists him as a co-author of multi-model analyses and methodological reviews (Stechow et al. 2015; Bleischwitz et al. 2018). Furthermore, Luderer, Popp, Bodirsky and van Vuuren belong to the list of co-authors of a more recent model review (van Soest et al. 2019). Jointly they also contributed to a multi-model study which applied five IAMs (GCAM, IMAGE, MESSAGE-GLOBIOM, POLES and REMIND) (Luderer et al. 2019).

The van Soest et al. (2019) review was also co-authored by Jan Minx (MCC Berlin & University of Leeds, UK). Further references to his work listed in our subset database are given by Stechow et al. (2015), Stechow et al. (2016), Bertram et al. (2018) and McCollum et al. (2018).

Moreover, in Tafadzwanashe Mabhaudhi we also identified a researcher from Africa with frequent contributions related to agricultural analyses. See Mabhaudhi et al. (2021), Naidoo et al. (2021a), Naidoo et al. (2021b), Nhamo et al. (2020a) as well as Nhamo et al. (2020b) as respective references.

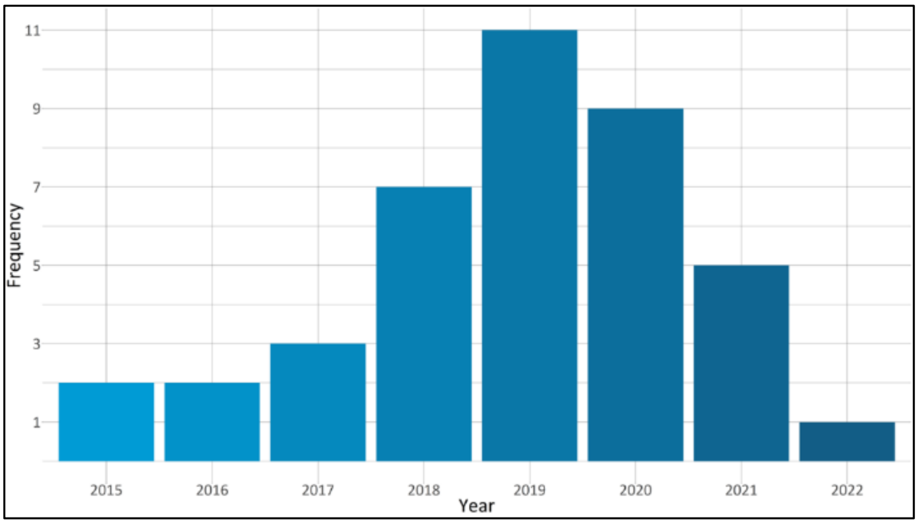
[32] https://www.pik-potsdam.de/en/institute/departments/activities/land-use-modelling/magpie (retrieved on April 24, 2024)

[33] https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind (retrieved on April 24, 2024)

[34] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/AMPERE_Scenario_database.html (retrieved on April 24, 2024)

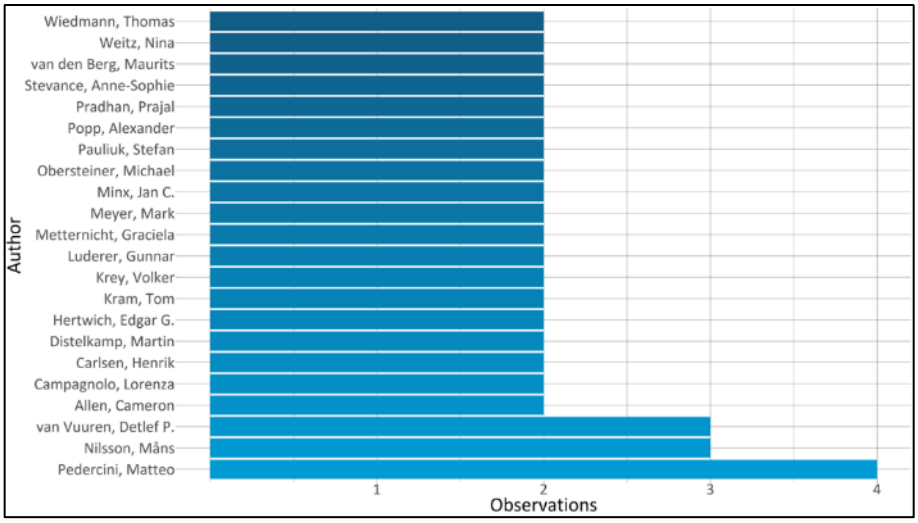
[35] https://www.pbl.nl/en/image/about-image (retrieved on April 24, 2024)

Figure 9: Number of database entries included in the full text analysis by publication year



Source: Own calculations

Figure 10: Authors with multiple contributions to our analysed paper shortlist (from 1993 to 2022)



Source: Own calculations

A longlist of the contributions included in the following screening phase may be provided upon request. As mentioned earlier, this longlist provided the starting point for the selection of 40 papers that were reviewed as part of the full-text analyses. For the resulting 40 paper shortlist, Figure 9 shows the in-sample distribution of the publication years of selected articles. As can be seen from this figure, our selection focuses exclusively on publications that have been published since 2015. This reflects an intentional decision by the research team: as the SDGs were only adopted in 2015, we did not include earlier contributions in the full-text analyses. Our most recent reference included in the full-text analysis dates from 2022.

A consolidated overview of all references and the contributing authors included in our full-text review is given by Table 6. A total of over 200 authors contributed to the literature included in the full-text analysis. While a tabular overview of all authors included in the full-text analysis can be provided by us upon request, Figure 10 shows the distribution for the number of contributions among all authors with multiple included publications.

Table 6: Literature selected for full text reviews

	Authors	Year	Title	Journal
1	Aguilar-Hernandez, Glenn A.; Dias Rodrigues, João F.; Tukker, Arnold	2021	Macroeconomic, social and environmental impacts of a Circular Economy up to 2050: A meta-analysis of prospective studies	Journal of Cleaner Production
2	Allen, Cameron; Metternicht, Graciela; Wiedmann, Thomas; Pedercini, Matteo	2019	Greater gains for Australia by tackling all SDGs but the last steps will be the most challenging	Nature Sustainability
3	Allen, Cameron; Metternicht, Graciela; Wiedmann, Thomas; Pedercini, Matteo	2021	Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing states	Global Sustainability
4	Barbero Vignola, Giulia; Acs, Szvetlana; Borchardt, Steve; Sala, Serenella; Giuntoli, Jacopo; Smits, Paul; Marelli, Luisa	2020	Modelling for Sustainable Development Goals (SDGs)	
5	Bennich, Therese; Weitz, Nina; Carlsen, Henrik	2020	Deciphering the scientific literature on SDG interactions: A review and reading guide	The Science of the total environment
6	Campagnolo, Lorenza; Carraro, Carlo; Eboli, Fabio; Farnia, Luca; Parrado, Ramiro; Pierfederici, Roberta	2018	The Ex-Ante Evaluation of Achieving Sustainable Development Goals	Social Indicators Research
7	Campagnolo, Lorenza; Davide, Marinella	2019	Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality	World Development
8	Capellán-Pérez, Iñigo; Blas, Ignacio de; Nieto, Jaime; Castro, Carlos de; Miguel, Luis Javier; Carpintero, Óscar; Mediavilla, Margarita; Lobejón, Luis Fernando; Ferreras-Alonso, Noelia; Rodrigo, Paula; Frechoso, Fernando; Álvarez-Antelo, David	2020	MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints	Energy Environ. Sci.
9	Dawes, Jonathan H. P.	2022	SDG interlinkage networks: Analysis, robustness, sensitivities, and hierarchies	World Development
10	Distelkamp, Martin; Meyer, Mark	2019	Pathways to a Resource-Efficient and Low-Carbon Europe	Ecological Economics
11	Ferri, Giovanni; Sedehi, Habib	2018	The System view of the Sustainable Development Goals	

	Authors	Year	Title	Journal
12	Haberl, Helmut; Wiedenhofer, Dominik; Pauliuk, Stefan; Krausmann, Fridolin; Mueller, Daniel B.; Fischer-Kowalski, Marina	2019	Contributions of sociometabolic research to sustainability science	Nature Sustainability
13	Hardt, Lukas; O'Neill, Daniel W.	2017	Ecological Macroeconomic Models: Assessing Current Developments	Ecological Economics
14	Hatfield-Dodds, Steve; Schandl, Heinz; Newth, David; Obersteiner, Michael; Cai, Yiyong; Baynes, Tim; West, James; Havlik, Petr	2017	Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies	Journal of Cleaner Production
15	Hertwich, Edgar G.; Lifset, Reid; Pauliuk, Stefan; Heeren, Niko; Ali, Saleem; Tu, Qingshi; Ardente, Fulvio; Berrill, Peter; Fishman, Tomer; Kanaoka, Koichi; Kulczycka, Joanna; Makov, Tamar; Masanet, Eric; Wolfram, Paul	2020	Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future	
16	International Resource Panel (Bruno Oberle; Stefan Bringezu; Steve Hatfield-Dodds; Stefanie Hellweg; Heinz Schandl; Jessica Clement et al.)	2020	Global Resources Outlook 2019	
17	Jackson, Tim; Victor, Peter A.	2020	The Transition to a Sustainable Prosperity-A Stock-Flow-Consistent Ecological Macroeconomic Model for Canada	Ecological Economics
18	Kluza, Krzysztof; Ziolo, Magdalena; Bak, Iwona; Spoz, Anna	2021	Achieving Environmental Policy Objectives through the Implementation of Sustainable Development Goals. The Case for European Union Countries	Energies
19	Kroll, Christian; Warchold, Anne; Pradhan, Prajal	2019	Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies?	Palgrave Communications
20	Le Blanc, David	2015	Towards integration at last? The sustainable development goals as a network of targets	Sustainable Development
21	Luderer, Gunnar; Pehl, Michaja; Arvesen, Anders; Gibon, Thomas; Bodirsky, Benjamin L.; Boer, Harmen Sytze de; Fricko, Oliver; Hejazi, Mohamad; Humpenoeder, Florian; Iyer, Gokul; Mima, Silvana; Mouratiadou, Ioanna; Pietzcker, Robert C.;	2019	Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies	Nature communications

	Authors	Year	Title	Journal
	Popp, Alexander; van den Berg, Maarten; van Vuuren, Detlef; Hertwich, Edgar G.			
22	McCollum, David L.; Echeverri, Luis Gomez; Busch, Sebastian; Pachauri, Shonali; Parkinson, Simon; Rogelj, Joeri; Krey, Volker; Minx, Jan C.; Nilsson, Måns; Stevance, Anne-Sophie	2018	Connecting the sustainable development goals by their energy inter-linkages	Environmental Research Letters
23	Meyer, Mark; Hirschnitz-Garbers, Martin; Distelkamp, Martin	2018	Contemporary Resource Policy and Decoupling Trends—Lessons Learnt from Integrated Model-Based Assessments	Sustainability
24	Miguel Ramos, Carlos de; Laurenti, Rafael	2020	Synergies and Trade-offs among Sustainable Development Goals: The Case of Spain	Sustainability
25	Miola, A.; Borchardt, S.; Neher, F.; Buscaglia, D.	2019	Interlinkages and policy coherence for the Sustainable Development Goals implementation	An operational method to identify trade-offs and co-benefits in a systemic way, Publications Office of the European Union
26	Nilsson, Måns; Chisholm, Elinor; Griggs, David; Howden-Chapman, Philippa; McCollum, David; Messerli, Peter; NEUMANN, Barbara; Stevance, Anne-Sophie; Visbeck, Martin; Stafford-Smith, Mark	2018	Mapping interactions between the sustainable development goals: lessons learned and ways forward	Sustainability Science
27	Obersteiner, Michael; Walsh, Brian; Frank, Stefan; Havlík, Petr; Cantele, Matthew; Liu, Junguo; Palazzo, Amanda; Herrero, Mario; Lu, Yonglong; Mosnier, Aline	2016	Assessing the land resource–food price nexus of the Sustainable Development Goals	Science advances
28	Oliveira, Agatha; Calili, Rodrigo; Almeida, Maria Fatima; Sousa, Manuel	2019	A Systemic and Contextual Framework to Define a Country's 2030 Agenda from a Foresight Perspective	Sustainability
29	Pedercini, Matteo; Arquitt, Steve; Chan, Derek	2020	Integrated simulation for the 2030 agenda	System Dynamics Review
30	Pedercini, Matteo; Arquitt, Steven; Collste, David; Herren, Hans	2018	Harvesting synergy from Sustainable Development Goal interactions	Proceedings of the National Academy of Sciences

	Authors	Year	Title	Journal
31	Philippidis, George; Shutes, Lindsay; M'Barek, Robert; Ronzon, Tévécia; Tabeau, Andrzej; van Meijl, Hans	2020	Snakes and ladders: World development pathways' synergies and trade-offs through the lens of the Sustainable Development Goals	Journal of Cleaner Production
32	Pradhan, Prajal; Costa, Luís; Rybski, Diego; Lucht, Wolfgang; Kropp, Jürgen P.	2017	A Systematic Study of Sustainable Development Goal (SDG) Interactions	Earth's future
33	Sebestyén, Viktor; Bulla, Miklós; Rédey, Ákos; Abonyi, János	2019	Network model-based analysis of the goals, targets and indicators of sustainable development for strategic environmental assessment	Journal of Environmental Management
34	Swain, Ranjula Bali; Ranganathan, Shyam	2021	Modeling interlinkages between sustainable development goals using network analysis	World Development
35	van den Berg, Maurits; Neumann, Kathleen; van Vuuren, Detlef P.; Bouwman, A. F.; Kram, Tom; Bakkes, Jan	2016	Exploring resource efficiency for energy, land and phosphorus use: Implications for resource scarcity and the global environment	Global Environmental Change - Human and Policy Dimensions
36	van Soest, Heleen L.; van Vuuren, Detlef P.; Hilaire, Jérôme; Minx, Jan C.; Harmsen, Mathijs J. H. M.; Krey, Volker; Popp, Alexander; Riahi, Keywan; Luderer, Gunnar	2019	Analysing interactions among Sustainable Development Goals with Integrated Assessment Models	Global Transitions
37	van Vuuren, Detlef P.; Kok, Marcel; Lucas, Paul L.; Prins, Anne Gerdien; Alkemade, Rob; van den Berg, Maurits; Bouwman, Lex; van der Esch, Stefan; Jeuken, Michel; Kram, Tom; Stehfest, Elke	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
38	van Zanten, Jan Anton; van Tulder, Rob	2021	Towards nexus-based governance: defining interactions between economic activities and Sustainable Development Goals (SDGs)	International Journal of Sustainable Development & World Ecology
39	Weitz, Nina; Carlsen, Henrik; Nilsson, Måns; Skånberg, Kristian	2018	Towards systemic and contextual priority setting for implementing the 2030 Agenda	Sustainability Science

	Authors	Year	Title	Journal
40	Zelinka, David; Amadei, Bernard	2019	A systems approach for modeling interactions among the Sustainable Development Goals Part 2: System dynamics	International Journal of System Dynamics Applications (IJSDA)

Source: Own representation

2.4 Substantive findings from our meta-study on SDG-trade-offs and -synergies

2.4.1 Expert judgements and statistical ex post assessments

2.4.1.1 Methodological overview

This section presents the applications of quantitative and statistical analyses identified by our literature review. A tabular overview of the references that emerged in this regard can be found in Table 7. As can be seen from the first column, we distinguish between five generic types of analysis: Expert judgement, Meta Analysis, Statistical assessments, Scenario Calculations and Statistical Modeling approaches. A variety of qualitative as well as quantitative methods are used for the respective types of analyses. For the selected references given in column three, the prevailing types of methods used are listed in column two. These methodological approaches are briefly presented below.

The examples of **Cross-Impact matrix** applications mentioned in the first part of the table represent the perhaps most well-known and certainly the earliest approaches to the identification of SDG interactions (Le Blanc 2015; Nilsson et al. 2016; ICSU 2017). Cross-Impact matrices provide a structured and concise overview of pairwise interrelationships. The just mentioned publications applied Cross-Impact matrices to summarise qualitative assessments of selected experts on directions and strengths of SDG interactions. To assess the individual strength of individual interactions considered, respective experts were asked to categorise their opinions ordinally on a discrete scale ranging from -3 to +3. Trade-Offs were coded by negative entries; synergies were coded by positive entries. The absence of any significant link between two considered SDG targets or goals was coded as 0.

An early review of findings from selected case study applications of this assessment approach for SDG-interlinkage analysis has been provided by Nilsson et al. (2018). These authors consider the flexible application of this method as an essential advantage. Insights from stand-alone data analyses as well as previously proven interrelationships or interlinkages deemed relevant by experts or stakeholders can be brought together in a structured way to be then systematically evaluated visually and statistically. For graphical presentations, network analysis tools are usually applied. Weitz et al. (2018) represent a widely cited publication in this regard. Focusing on selected SDG targets from a Swedish perspective, they demonstrate the usefulness of tailored network graphs for visualisations of the information content of Cross-Impact Matrixes.

On the other hand, such a knowledge co-creation approach suffers from typical "technical" disadvantages. Key issues to be considered in this regard may be summarised as follows: "How to bring different academic disciplines to the table and generate a common knowledge base for the assessment; how to select the ''key'' interactions from all possible alternatives; how to tap into statistical data sources; and how to gauge or ''calibrate'' the different experts' estimates and characterizations of interactions." (Nilsson et al. 2018, p. 1500). In addition to these technical aspects, it also must be noted that corresponding analyses and evaluations of SDG-interactions are always context-specific. If framing contextual conditions are changed, the respective conclusions may also vary significantly. One interesting conclusion of the authors is therefore given in their indication on the suitability of this method for local analyses: "While the applications so far have been generic or national-level, this experience suggests that there would be value in applying the framework at the local scale—a scale at which many interactions become very tangible and concrete, and the contextual factors become clear" (Nilsson et al. 2018, p. 1499).

Table 7: Overview of qualitative and quantitative applications identified from the literature review

Type of analysis	Method	Reference
Expert judgement	Cross-Impact matrix, Network Analysis	Le Blanc (2015)
Expert judgement	Cross-Impact matrix	Nilsson et al. (2016)
Expert judgement	Cross-Impact matrix	ICSU (2017)
Expert judgement	Cross-Impact matrix, Network Analysis	Weitz et al. (2018)
Meta Analysis	Cross-Impact matrix, Network Analysis	Pham-Truffert et al. (2020)
Meta Analysis	Cross-Impact matrix, Network Analysis, Mathematical Modelling	Dawes (2022)
Meta Analysis, Statistical ex post assessment	Count Data Analysis, Chi-Squared tests	van Zanten and van Tulder (2021)
Meta Analysis, Statistical ex post assessment	Spearman rank correlation	Miola et al. (2019)
Statistical ex post assessment	Spearman rank correlations	Fonseca et al. (2020)
Statistical ex post assessment	Spearman rank correlations	Pradhan et al. (2017)
Statistical ex post assessment	Spearman rank correlation	Kroll et al. (2019)
Statistical ex post assessment	Pearson correlation, Network Analysis	Bali Swain and Ranganathan (2021)
Statistical ex post assessment	Correlation Analysis, Network Analysis	Sebestyén et al. (2019)
Statistical ex post assessment	Granger-causality tests, Network Analysis	Dörgő et al. (2018)
Statistical ex post assessments	Trend Analysis & Interpolation, Cross-National cluster analysis	Sebestyén and Abonyi (2021)
Dynamic modelling	Factor Analysis	Spaiser et al. (2017)
Statistical ex post assessment	Structural Equation Modeling	Bali Swain and Yang-Wallentin (2020)
Statistical ex post assessment, Scenario Calculations	Static Input-Output Analysis	Scherer et al. (2018)
Multivariate statistical Assessments	Regression Analysis	Miguel Ramos and Laurenti (2020)
Multivariate statistical Assessments	Regression Analysis	Kluza et al. (2021)
Dynamic modelling	Regression Analysis, Monte Carlo Simulations	Ranganathan et al. (2017)
Dynamic modelling	SUR estimation, Panel VAR Modeling	Bali Swain and Karimu (2020)

Source: Own representation of findings from the literature review

Whereas initial applications of network tools merely served to illustrate the contents of Cross-Impact matrices, Weitz et al. (2018) also apply related concepts for a more advanced statistical analysis of the identified network structures. This enables them to calculate measures for the quantitative accounting of indirect interactions. For each individual network node (a single Goal or Target), the resulting total effect of a desired intervention is quantified as the sum of all triggered variations in the interlinked nodes. As a result, key intervention points can be identified, i.e., those goals or targets for which a desired change at this point would also trigger the greatest overall indirect effects.

The calculation of respective centrality measures is intuitively appealing, as this may theoretically enable the establishment of an overall ranking of SDG synergies and trade-offs by key impact nodes. This would apparently provide necessary information for the prioritisation of political measures to achieve the SDGs. In fact, though, the calculations addressed here did not take all network interactions into account. Rather, only the net effect on all directly connected neighbour nodes (first-order interaction) as well as on the other neighbour nodes directly connected to these neighbour nodes (second-order interaction) were calculated. Whereas Weitz et al. (2018) presented findings from a Swedish case study, Pham-Truffert et al. (2020) analyse global interactions at the target level. Their calculated "weighted in-degree and out-degree" measures quantify first-order interactions. The dataset gathered by them is based on SDG-interlinkages identified from a systematic literature review that have been ordinally recoded as suggested by Nilsson et al. (2018).

The incomplete consideration of systemic network interactions by considering only first-order or second-order interactions can be criticised as more extensive network analysis methods are well available. Dawes (2022), referring to Newman (2018) for further methodological references in this regard, therefore provides a well-arranged presentation of the mathematical relationships between matrices, eigenvalues and eigenvectors that appear relevant in this context. This paper is based on his previous analyses of the ICSU and ISSC (2015) findings documented in Dawes (2020). As illustrated by him, straightforward applications of algebra calculus may provide a holistic view on the implied dynamics of the overall network. As a relevant system characteristic, he defines "self-consistency" as a network property (that can be tested against the observed structures of an impact matrix), which indicates that a simultaneous achievement of all considered goals or targets is basically possible in the long term. This apparently most desirable system property cannot be universally assumed as a complex interplay of synergies and trade-offs could for example also generate oscillating long run system dynamics. Hence, the findings of first order or second order interaction associations are certainly interesting, but not sufficient for dynamic assessments of SDG interactions.[36] See, for example, Zhou and Moinuddin (2017, pp. 46–68) for exemplary empirical applications of a variety of centrality measures on selected empirical datasets.

Of all correlation analyses listed in the table (Miola et al. 2019; van Zanten and van Tulder 2021; Fonseca et al. 2020; Pradhan et al. 2017; Kroll et al. 2019; Bali Swain and Ranganathan 2021), the article by Bali Swain et al. (2021) stands out in that the criticisms just mentioned with reference to Dawes' publications are comprehensively considered in their supplementary network analyses. The remaining analyses refrain from respective network representations. The calculated correlation patterns are instead visualised in common statistical result representations. The natural approach of calculating bivariate correlation coefficients between selected indicator time series was applied by Pradhan et al. (2017) who calculated country-specific Spearman rank correlations and aggregated these results into global findings. Methodologically, this approach is closely related to the statistical analysis of Miola et al. (2019). In a follow-up study to Pradhan et al. (2017), Kroll et al. (2019) analyse individual yearly Cross-

[36] Additionally, Dawes 2022 also demonstrates how applications of further mathematical-statistical techniques may be usefully applied to infer the robustness and sensitivity of the analysed matrixes and to visualise the implied hierarchies.

Sectional data observations to estimate bivariate rank correlations across countries for nine consecutive years. If, as for instance in the application in Miola et al. (2019), ordinally scaled databases are analysed, an application of rank correlation coefficients is imperative. However, if cardinal scaled data sets are analysed, other correlation measures may also be reasonably applied.[37]

Apart from these bivariate correlation studies, a magnitude of further statistical methods has already been applied to examine available SDG datasets for trade-offs and synergies. A Hungarian group of researchers (Dörgő et al. 2018; Sebestyén et al. 2019; Sebestyén and Abonyi 2021) also estimated correlation patterns for multi-national indicator time series and visualised the resulting findings as network diagrams (Sebestyén et al. 2019). In Dörgő et al. (2018), they apply a battery of econometric standard test procedures to infer bivariate correlation patterns from observed dynamics of a magnitude of national indicator time series. The appropriateness of their applied methodology can, however, be questioned. Given that only a small proportion of the time series analysed by them contained more than 10 consecutive observations, it may at least be assumed that the empirical test quality of applied ADF and cointegration tests suffered from serious weaknesses.[38] Accordingly, in a subsequent publication (Sebestyén and Abonyi 2021), these authors refrain from applying complex time series econometric test approaches. Instead, this study provides a statistical analysis of empirical distribution functions based on 1319 national indicator time series from the United Nations SDG Global Database. However, this approach is mainly suggestive for international comparative monitoring purposes (including trend extrapolations), but not for an analysis of SDG-interactions.

The factor analyses applied by Spaiser et al. (2017) represent a natural approach for monitoring activities. They apply their statistical modelling approach to an originally compiled panel data set for 217 countries and identify a trade-off between classical development goals and CO_2 emissions. These findings are notable because they are based on observations from over 1400 indicator time series covering the period 1980 to 2014. However, while their methodology seems to be well suited to summarize and update the diversity of information provided by comprehensive indicator datasets into composite indices (statistically weighted) for reporting purposes, the authors agree that more appropriate methods are available for any mapping of future transformation pathways: “Finally, we do acknowledge that the SDGs are a future-oriented programme and sustainable development is a long-term process with potentially unforeseen future turns like major technological innovations, for instance, not present in data records. Data analyses show the world as it was in the past and at best at it is in the present, not as it could or will be. (Field-)experimental approaches […] and scenario analysis, thus theoretically informed examinations of various possible scenarios are better suited to test ‘alternative worlds’” (Spaiser et al. 2017, p. 468). This work is continued by Bali Swain and Yang-Wallentin (2020) so as to quantify the individual contributions of the three fundamental dimensions of sustainable development (economic, social and ecological sustainability). For this purpose, indices for mapping the three sustainability dimensions are again determined by factor

[37] Ordinally scaled indicators can only be interpreted according to their underlying rank order. An example of this is given by the cross-impact matrices already mentioned earlier in the text. The numerical values applied for coding any cross-impact matrix can be arbitrarily chosen (covering, for example intervalls from -3 to 3, as well as intervalls from -5 to 5). Therefore, individual numerical values as well as distances between individual cross matrix elements cannot be interpreted in a meaningful way. (A matrix element coded „3“ in a cross-impact matrix does not automatically represent the triple of a „1“-impact element). In contrast, for cardinally scaled indicators, the distances between individual observations can also be interpreted in terms of content. For example, a percentage share of 10% is twice as large as a share of 5%.

[38] Cointegration tests are applied in regression studies to avoid reporting of so-called „spurious regression“ results. From a statistical point of view, this is always necessary when trended indicators are analysed, as the distributional assumptions commonly made for usual test measures of regression results (such as t-statistics) are then no longer valid. The so-called Augmented Dickey Fuller (ADF) test (Dickey and Fuller 1979) is a test approach that was originally developed for the statistical identification of the trend dynamics of individual time series. Applied to regression results, this testing approach can also be applied as a cointegration test.

analyses. Their interaction is then modelled statistically by estimating so-called Structural Equation Models (SEM). The results illustrate that the respective importance of individual sustainability dimensions varies with established development levels across different world regions. In this sense, corresponding calculations may guide the identification of region-specific focal points of applied sustainability policy. See the following note as an example in this regard: “Our results suggest that while all three factors are critical to sustainable development, the developing countries should focus their resources and policies in the short run on economic growth and social development. Resources are limited and SDGs are fraught with trade-offs and inconsistencies. Therefore, strategic policy focus on socio-economic development in the developing countries may be a successful short-run policy to achieve sustainable development. Developed countries' results, however, suggest a greater propensity to achieve sustainable development by focus on the environmental and social factors” (Bali Swain and Yang-Wallentin 2020, p. 105). While strategic policy prioritisation may be facilitated by respective statistical analyses, the elaboration of individual policy measures as well as the assessment of the impact of alternative policy instruments will nevertheless require more detailed information and more in-depth modelling frameworks.

As an evidence for the need of a sufficiently detailed modelling of sustainability developments, reference can also be made to the study by van Zanten and van Tulder (2021). Based on a systematic review of 876 articles focussing on the nexus between economic activities and the SDG, these authors apply chi-square tests to statistically demonstrate apparent variations in the number of synergies and trade-offs between individual economic sectors. Due to the descriptive nature of this study, any direct conclusions for our own project can hardly be inferred. However, we consider it relevant to note that van Zanten and van Tulder (2021) provide statistical evidence confirming that different economic sectors (as defined by the ISIC Rev. 4 classification) may be exposed to markedly different SDG-interactions. Whereas this context has not been explicitly considered in the statistical SDG-interlinkage studies presented so far, Scherer et al. (2018) represent a notable reference from our database in this regard. They provide a scenario study based on the detailed global Multi Region Input-Output Datbase EXIOBASE (https://www.exiobase.eu/index.php/about-exiobase, accessed on January, 30, 2024). For this, they link the structures of the EXIOBASE database to per capita Household Final Consumption Expenditures available for individual income groups from the WORLDBANK. This framework is then applied in static scenario analysis (redistribution of income, increased income levels) to assess impacts on SDG 13 Carbon, SDG 15 Land, and SDG 6 Water. Methodologically, this approach is clearly very similar to the URMOD application in the RESCUE framework. While the number of mapped economic services, products and sectors is somewhat smaller compared to URMOD, it stands out for a much more detailed consistent mapping of global economic structures. The additional account for income structures provides information on interrelationships that were not considered in the URMOD analyses. However, we consider the explicit representation of dynamic developments and interdependencies that arise in transformation processes to be particularly relevant for our study of SDG-interactions. Static analyses of Input-Output tables (whether based on URMOD or EXIOBASE) are generally not suitable for this purpose.

While most statistical analyses of SDG interactions have so far looked at pairwise correlations, it is also possible to look at multidimensional interactions. In this sense, multivariate regression analyses have been carried out, for example, by Kluza et al. (2021). For 25 member countries of the European Union, they analysed the interaction between GHG emissions, further Eurostat SDG-indicators, and potential interlinkages between these SDG-indicators and GHG emissions based on a pooled dataset of national indicator values for observation years 2017 and 2018. Studying SDG interactions in Spain over the years 2000 to 2019, Miguel Ramos and Laurenti

(2020) also extend bivariate correlation analyses by a multivariate regression study of the influence of other indicators on the identified weakest developed target. Both regression studies were performed in an exploratory manner. This means that for an initially chosen dependent variable, a comprehensive set of statistically significant covariates were identified through extensive applications of automated estimation and specification algorithms. Such studies have their merits in that they allow for a focused identification of relevant nexus relationships. However, a further causal interpretation of the identified relationships is not straightforward. In both studies, it was not further examined whether and to what extent the "explanatory" variables are in turn influenced by the chosen dependent variable. Considering only a single selected equation in this way, it cannot be ruled out that important system structures (that could arise from mutual interdependencies) are overlooked. Thus, both studies apply useful procedures for the preliminary identification of relevant SDG-interdependencies for selected Goals or Targets. However, these should then be modelled under explicit consideration of all relevant (sub-)system interdependencies.

For a simplest possible example of a corresponding multi-equation modelling, we can refer to Ranganathan et al. (2017). They specify and estimate two dynamic difference equations to model the nexus between child mortality and per capita gross domestic product. Specifying both equations on an international panel data set for the years 1960 to 2000, they find that the change in child mortality depends (inter alia) on per capita GDP and the change in per capita GDP depends (inter alia) on child mortality. As a key argument for explicitly considering corresponding interdependencies, Ranganathan et al. (2017) point out that by applying their dynamic modelling approach, it is possible to assign individualised and therefore more appropriate target values for individual countries. They point out that this has not always been achieved in the past when setting targets for the MDGs. Bali Swain and Karimu (2020) also estimate interdependent development relationships. In contrast to Ranganathan et al. (2017), they specify Vector Autoregressive (VAR) systems. This is a time-series econometric framework that captures complex development dynamics that evolve over several observation periods. Using a panel data set with observations for the EU28 countries in the period 2000 to 2016, they map the development dynamics between renewable electricity prices and six other selected indicators by means of this methodology. Their choice of indicators is designed to cover the interplay between renewable energy prices and SDGs 7, 8, 9, 12 and 13. Corresponding VAR estimates offer relevant methodological advantages (avoidance of the so-called endogeneity problem, comprehensive options for applying time-series econometric specification and falsification tests, high applicability for short-term forecasting purposes).[39] However, these benefits can usually only be exploited with sample sizes that are often not empirically available for real economic impact analyses.[40] Furthermore, since this is again an exclusively statistical modelling approach, long-term causality relationships can only be depicted if they already marked the analysed past system behaviour. For long-term transformation studies, this will generally not be the case. Therefore, a direct application of VAR modelling approaches cannot be recommended for transformation studies in general. But we recommend applying the estimation and test procedures known from the VAR literature when calibrating alternative simulation models as far as possible.

[39] See, for example, Lütkepohl 2005 for a thorough methodological introduction.

[40] See in this context also the observation that Bali Swain and Karimu 2020 generally failed to specify stable VAR models for mapping individual country interrelationships.

2.4.1.2 Selected findings

Table 8: Distribution of Synergies, Trade-Offs and Ambiguities on Goal-Levels across individual studies

	Total matches	Synergies	Trade-Offs	Ambiguity	Share of Ambiguity in %
SDG 1	20	13	1	6	30.00
SDG 2	40	25	5	10	25.00
SDG 3	9	9	0	0	0.00
SDG 4	15	11	0	4	26.67
SDG 5	6	6	0	0	0.00
SDG 6	116	67	1	48	41.38
SDG 7	44	18	0	26	59.09
SDG 8	14	6	0	8	57.14
SDG 9	7	7	0	0	0.00
SDG 10	11	6	1	4	36.36
SDG 11	14	10	0	4	28.57
SDG 12	24	18	0	6	25.00
SDG 13	16	8	2	6	37.50
SDG 14	197	90	3	104	52.79
SDG 15	8	3	1	4	50.00
SDG 16	1	1	0	0	0.00
SDG 17	0	0	0	0	0.00

Source: Own representation of the contents of (Miola et al. 2019)

Overall, international statistical analyses of SDG interactions reveal more synergies than trade-offs. It is important to note, however, that these relations can vary significantly between individual SDGs. The pairwise rank correlations calculated by Pradhan et al. (2017) show that SDG 3 (Good health and well-being) features the most synergies with other SDGs. In contrast, SDG 12 (Responsible consumption and production) is subject to many trade-offs in relation to other SDGs. For a specific national analysis, these findings are initially not very useful, as individual country developments have been pooled for this illustration. The authors note in their text that Germany, like Finland and Japan, is characterized by an exceptionally high proportion of synergies compared with trade-offs. Overall, however, it must be noted that, for this publication as well as for the subsequently published Cross-Section analyses of Kroll et al. (2019), the very high degree of aggregation in the presentation of results does not allow any direct conclusions regarding the design of the own analyses in the further project.

It is worth noting, however, that the proportion of ambiguous results (marked yellow in the figure) is relatively low. This may be suggestive of methodological advantages of quantitative methods and modelling frameworks compared to qualitative approaches. See also the comprehensive meta-analysis of published interlinkage-assessments (which is based on applications of a wide variety of methods) in Miola et al. (2019) in this regard. As illustrated by Table 8 their comparison of the findings from different SDG interaction studies documents that, when studying identical interactions, different authors often arrive at significantly different assessments. As noted by Miola et al. (2019), most publications analysed by them applied qualitative methodologies which had to rely on subjective judgments. Consequently, “it can be expected that more different authors draw different conclusions that are based on different assumptions and will thus, come to different results for the evaluation” (Miola et al. 2019, p. 17). According to their results, SDGs 1, 2, 3, 5, 9 and 12 are yet marked by a relatively low proportion of ambiguities. Since Miola et al. compare the analysed interactions at the Goal level, it could be assumed that corresponding ambiguities tend to be smaller when analysing individual Targets. However, Miola et al. could not carry out a corresponding analysis as not all respective interaction relationships were already studied at Target levels by the publications considered in their literature review.

2.4.2 Dynamic models for ex ante assessments of SDG-interactions

2.4.2.1 Methodological overview

2.4.2.1.1 Types of models considered

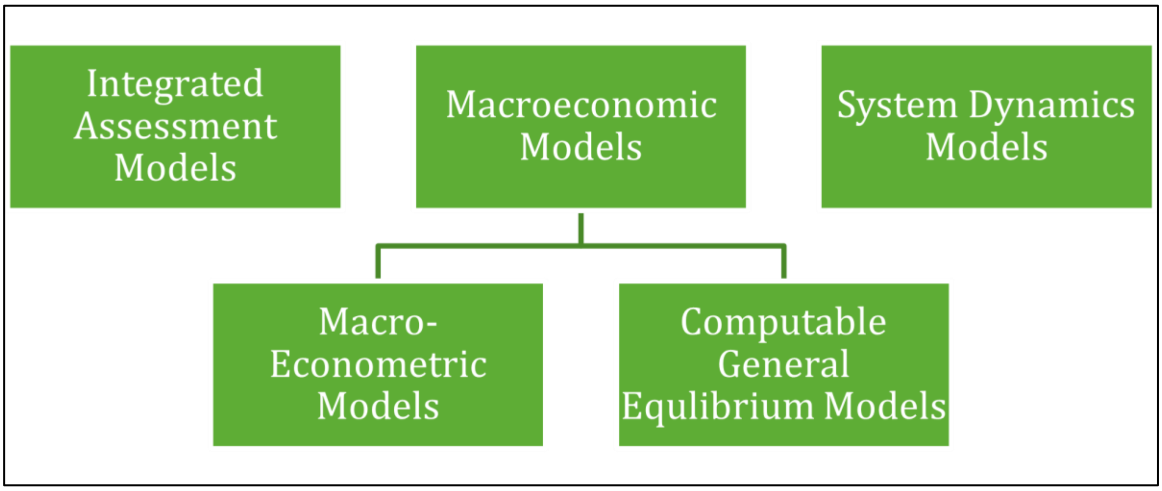
As already discussed in section 2.1.2 of this report, we prefer to subdivide the Dynamic models for SDG-interlinkage analyses in a three-part classification scheme. By the inclusion of IAM, this classification scheme can be understood as a slightly more detailed categorisation of assessment models as that applied by (UNEP 2017). A schematic overview of our classification scheme for Dynamic modelling approaches is provided by Figure 11. Readers interested in broader overviews on currently available ex ante assessment tools are referred to Barbero Vignola et al. (2020) who assess 108 JRC modelling tools on their availabilities for ex ante SDG assessments.

Most recent prominent arguments for the inclusion of an individual IAM category can be taken from the literature review by van Soest et al. (2019). UNEP (2017), reviewing dynamic modelling tools for Macroeconomic assessments of resource policy measures, distinguish between Computable General Equilibrium (CGE) models, Macro-Econometric models, and System Dynamics models. In this report, we group the first two model categories of the UNEP report (CGE models and Macro-Econometric [Input-Output] models) under the term Macroeconomic models. This definition of the class of macromodels corresponds in essential features also to the understanding of Pollitt et al. (2010).

To avoid fundamental ambiguities, we would like to stress that different research groups sometimes apply (almost) identical classification terms to label dissimilar model types. The Input-Output modelling approaches reviewed by Pollitt et al. (2010) are, for example, not of a dynamic nature and were therefore already presented by us in section 2.4.1 (Scherer et al. 2018). According to this classification, the URMOD assessment approach of the RESCUE analyses is also to be classified as static (opposed to dynamic) Input-Output modelling. The models that we classify as Macro-Econometric Input-Output approaches, on the other hand, are characterized by the fact that they are able to project the evolution of mapped economic structures (and accompanying impacts on other sustainability dimensions) autonomously over time. In this respect, they appear (at least at first glance) comparable to CGE models.

There are, indeed, important methodological differences between these two types of models: "Macroeconometric [Input-Output] models have quite different theoretical foundations to CGE models. The equations describing the relationships within the model are estimated econometrically from historical data, which is not normally the case in CGE models, and they do not assume market clearing. This means that base case model outcomes tend not to be economically efficient and to have unemployed resources, meaning that policy and other interventions can improve economic efficiency and lead to increases in output and employment. This mechanism is in addition to the possible increases in output from technological change leading to reduced costs (perhaps through increased resource efficiency), which is the route through which CGE models can show increases in output […]" (UNEP 2017, p. 102).

Figure 11: Own classification scheme for the identified dynamic modelling approaches



Source: Own representation

Some model overviews also distinguish between further types of models. For example, agent-based modelling was also explicitly mentioned by Pollitt et al., but with specific reference to the fact that "... so far, there is no fully specified agent-based representation of the macroeconomy" (Pollitt et al. 2010, p. 48). Since our current literature search did still not reveal key references to agent-based macroeconomic modelling activities deemed relevant in our research context, we do not consider this class of models here explicitly. Additionally, we did not intended to take a closer look at partial sector modelling approaches (another macroeconomic modelling approach explicitly mentioned byPollitt et al. 2010). Finally, we understand the model class of "fully-specified macroeconomic models based on the theories provided by ecological economics" (Pollitt et al. 2010, p. 48) as one of many possible entry points to the development of system dynamics models. However, taking into account also earlier work by Allen et al. (2016), we consider it appropriate to list system dynamics modelling as a separate model class.

2.4.2.1.2 Conceptual outline of the respective model types

2.4.2.1.2.1 Integrated Assessment Models

IAM have been traditionally developed and applied as decision support and information tools for policymakers to design, assess and evaluate climate policy solutions. Corresponding SDG indicators are therefore typically mapped comprehensively by IAM. From a broader nexus perspective (Bleischwitz et al. 2018), it can also be noted that IAMs generally map the water-energy-land use- climate nexus (and associated interactions) well (van Soest et al. 2019). However, minerals and materials are not yet well represented in IAMs (Bleischwitz et al. 2018). A further disaggregation of socio-economic interactions and a better inclusion of social scientists in IAM development and application is also considered to be necessary in future research (van Soest et al. 2019).

IAMs vary in the level of detail, complexity, and interconnections considered (Weyant 2017; Lamperti et al. 2018): some models represent the complete Earth system with a small number of relatively simple equations (e.g. Nordhaus 2014), while others consist of thousands of physical, chemical, biological, and economic equations (e.g. Reilly et al. 2012). The economic part of an IAM is often based on a CGE approach (Balint et al. 2017). An in-depth overview over IAMs including an extensive discussion is given in Mendelsohn (2020) or Weyant (2017).

There are two basic types of global IAMs: **Detailed Process (DP) IAMs and Benefit-Cost (BC) IAMs** (Weyant 2017). DP IAMs are more disaggregated and provide detailed projections regarding climate change impacts at regional and sectoral scales, using both economic units and physical units to represent results. In contrast, BC IAMs aggregate climate change costs and impacts by sector and region into single economic metrics. In general, IAMs are based on a linear cycle consisting of six steps (Ciarli and Savona 2019): (1) Consumption and production cause greenhouse gases (GHG); (2) GHGs accumulate in the atmosphere; (3) This growing stock of GHGs traps heat and results in global warming at a certain rate; (4) Warming leads to climate change; (5) Climate change affects individuals and the environment through a damage function. The exact impacts are complex and difficult to estimate; (6) Inventory and fluxes of greenhouse gases can be reduced at some cost. Costs depend on current and future costs of climate change, current costs to mitigate climate change, and time preferences.

IAMs have been criticized for

- having arbitrarily set damage functions and discount rates (Pindyck 2013; Stern 2013, 2016; Weitzman 2013; Revesz et al. 2014; Farmer et al. 2015; Balint et al. 2017, among others),
- aggregate damage function not distinguishing between different microeconomic impact channels (Lamperti et al. 2020),
- the cost of emission reductions being independent of past emission levels in time (Grubb et al. 2021),
- giving the impression of control and exact results (Ackerman et al. 2009; Pindyck 2013; Stern 2013; Weitzman 2013; Revesz et al. 2014; Farmer et al. 2015, among others),
- paying little attention to the principles of a functioning social system and the behaviours of the actors involved (Mathias et al. 2020),
- the possibility of underestimating both the costs of climate change and the benefits of transitioning to a low-carbon economy (Stern 2016),
- missing feedback loops and neglecting climate policy reflexivity (Balint et al. 2017).

2.4.2.1.2.2 Macroeconomic models

Macro-Econometric Input-Output (IO) models and Computable General Equilibrium (CGE) models are used to analyse the long-term macroeconomic development and the long-term energy-environment-economy interplay (Cambridge Econometrics 2019). Extended and combined with energy and emissions modules these types of models can be applied for an integrated projection, evaluation and assessment of energy, climate and Circular Economy policies. The inclusion of water, food, land and energy in the models facilitates to analyse economy-wide implications of resource-use interlinkages and trends (Bleischwitz et al. 2018, p. 741).

Both model types are characterised by a high level of detail regarding economic sectors, industries, and regions and are based on Input-Output tables illustrating the interdependencies between producing industries and consuming users. They can respond to price changes, account for input and import substitutions, and explicitly deal with supply constraints. They are typically characterised by full coverage of macroeconomic income cycles. Thus, economy-wide rebound effects and resulting non-linearities are explicitly taken into account by respective model simulations.

The fundamental differences between macroeconometric IO models and CGE models stem from their theoretical foundations as well as the derived calibration methods: While CGE models are based on neoclassical theory, Macro-Econometric IO models are based on empirically observed economic impact dynamics (Lehr and Lutz 2020). Whereas traditional CGE approaches are calibrated by fitting theoretical model structures to observed datasets of an individual benchmark year, Macro-Econometric IO models are calibrated against observed historical development patterns over time.

In the CGE models, individual (representative) consumers and firms optimise their behaviour simultaneously in response to price signals subject to market and aggregate equilibria and resource constraints (Rose 2004). Production technologies are usually modelled with constant elasticities of substitution (CES), and household demand behaviour is based on the linear expenditure system (LES) (Faehn et al. 2020). Technological change and behavioural changes in energy are represented with a mixture of endogenously substituted production factors and consumption goods, induced changes in the energy mix, autonomous growth in total factor productivity (TFP), and factor-specific productivity advances (including energy efficiency improvements) (Faehn et al. 2020). CO_2 and other greenhouse gases are usually integrated into the model via fixed ratios to energy coefficients in a reference year (Faehn et al. 2020).

The optimum is achieved by assuming constant returns to scale, full competition in all markets, maximization of social welfare (measured in discounted private wealth), no involuntary unemployment, and exogenous technical progress that follows a constant time trend. As a result of these optimising simulation assumptions, it is also acknowledged by CGE modelers that interactions between environmentally relevant and socio-politically relevant SDGs are typically not covered by traditional CGE approaches: "CGE models are well-suited to assess the performance of economic indicators. Moreover, past modelling literature has highlighted the fact that they are also a powerful tool for assessing the evolution of key environmental indicators […] Modelling social indicators in a CGE framework, however, is a difficult task, especially when these imply dispersion measures such as poverty prevalence and inequality at the core of SDG1 and SDG10" (Campagnolo and Davide 2019, p. 97).

Other weaknesses observed in applications of CGE models concern lacking economic feedback effects in the applied IO modelling approach (Ciarli and Savona 2019): calibrated input coefficients are mostly fixed and cannot change due to changes in the division of labour, e.g. caused by environmentally friendly new technologies. Also, the intermediate input composition mostly changes only as a function of learning-by-doing and technological change and is thus disconnected from changes in GHG emissions of individual industries. This means that, for considering an energy related example, changes in energy efficiency and GHG emissions can only be modelled indirectly. The consumption preferences of different household types are independent of time, saturation and new (more environmentally friendly) goods, so that consumption patterns change solely as a function of income.

In contrast to this, Macro-Econometric IO approaches do not assume a priori that social and economic developments are determined by optimising behavioural patterns. Hence, markets are usually not cleared, supply-demand imbalances occur that are balanced by quantity effects rather than price effects, and there is the possibility of involuntary unemployment in Macro-Econometric models (Kemmler et al. 2020). These effects can be mapped as Macro-Econometric models derive the future evolution of the macroeconomic system from observed dynamics of past socioeconomic interactions. The parameters required to specify the respective behavioural equations are inferred from applications of econometric methods to historical data series. A wide variety of causal effects can be represented by the parametrised behavioural hypotheses. However, usually the Macro-Econometric modelers restrict themselves to an exclusive consideration of variables which can be mapped by means of adequate historical datasets. From the application of appropriate econometric methods, dynamic system properties can be explicitly inferred. Macro-Econometric models are therefore suitable to capture disequilibria, path dependence, lock-ins, multiple equilibria or irreversibility (Hafner et al. 2020). Consequently, the model outcomes of the baseline are not necessarily economically efficient which is why policy measures and interventions can improve the initial economic efficiency increasing output and employment (UNEP 2017, p. 102). While Macro-Econometric models can represent economic and environmental indicators with the same degree of accuracy as CGE-models, they therefore appear to be considerably better suited for the complementary representation of social indicators and related SDG-interlinkages.

The weakness of Macro-Econometric IO models lies in their econometric core: Long and high-quality time series are needed for valid estimation results (Cambridge Econometrics 2019). In addition, further points of criticism are sometimes mentioned in the literature on Macro-Econometric models. In our opinion, however, these can be basically raised against all model simulation approaches: On the one hand, this concerns the fact that in the absence of further specific scenario assumptions, even elaborately calibrated models will only project regular trajectories (Avelino and Dall'erba 2019). The impacts of future extreme or unprecedented events can therefore only be incorporated into the modelled scenarios by a careful setting of the respective boundary conditions for individual model runs. However, the needs for individual parameterisations of scenarios assumptions which would otherwise not be directly mapped within the model are also known from the applications of the remaining model classes.

2.4.2.1.2.3 System dynamics models

A recent summary of the conceptual background of System Dynamics (SD) models can be found (among others) in the model overview by Hafner et al. (2020). Following closely the description given there, essential principles of SD models can be summarised as follows: The basic concept of SD modelling was developed in the 1960s (Forrester 1958). The SD modelling approach is neither rooted in natural science nor social science theories. Rather, it describes a general modelling approach rooted in systems thinking that can be applied in various areas to examine the dynamics of complex systems over time (Hardt and O'Neill 2017). Key features of SD models arise from the application of general principles from engineering and feedback control theory (nonlinear dynamics mapped by differential equations, representation of feedback loops arising from interdependent stock-flow interrelationships). Starting with initial applications in industrial engineering, this modelling approach has been applied in a diverse variety of use cases. (Hafner et al. refer to Sterman 2000 for respective references).

Within the sustainable development context, a pivotal early reference is provided by the Meadows et al. (1972) report. While this publication was intensively criticised, notably for lacking integration of social science (and especially economic) expertise as well as for empirical weaknesses (Vieille Blanchard 2010), it is today regarded as an essential pioneer for establishing computer-based simulation studies as a mean for long-term assessment of societal developments and associated environmental impacts (van Beek et al. 2020). Prominent recent references to applications of system dynamic models for simulation studies of SDG-interactions are, inter alia, given by Collste et al. (2017), Pedercini et al. (2018b), Randers et al. (2019), Pedercini et al. (2020), or Allen et al. (2021).

Compared to IAM and Macroeconomic models, System Dynamics models are often attributed outstanding flexibility in terms of type and scope of the represented system interrelationships. [41] It must be noted, however, that corresponding statements should not be misunderstood as an indication of any technical limitations of IAM or macroeconomic models. From a technical point

[41] See, for example, the following quotations in this regard: „SD model can include any effects or scenarios that experts or case-studies would consider as relevant“ Hafner et al. 2020, p. 8. "System dynamics approaches allow the testing of a novel hypothesis and determination of trade-offs and other impacts. It facilitates understanding of the dynamics of coordination between different factors and relationships between environmental resources" Bleischwitz et al. 2018, p. 741.

of view, both the IAM community and macroeconomic model builders would be perfectly capable of adding additional causal structures and implicit feedback structures to existing model structures, for instance to illustrate the system-wide applications of new socio-economic behavioural hypotheses.[42]

According to our observation, such statements instead merely relate to the fact that system dynamic models are often developed out of group model building processes (Andersen et al. 2007). In this modelling tradition, the conceptualization and representation of relationships between key variables is typically organized by means of so-called Causal Loop Diagrams (CLD). For any chosen system, a CLD may provide a visual representation of its key elements together with their cause-effect interrelationships. Due to the intuitive visual representation of system interrelationships, no quantitative modelling experience is required to create and discuss CLDs. Thus, they represent a frequently applied qualitative method for the implementation of participatory modelling approaches (Voinov et al. 2018). The shift to an applicable quantitative simulation model is then achieved by subsequent numerical parameterizations of the conceptual CLD. In a system dynamic modelling environment, this usually involves transforming the CLD into a stock-flow diagram (SFD). [43] However, the qualitative system representations mapped by a CLD could as well be parametrized by scholars from other modelling traditions in other modelling environments.[44]

We therefore prefer to differentiate the modelling approaches we consider also by the extent to which participatory methods are applied in the model development phase. For this, we refer to Figure 12, which provides a corresponding classification for several qualitative as well as quantitative modelling approaches. On the x-axis, all considered methods are ordered by the degree of participation usually achieved in a given application. The y-axis groups the respective methods in ascending order in terms of their respective degree of formalisation (from qualitative to quantitative approaches).

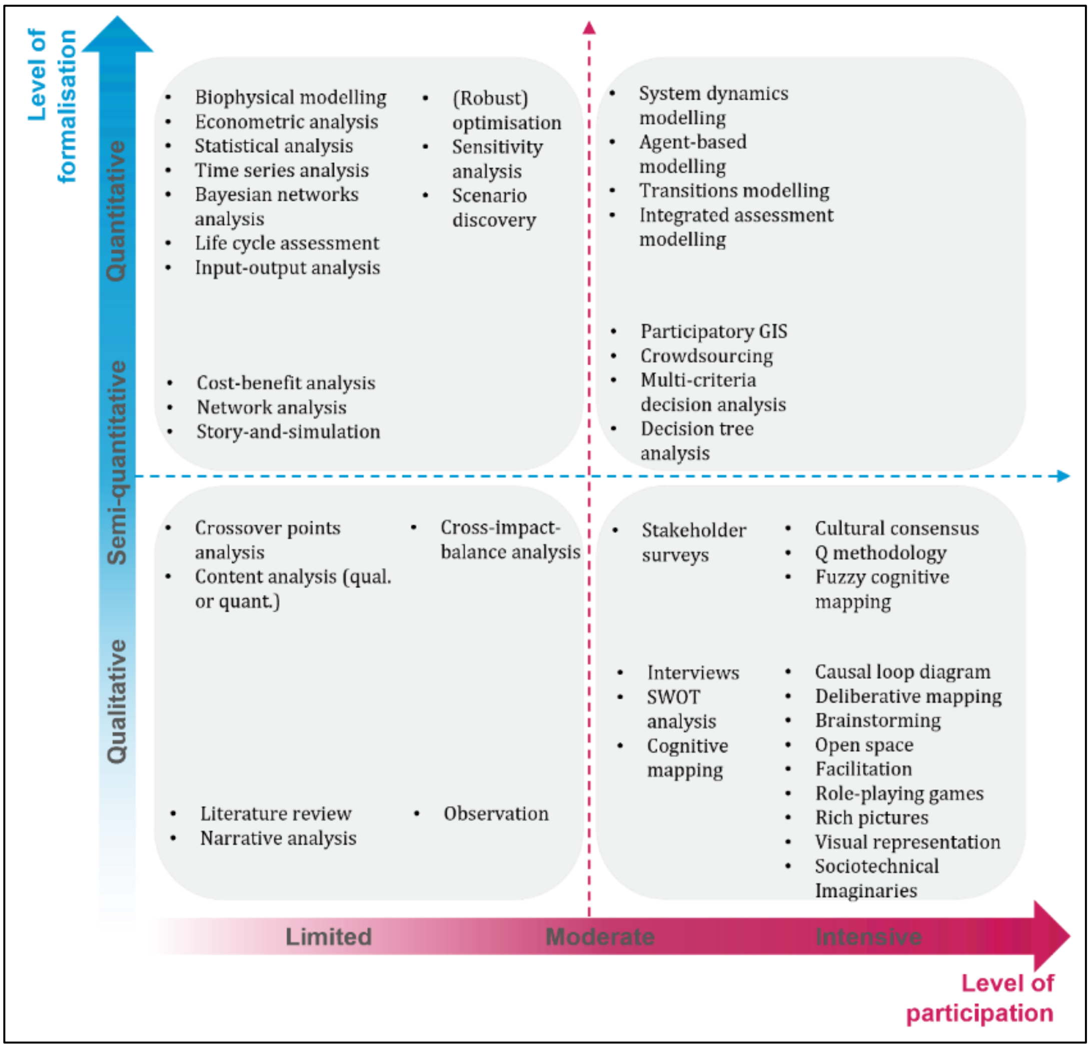
Biophysical modelling, econometric analyses as well as System Dynamic models are arranged as highly formalised quantitative methods in the upper part of the resulting graph. Apparently, both, biophysical modelling and econometric analyses, tend to be characterised by only low participation levels. They usually represent expert systems whose system boundaries and mapped system elements tend to be predetermined by given subject-specific academic knowledge. System dynamics models differ in this respect, as they emerge much more frequently from case specific applications of participatory modelling approaches. However, these conceptual differentiations are clearly of a stylized nature. We therefore emphasise the fact that also within the SD community several development strands have been followed. As a result, some SD models are very much shaped by subject-specific expert knowledge.

[42] Interested readers are referred to Section 1.3 in Hirschnitz-Garbers et al. (2018) for further introductory remarks on these methodological issues.

[43] Following Voinov et al. (2018), we refer to Lane (2008) for a critical review of the role of both diagramming methods (CLD and stock-flow diagrams) in system dynamics.

[44] In the system dynamics community, Stella (https://www.iseesystems.com/) represents a popular visual software environment for model development based on stock-flow representations of the modelled system. Main advantages of this software environment are commonly seen in its excellent suitability also for participatory modelling processes. Nevertheless, there is no question that any simulation model implemented in Stella could be parametrised (at least) just as well in powerful data science programming frameworks like, for example, Matlab (https://de.mathworks.com), Python (https://www.python.org/) or R (https://www.r-project.org/) (all websites retrieved on April 24, 2024)

Figure 12: Participatory modelling methods for co-creating pathways to sustainability



Source: Own representation of the contents of Moallemi et al. (2021)

Finally, we would like to comment on some frequently repeated criticisms which seem to apply to all socioecological macro modelling frameworks. This concerns first of all the robustness of historically observed impact relationships in Long-Term Socio-Economic Simulation studies. See, for example, related comments on Macro-Econometric models in Allen et al. (2016) or Ellen MacArthur Foundation (2015b). Fundamentally, this criticism is true: Human behaviour and resulting social interactions are not governed by any natural laws. They are always subject to the complex interplay of sociocultural norms, individual preferences, and values. Since social development processes are accompanied by a continuous adjustment and balancing of respective influencing factors, any long-term projection of existing development trends will always be subject to a high degree of uncertainty. Therefore, it is necessary to at least reflect very critically on the usefulness of any simulation approach that projects human behaviour over long-term periods (such as centuries) by means of parametrized response patterns.

However, this intrinsic research challenge apparently applies to all sociological modelling attempts. Hence, regardless of whether the economic module of an IAM, a Macro-Econometric IO model, a CGE model, or a socioeconomic system dynamics application is considered, essentially all social science modelling attempts are subject to this criticism. The reason for this lies in the simple fact that, in absence of any certainty about future socio-economic relationships, every computer model somehow has to parameterise respective future behaviour patterns and adaptation reactions. In fact, econometricians would typically comment on this that they devote substantial efforts (unmatched by other modelling approaches) to the reduction of respective uncertainties.

Additional limitations, that are not attributable to individual modelling approaches but to general information deficits, have for example been noted by Aguilar-Hernandez et al. (2021). They rightly conclude that not much is known about public (as well as private) investment required to implement intended transformative interventions. Explicitly named exceptions in this regard refer to Best et al. (2018) and McCarthy et al. (2018). We agree that this addresses relevant knowledge gaps. Future research activities thus must aim at a much better assessment of required direct investment costs (for example through comprehensive involvement of suitable practice partners from industry).

Finally, Aguilar-Hernandez et al. (2021) also note that little is known so far about which policy measures need to be taken today to initiate targeted transformational developments. At least to some degree, we also share this criticism. However, we question whether Macro frameworks can be blamed for this as these modelling approaches have been developed and are first and foremost applied to identify aggregate impact interrelationships and resulting Cross-Sectoral feedback effects. The aggregation level that must be applied in any Dynamic simulation of respective cause-effect relationships is inevitably not comparable with the substantially higher level of detail of complementary sectoral models. Our conclusion is therefore that whenever detailed policy instruments are to be assessed, a coupling of macro frameworks with detailed sectoral models of analysed action areas should be undertaken. Since this usually requires very high development efforts, such simulation approaches have so far been implemented rather scarcely for concrete policy consultancy services.

2.4.2.2 Selected findings

2.4.2.2.1 Overview on identified models, their mapped SDG-interactions and available results

While the previous subsection provided a conceptual presentation of those model types we identified as relevant for dynamic modelling of SDG interactions, this section serves as an exemplary presentation of model applications, which were selected by us based on our full text analyses. In doing so, we do not intend to present all reviewed studies (see Table 9 for a tabular summary of all model applications identified by our review process).

Instead, we intend to highlight relevant available data sources and references to already published simulations of transformation pathways identified by us. This overview can necessarily only be provided on a case-by-case basis and in a relatively condensed form. Therefore, we prefer to provide supplementary references in Table 9. The comprehensive overview of identified model applications listed there is based on respective references provided by Aguilar-Hernandez et al. (2021), van Soest et al. (2019) and UNEP (2017) and may be followed up by interested readers for further methodological considerations. See also Appendix D.1 in Oberpriller et al. (2021) for short introductions to selected IAMs.

Table 9: Overview of model applications identified from the literature review

Model type	Model name	Key reference	Keywords
Macro-economic models	ICES/MEMO/MEWA	Bosello et al. (2016)	
Macro-economic models	E3ME	European Commission et al. (2018), European Commission (2014)	1. Circular Economy; economic consequence; Economic policy; Environmental impact; EU member state; Job creation; Labour market; New type of employment; Professional qualifications; Renewable energy; Report; Sustainable development; Waste management; Waste recycling
Macro-economic models	PANTA RHEI	Distelkamp et al. (2010)	
Macro-economic models	EXIOMOD/LPJmL	Hu et al. (2015)	Resource Economics, Economic impact modelling, Resource efficiency policy, Land use, Water abstraction, Environmental indicators
Macro-economic models	GINFORS/LPJmL	Meyer et al. (2015), Distelkamp and Meyer (2019)	2. Consumption-based accounting; Decoupling; Dynamic assessment model; Economy-energy-environment model; Macro-econometric models; Material and energy use; Material Footprint; Multi-region Input-Output model; Raw material equivalents; Resource efficiency
Macro-economic models	GINFORS3	Meyer et al. (2018)	Climate policy; Environmental systems thinking and modelling; Macro-econometric models; Material Footprint; Multi-region Input-Output model; Policy assessment; Rebound effects; Resource policy; Simulation; transformation
Macro-economic models	GTAP	Lee (2019)	Biohydrogen, Circular Economy, Circularity, Secondary material, Waste management
Macro-economic models	NewERA	Tuladhar et al. (2016)	Circular Economy, Zero waste, Recycling, Sustainability, Energy efficiency, Macroeconomic impact
Macro-economic models	GTEM, GLOBIOM	UNEP (2017)	
Macro-economic models	ENGAGE-material	Winning et al. (2017)	Resource efficiency, Circular Economy, Recycling, Iron and steel, Computable general equilibrium

Model type	Model name	Key reference	Keywords
Macro-economic models	Miscellaneous Various CGE applications	Rutherford and Böhringer (2015), Ellen MacArthur Foundation (2015b), Ellen MacArthur Foundation (2015a), Hatfield-Dodds et al. (2017), Rademaekers et al. (2017), Groothuis (2016)	4. Climate mitigation; Decoupling; Policy analysis; Resource efficiency 6. Consumption tax, Environmental tax, Mining industry, Natural resources, Circular Economy, Tax reform, Tax shift, Tax system, Tax incentive
Macro-economic models	ENV-Linkages CGE model	Château et al. (2014)	Climate change policy; General equilibrium models; Long-term scenarios
Integrated assessment models	GIAM	Schandl et al. (2016)	General equilibrium model, Climate change, Long-term scenarios
Integrated assessment models	AIM-CGE	Fujimori et al. (2017)	AIM; Climate mitigation; Computable General Equilibrium Models; Integrated Assessment Model; Socioeconomic scenarios; SSPs
Integrated assessment models	China TIMES	Chen et al. (2016)	Carbon emission, Carbon price, Reference scenario, Marginal abatement cost, Primary energy consumption
Integrated assessment models	DNE21+	Akimoto et al. (2010)	Climate change; Emission reduction cost; Sectoral approach
Integrated assessment models	GCAM	Calvin et al. (2017)	
Integrated assessment models	GEM-E3	Capros et al. (2014)	PRIMES, GEM-E3, TIMES-PanEu, NEMESIS, WorldScan, Green-X, GAINS
Integrated assessment models	IMAGE	van Vuuren et al. (2017b)	Climate change research; Integrated assessment; Scenarios; Shared socio-economic pathways (SSPs); Sustainable development
Integrated assessment models	IPAC	Jiang et al. (2016)	2°C target; China; Climate change; Investment; Mitigation; Modelling
Integrated assessment models	PRIMES	Capros et al. (2014)	PRIMES, GEM-E3, TIMES-PanEu, NEMESIS, WorldScan, Green-X, GAINS

Model type	Model name	Key reference	Keywords
Integrated assessment models	REMIND-MAgPIE	Kriegler et al. (2017)	Emission scenario; Energy transformation; Integrated assessment modelling; Land-use change; Shared socio-economic pathway; SSP5
Integrated assessment models	MESSAGE- Brazil	Nogueira et al. (2014)	Brazilian energy mix; Carbon capture and storage; CCS; Integrated assessment modeling; Message; Thermal power generation
Integrated assessment models	MESSAGE-GLOBIOM	Fricko et al. (2017)	Adaptation; Climate change; Greenhouse gas emissions; Integrated assessment modeling; Mitigation; Shared socioeconomic pathways; SSP
Integrated assessment models	WITCH	Emmerling et al. (2016)	Integrated assessment model, SSPs, Climate change, Scenarios
System dynamics models	Threshold21 (T21-World) model	UNEP (2011)	

Source: Own representation of findings from the literature review

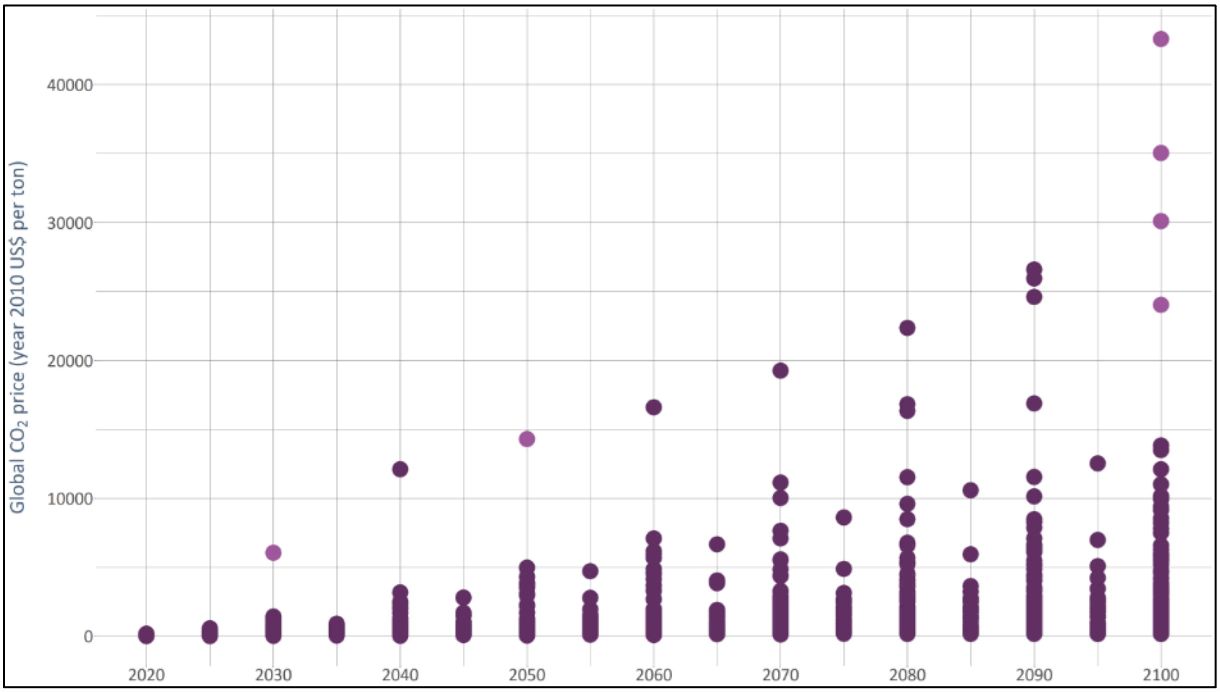
2.4.2.2.2 Integrated Assessment models

An extensive database of simulation results from ambitious climate projections was created by the Integrated Assessment Modelling Consortium (IAMC) during the preparation of the Special Report on Global Warming of 1.5°C (SR15, IPCC 2018). For this, IAM users were invited to provide the results of their available 1.5°C-compatible (and thematically related) scenario simulations in a coordinated process. The systematic compilation and assessment of these result sets was conducted by SR15-authors. The final database is hosted by the International Institute for Applied Systems Analysis (IIASA) and is freely accessible via the internet.[45] This so-called IAMC 1.5°C Scenario Explorer provides access to “more than 400 emissions pathways with underlying socio-economic development, energy system transformations and land use change until the end of the century, submitted by over a dozen research teams from around the world” (Huppmann et al. 2019, accessed on March 2022).

The research project "Models for the analysis of international interrelations of the EU ETS" (UBA FKZ 3718 42 001 0) already provided some funding for an initial evaluation of the information content from IAMC 1.5°C Scenario Explorer Release 1.1 (as of February 2019) by GWS experts. While these analyses focused exclusively on an examination of the role of global CO_2 prices in ambitious climate change simulations (see Figure 13 for a visual representation of the analysed carbon price scenarios), they lend themselves also perfectly as an illustration of the wealth of information provided by the Scenario Explorer database. The following pages therefore present a selected summary of findings from this thematically closely related preliminary work. See Meyer et al. (2021) for a full stand-alone documentation of the analyses on which the findings presented here are based.

[45] https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login?redirect=%2Fworkspaces (retrieved on April 24, 2024)

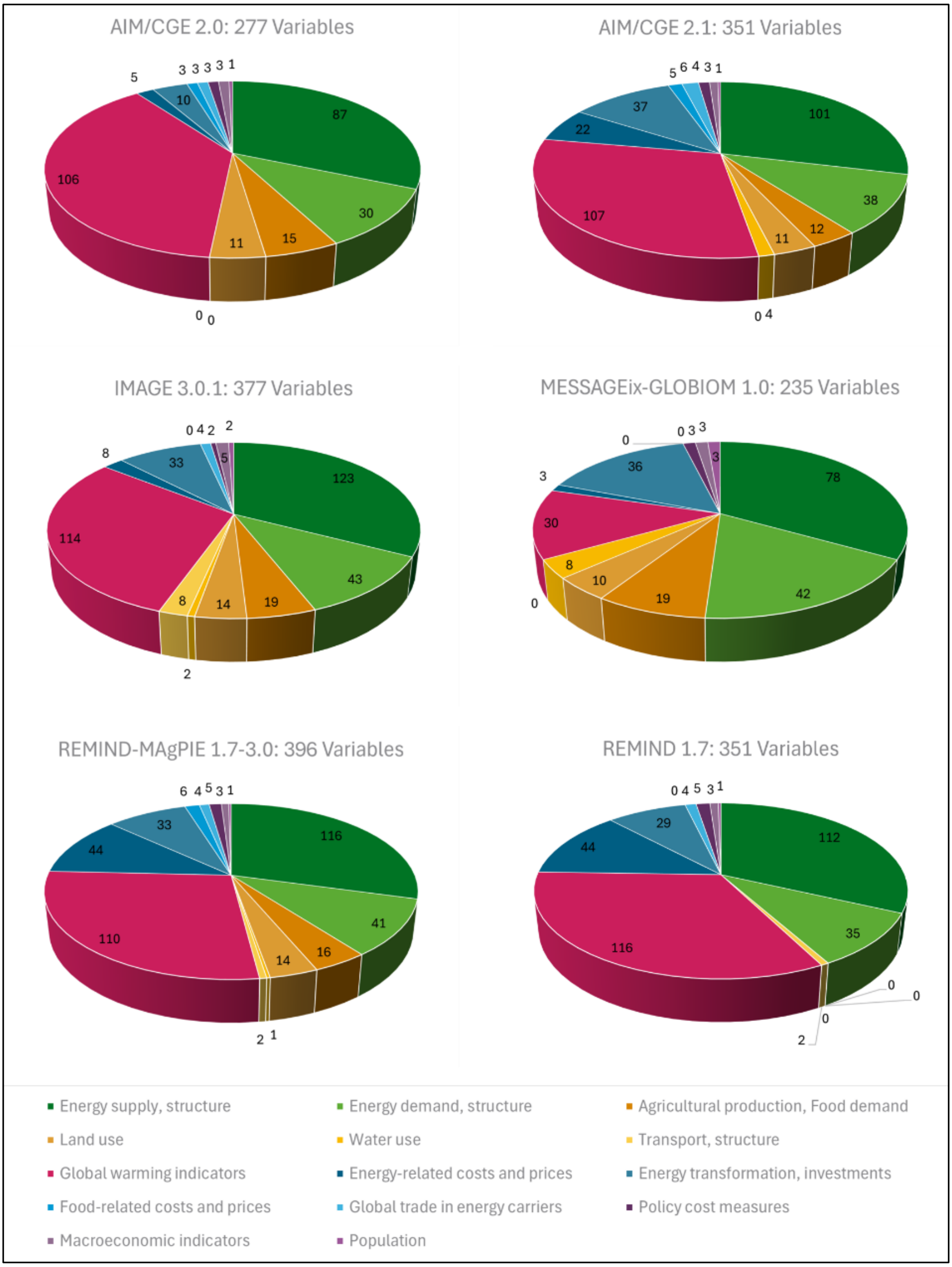
Figure 13: Carbon price simulation results from the Special Report on Global Warming of 1.5°C



Source: Meyer et al. (2021), based on information retrieved from the IAMC 1.5°C Scenario Explorer Release 1.1

Figure 13 shows the global carbon price simulations that have been analysed. As indicated on the y-axis, CO_2 prices are represented in year 2010 US-$. The chronological development of the simulation period is shown on the x-axis. As can be seen, IAMs usually cover a long simulation period (until the end of the century), but do not generate annual time series projections. Instead, most observations are available at 10-year intervals. From this compilation of the various scenario parameterizations for different IAMs, it can also be seen that the respective values of observed variables (in this case, the global CO_2 price) exhibit a widening interval over the simulation period. It should be noted that every simulation run considered in this figure has been characterised as an ambitious climate protection scenario. In this sense, there are no fundamental differences between the respective model results. Consequently, even if individual observations (marked by lighter shaded circles in the figure) may be identified as apparent outliers, it can therefore be stated that a comparison of different transformation pathways will usually not reveal a single prototypical trajectory.

Figure 14: Information content of well-established Integrated Assessment Models



Source: Own summary of the analyses documented in Meyer et al. (2021)

Figure 14 illustrates that, whereas the scope of mapped causalities does of course differ between individual IAMs, they tend to report primarily on physical developments: For those models analysed by Meyer et al. (2021) which feature the most comprehensive reporting scopes, this overview illustrates the thematic areas covered by the individual models. In the individual pie charts, the total amounts of energy related physical model variables (like, for example, primary energy supply or final energy demand by individual energy carriers) reported by the selected models have been coloured green. The resulting diagrams clearly indicate that this sector is modelled extensively by all analysed models. The coverage of additional biophysical developments has been coloured in brown and yellow in the individual pie charts. Total amounts of respective model variables (involving, inter alia, agricultural production and demand in tons, cropland areas in hectares, water consumption in cubic meters, or railway transportation services in person kilometres per year) have been categorized for the agriculture sector, land use, water use and transport services. A comparison across the resulting pie charts clearly shows noticeable differences in respective reporting scopes. While the Message-Globiom modelling system stands out here, it can be observed for all remaining models shown here that - alongside the already mentioned extensive coverage of the energy sector - comprehensive reporting on emissions and resulting radiative forcing levels represents a common model feature. Respective amounts of reported model variables have been coloured in red.

Overall, it can generally be stated for all models analysed here that more than ¾ of all modelled variables report about biophysical developments. Economic developments are also mapped, but to a much lesser extent. Moreover, the modelling of economic developments tends to be highly focused on the energy sector (areas coloured in darker blue). But the reporting on other macroeconomic variables (such as subsidies, value added or consumption) proves to be extremely underdeveloped. In this sense, remaining coloured areas exemplify the weaknesses of IAM in the depiction of socio-economic interrelationships, as introduced earlier in this report.

2.4.2.2.3 Macroeconomic models

Comprehensive macroeconomic models feature an entire integration of internationally harmonized accounting systems for economy-wide expenditure flows in a dynamic simulation environment. This enables researchers to quantify prospective developments of the mapped socio-economic variables under systemic consideration of economy-wide causal feedback effects. As shown in the following pages, respective modelling approaches can represent economic impact relationships with an extraordinary level of detail by incorporating the information sets of empirical Input Output Tables.

Our selection of references to Macroeconomic models to be presented here is based on the findings from the meta-analysis documented in Aguilar-Hernandez et al. (2021). These authors reviewed over 300 Circular Economy scenarios for the period 2020 to 2050 in terms of their impacts on GDP, employment, and CO_2 emissions. The indicators were selected by them to represent the three main dimensions of sustainability (macroeconomic, social, and environmental impacts). Based on a correlation analysis of the available scenario quantifications for these indicators they conclude that the macroeconomic diffusion of Circular Economy principles can lead to win-win-win situations in terms of GDP, employment, and emissions developments. Concerning the variety of projection methods applied in the analysed studies, they conclude as follows: "This modelling can be improved by incorporating public investments and rebound effects in the analysis. Moreover, in order to support decision making, we find it relevant to consider a normative approach on circularity assessments, i.e., to identify key measures in the present that contribute to a more cost-effective circularity transition.[…] Furthermore, we suggest that studies focusing on a single country or region may miss trade-offs on the global scale and may hence suggest win-win effects that may exist on the national or regional scale, but are absent on the global scale. Thus, we suggest that future studies should include such trade-offs between regions and countries, which implies that they must consider the global scale and present region- or country specific advantages and disadvantages of the implementation of circularity interventions" (Aguilar-Hernandez et al. 2021, p. 10).

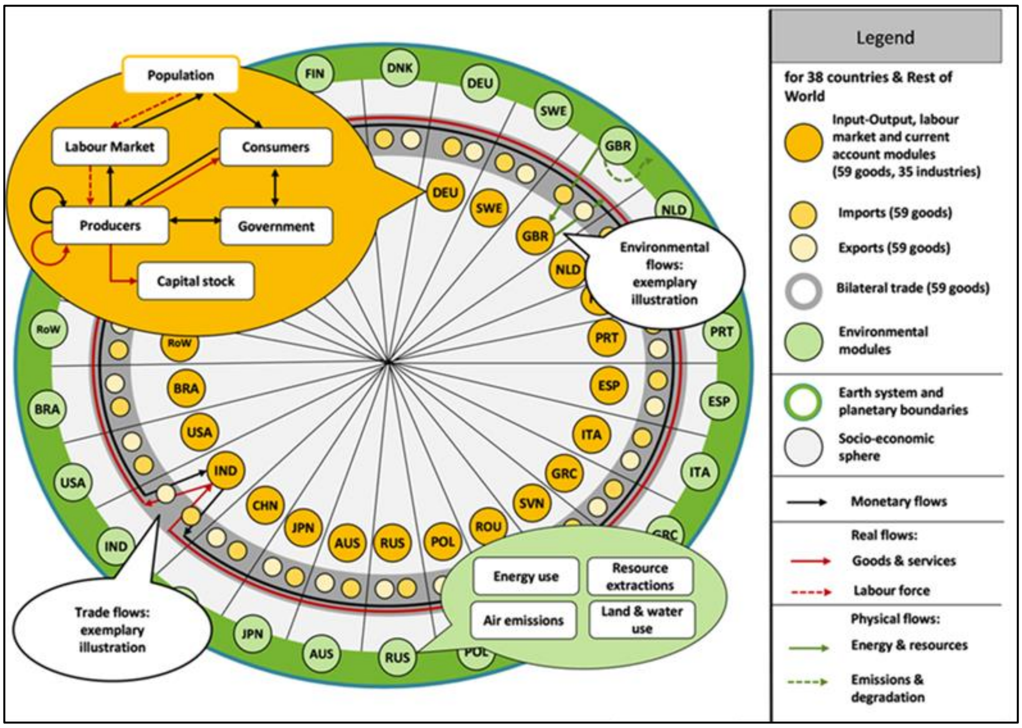
Interestingly, only two of the ambitious scenarios which they analysed were also able to report employment impacts for periods after 2030. These are, on the one hand, a CGE-based study by the Ellen MacArthur Foundation (2015a) and, on the other, the macro-econometric IO simulation results reported by Meyer et al. (2015). The Ellen MacArthur Foundation (2015a) provides insights from a piloting modelling study on the potentials of six case study applications to the Danish economy. They apply a global Multi-Region CGE model from the NERA Economic consultancy (NewERA). Besides the Danish economy, all other economies are aggregated to four major world regions (rest of Europe, China, oil-exporting countries, rest of the world). The model maps 21 economic sectors for Denmark and 17 economic models for the remaining world regions. The studied projection period ranges from 2015 to 2035. Quantified scenario results are provided in a 5-year frequency. Meyer et al. (2015) apply $GINFORS_3$, a global Multi-Region Macro-Econometric IO developed and maintained by project partner GWS. Their applied model version jointly maps 38 national economies together with an aggregated "Rest of World" region. For each modelled world region (the 38 national economies as well as the "Rest of World" region), 35 industry sectors and 59 product and service groups are mapped. As the model is time series based, all scenario results generated by the model are also given as annual time series up to the year 2050. Given that the GWS-staff involved in our research team can fall back to an exceptional expertise from the development and application of the GINFORS model, we revisit here the previously cited methodological conclusions of Aguilar-Hernandez et al. (2021) with an exclusive view on this Macroeconomic IO model.

Introduction to $GINFORS_3$

Two pillars were essential for the development of the model $GINFORS_3$ as a multi-national macro-econometric IO simulation model with outstanding capabilities in the modelling of circularity interventions:

- In 2012 the World Input-Output Database (WIOD) was launched, a milestone regarding the availability of data that shows – on a time series base – the interconnectedness of industries on a national and international scale as well as environmental accounts (energy use, CO_2 emissions, material use, land use, water use) on a sector base.
- The research questions stemming from the EU funded project: 'Policy options for a resource efficient economy (POLFREE)' led by Paul Ekins (University College London). In its responsibility for the 'Scenarios and modelling of policy implementation for resource efficiency' work package, the GWS designed and parametrised $GINFORS_3$ as an integrated dynamic modeling framework for quantitative assessments of the interplay between socio-economic development, material flows, transformative societal changes and environmental impacts.

Figure 15: Conceptual framework of $GINFORS_3$



Source: Own representation

During the POLFREE project three scenarios have been established: A 'global cooperation' scenario, in which all countries co-operate through international agreements and harmonized economic and regulatory policy instruments to pursue decarbonisation and a resource-efficient global economy. A 'EU goes ahead' scenario, in which the EU countries act as forerunners and the rest of the world fails to increase ambition. And a 'Civil society leads' scenario in which voluntary changes in preferences and behaviour are the main drivers of the transformation towards resource-efficiency and decarbonization. All three scenarios (and a 'business-as-usual' scenario) parametrizations were elaborated to figure out the direct impacts of extensive policy packages (and changed attitudes).

To conduct the simulation experiments the environmentally extended economic model, GINFORS was soft-linked with the bio-physical model LPJmL ("Lund-Potsdam-Jena managed Land") by PIK Institute. A more focused documentation of the just mentioned Meyer et al. (2015) GINFORS simulations has also been published by Distelkamp and Meyer (2019). In subsequent projects, the GWS-model GINFORS was also applied on behalf of the UBA for the simulation of resource and climate policy relevant indicators (Meyer et al. 2018; Distelkamp and Meyer 2018). For the following self-contained conceptual introduction to the GINFORS model, we draw on corresponding presentations in Meyer et al. (2018).

$GINFORS_3$ is based on a deep mapping of country and sector structures. These structures depict mutual international as well as inter-sectoral economic interdependencies by means of a bottom-up approach. This means that projections for macroeconomic indicators (such as GDP) are consistently derived from dynamic mappings of their constitutive parts (such as private household expenditure, government spending, gross fixed capital formation and exports and imports). Hence, at the core of the $GINFORS_3$ model lies an economic module. It encompasses 35 industries with 59 products groups in 38 national economies (including the EU-27 and BRICS countries as well as an overwhelming majority of OECD member states) and a Rest of World (RoW) region.

Table 10: Regional coverage of the simulation model GINFORS3

n	Country or Region	Code	n	Country or Region	Code
1	Austria	AUT	21	Hungary	HUN
2	Belgium	BEL	22	Latvia	LVA
3	Cyprus	CYP	23	Lithuania	LTU
4	Estonia	EST	24	Poland	POL
5	Finland	FIN	25	Romania	ROU
6	France	FRA	26	Sweden	SWE
7	Germany	DEU	27	United Kingdom	GBR
8	Greece	GRC	28	Russia	RUS
9	Ireland	IRL	29	Turkey	TUR
10	Italy	ITA	30	Brazil	BRA
11	Luxembourg	LUX	31	Canada	CAN
12	Malta	MLT	32	Mexico	MEX
13	Netherlands	NLD	33	United States	USA
14	Portugal	PRT	34	China	CHN
15	Slovak Republic	SVK	35	India	IND
16	Slovenia	SVN	36	Japan	JPN
17	Spain	ESP	37	Korea	KOR
18	Bulgaria	BGR	38	Australia	AUS
19	Czech Republic	CZE	39	Rest of World	ROW
20	Denmark	DNK	40	Total World	

Source: Own representation

A full list of the geographical coverage is given in Table 10. Industry and product classification details are given in Table 11 and Table 12.

Table 11: Classification of industries in $GINFORS_3$

n	NACE	Label	n	NACE	Label
1	A to B	Agriculture, Hunting, Forestry and Fishing	**19**	50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles
2	C	Mining and Quarrying	**20**	51	Wholes. Trade and Commission Trade, except Motor Vehicles
3	15 to 16	Food, Beverages and Tobacco	**21**	52	Retail Trade, except of Motor Vehicles and Motorcycles
4	17 to 18	Textiles and Textile Products	**22**	H	Hotels and Restaurants
5	19	Leather, Leather and Footwear	**23**	60	Inland Transport
6	20	Wood and Products of Wood and Cork	**24**	61	Water Transport
7	21 to 22	Pulp, Paper, Paper , Printing and Publishing	**25**	62	Air Transport
8	23	Coke, Refined Petroleum and Nuclear Fuel	**26**	63	Other Supporting and Aux. Transp. Activities; Travel Agencies …
9	24	Chemicals and Chemical Products	**27**	64	Post and Telecommunications
10	25	Rubber and Plastics	**28**	J	Financial Intermediation
11	26	Other Non-Metallic Mineral	**29**	70	Real Estate Activities
12	27 to 28	Basic Metals and Fabricated Metal	**30**	71 to 74	Renting of Machines and Equipment and Other Business Activities
13	29	Machinery, n.e.c.	**31**	L	Public Admin and Defence; Compulsory Social Security
14	30 to 33	Electrical and Optical Equipment	**32**	M	Education
15	34 to 35	Transport Equipment	**33**	N	Health and Social Work
16	36 to 37	Manufacturing, n.e.c.; Recycling	**34**	O	Other Community, Social and Personal Services
17	E	Electricity, Gas and Water Supply	**35**	P	Private Households with Employed Persons
18	F	Construction			

Source: Own representation

Table 12: Classification of products and services in GINFORS3

n	sec	label	n
1	Products of agriculture, hunting and related services	31	Secondary raw materials
2	Products of forestry, logging and related services	32	Electrical energy, gas, steam and hot water
3	Fish and other fishing products; services incidental of fishing	33	Collected and purified water, distribution services of water
4	Coal and lignite; peat	34	Construction work
5	Crude petroleum and natural gas; services incidental to oil and gas extraction excluding surveying	35	Trade, maintenance and repair services of motor vehicles and motorcycles; retail sale of automotive fuel
6	Uranium and thorium ores	36	Wholesale trade and commission trade services, except of motor vehicles and motorcycles
7	Metal ores	37	Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods
8	Other mining and quarrying products	38	Hotel and restaurant services
9	Food products and beverages	39	Land transport; transport via pipeline services
10	Tobacco products	40	Water transport services
11	Textiles	41	Air transport services
12	Wearing apparel; furs	42	Supporting and auxiliary transport services; travel agency services
13	Leather and leather products	43	Post and telecommunication services
14	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials	44	Financial intermediation services, except insurance and pension funding services
15	Pulp, paper and paper products	45	Insurance and pension funding services, except compulsory social security services

n	sec	label	n
16	Printed matter and recorded media	46	Services auxiliary to financial intermediation
17	Coke, refined petroleum products and nuclear fuels	47	Real estate services
18	Chemicals, chemical products and man-made fibres	48	Renting services of machinery and equipment without operator and of personal and household goods
19	Rubber and plastic products	49	Computer and related services
20	Other non-metallic mineral products	50	Research and development services
21	Basic metals	51	Other business services
22	Fabricated metal products, except machinery and equipment	52	Public administration and defence services; compulsory social security services
23	Machinery and equipment n.e.c.	53	Education services
24	Office machinery and computers	54	Health and social work services
25	Electrical machinery and apparatus n.e.c.	55	Sewage and refuse disposal services, sanitation and similar services
26	Radio, television and communication equipment and apparatus	56	Membership organisation services n.e.c.
27	Medical, precision and optical instruments, watches and clocks	57	Recreational, cultural and sporting services
28	Motor vehicles, trailers and semi-trailers	58	Other services
29	Other transport equipment	59	Private households with employed persons
30	Furniture; other manufactured goods n.e.c.		

Source: Own representation

Overall, the following economic interrelationships are (inter alia) mapped by the model:

1. production, basic prices, intermediate demand and value added;
2. international supply chains (bilateral trade matrices; the grey circle in Figure 15);
3. final demand (consumption expenditures by households and non-profit organisations, government spending and gross fixed capital formation by industries); and
4. labour markets (labour demand, wages, (un-)employment).

For each economy modelled, all relevant monetary flows are completely integrated on the macroeconomic scale. The economic activities on the demand and supply side are consistently inter-linked with Approved Statistical Accounting schemes capturing the generation, distribution and use of income for individual transactors (e.g., private households and government).

The environmental extensions comprise an Energy module and resource modules. The Energy model simulates endogenously the energy demand (differentiated for 20 energy carriers) of different industries and private households as well as the evolution of the energy carrier mix in electricity production with regards to central scenario parameters (nuclear energy and total share of renewables) and individual shares for specific renewable technologies and fossil energy carriers. Thus, the Energy module captures resulting CO_2 emissions.

The resource module encompasses different kinds of resource extraction (abiotic and biotic materials) as well as land and water use. $GINFORS_3$ is thus able to explain and project the evolution of

1. used and unused extractions of abiotic resources; thereby allowing the calculation of
2. sophisticated environmental indicators (such as raw material consumption RMC and raw material input RMI that identify/consider the environmental impacts of domestic activities along the diversified international supply chains);
3. demand and supply/production for 13 different crop groups and 3 different live-stock categories and the resulting impacts on prices and agricultural land use; and
4. water abstraction for 38 national economies and a RoW region.

Notably for assessments of global raw material requirements, the model facilitates essential insights into the MF of nations. Within this total modelling framework for global macroeconomic interrelationships, physical material extraction activities are consistently derived from economic projections for respective extraction industries. Therefore, due to its detailed mapping of multi-national supply chains, it is ensured that in any simulation of individual economic impulses (e.g., a regional efficiency increase in the use of basic metals in car manufacturing) all globally induced responses in regional raw material ex-traction activities are endogenously projected by the model. The simulated variations in regional extraction activities can then be communicated by applications of individual indicator concepts. For this purpose, $GINFORS_3$ has been augmented by algorithms, which facilitate an application of well-established RME accounting routines. Material footprint indicators like RMI and RMC can therefore be reported from historical analyses as well as from own ex-ante scenario projections.

Referring back to the conclusions of Aguilar-Hernandez et al. (2021) from their meta-study of the macroeconomic, social and environmental impacts of Circular Economy scenarios, it is important to note that the $GINFORS_3$ model proves remarkably powerful in light of their noted limitations of other previous studies: Whereas the majority of studies included in their meta-analysis focused on a single economy only, any $GINFORS_3$ scenario study does always reflect the impacts of national transformations on other world regions. Hence, trade-offs between world regions can be uncovered.

Furthermore, given the dynamic nature of the applied modelling framework, economic rebound effects (like savings from a more resource efficient and Circular Economy resulting in additional consumer spending) are always taken into account. Given these specific model characteristics, the $GINFORS_3$ model would generally also be very well suited for applications in this project.

However, while many (at least socio-economic) SDG impact relationships are already implicitly captured by this model, an explicit representation of official SDG indicators has not been a development goal of the GINFORS model so far.

2.4.2.2.4 System dynamics models

In 1972, a team at MIT developed the first global system model that connected economic development to social and environmental aspects (Meadows et al. 1972). The World3 model encompassed five main modules, namely: Population, Capital Investments, Natural Resources, Agriculture and Pollution. The model provided the basis for the famous and often criticized Limits to Growth (LtG) report by the Club of Rome (Meadows et al. 1972) which analysed the causes of five major trends of global concern at the time (i.e. accelerating industrialization, rapid population growth, widespread malnutrition, depletion of non-renewable resources, and a deteriorating environment).

Despite the model being developed more than 50 years ago, when computing power was nowhere close to where it is today, insights generated through the scenarios modelled with World3 and presented in the first LtG report are still interesting today and especially for this project as it included a resource and pollution module that were linked and connected to the complex socio-economic dynamics of the other socio-economic modules. The most prominently cited but not the only scenario of the LtG report is the business as usual (BAU) one. In this scenario, food, industrial output, and population grow exponentially until the rapidly diminishing resource base forces a slowdown in industrial growth. After natural delays in the system, population growth is finally halted by rise in death rate due to decreased food and health services. The second scenario that is relevant in the context of this project is the scenario in which the resource base was doubled. In this scenario, pollution exceeds absorption mechanism and rises very rapidly, causing an immediate increase in the death rate and a decline in food production. At the end of the run resources are severely depleted despite the doubled amount initially available. It is important to mention that the authors never intended to provide (precise) predictions but rather wanted to explore how different key variables within the modules would develop if the interrelations between them are accounted for. Some argue the data shows that we are currently following the path of the BAU scenario (see Turner (2014).

Since then, several SD models focusing on various issues of sustainable development have been developed. Another global model that has not been part of the reviewed literature but was developed at MIT like World3 and is particularly focused on climate futures on the global level is En-Roads (Climate Interactive 2020). It explores interrelations between the energy and the climate system on an aggregated level. The model allows simulating different scenarios to explore how taxes, subsidies, economic growth, energy efficiency, technological innovation, carbon pricing, fuel mix and other factors affect global carbon emissions and temperature. Therefore, it is possible to investigate synergies and trade-offs between policies.

The models identified and considered in the literature review include among others the MEDEAS model that has “the following relevant characteristics: representation of biophysical constraints to energy availability; modeling of the mineral and energy investments for the energy transition, allowing a dynamic assessment of the potential mineral scarcities and computation of the net energy available to society; consistent representation of climate change damages with climate assessments by natural scientists; integration of detailed sectoral economic structure (Input–Output analysis) within a system dynamics approach; energy shifts driven by physical scarcity; and a rich set of socioeconomic and environmental impact indicators" (Capellán-Pérez et al. 2020). Although the findings of their integrated SD analysis did not lead to findings that depicted a positive picture of the future, they believe this can help to define more sustainable pathways for the future.

Jackson and Victor (2020) present a SD stock-flow consistent macroeconomic model for Canada, in which they investigated potential future scenarios of the Canadian economy until 2067. The three scenarios were "a Base Case Scenario in which current trends and relationships are projected into the future, a Carbon Reduction Scenario in which measures are introduced specifically designed to reduce Canada's carbon emissions, and a Sustainable Prosperity Scenario, which incorporates additional measures to improve environmental, social and financial conditions across society." The last scenario is especially interesting as it showed that sustainable prosperity could be maintained despite the growth rate going to zero.

A more or less direct descendent of the World3 model, which was also identified during the literature review, was the Threshold21 (T21) model developed by the Millennium Institute. This national SD simulation model was originally built to aid integrated policy planning for achieving the Millennium Development Goals (MDGs) on a national level (Pedercini 2011). Hence, in its original version, it did not have an elaborated climate module, but it included a GHG emission module connected to the technological, energy and production sectors and was more focused on the social and economic aspects of development (Spittler et al. 2019). From this, the iSDG model, which was also one of the identified models in the literature review, was developed. The model captures interactions among the SDGs and their sub-targets (Allen et al. 2019b, 2021). Due to the model originating from the T21 model, so far it was mostly applied in the context of low-income countries (Collste et al. 2017; Pedercini et al. 2019; Allen et al. 2020) but is increasingly applied in high-income countries as well (Allen et al. 2019b). Hence, the iSDGs structure relies on profound and robust previous SD model structures that have by now been improved over several decades. The model and its relevant characteristics for this study are described in more detail in section 3 of this report.

Apart from the literature on the iSDG and Zelinka and Amadei (2019), none of the considered studies focused explicitly on modelling the SDGs. Only one study that was considered for the full text analysis applied a qualitative SD method to map the SDGs: Ferri and Sedehi (2018) depicted the multilayered relationships among the SDGs by drawing Causal Loop Diagrams (CLDs) of them. In their conclusion they suggest adding three more goals (i.e. sustainable growth of the population, sustainable migration, and sustainable security in all its forms) to enable quantitative analysis and building a full SD computer simulation model.

2.4.3 Conclusions from the literature review

The systematic literature review presented in this chapter examined the work done to date on identifying SDG interactions as well as available models which can be applied for assessments of benefits, trade-offs and synergies between SDGs. Particular attention was paid to Macro Framework models, which target climate and/or resource policies. At the end of a three-step screening process, 40 contributions were selected for full text analysis out of the 1701 database entries scoped for the review.

We found that most studies identified synergies rather than trade-offs between SDGs, but also that what counts as synergy or trade-off depends on national contexts. Cross-Impact matrices and network analysis based on first and second order interaction between SDGs did not emerge as suitable tools for a dynamics assessment of SDG interactions. Instead, we identified three types of relevant models, which provide more complex and dynamic results: integrated Assessment models (IAMs), Macroeconomic models and System Dynamics models.

IAMs mostly dealt with climate action policy, while showing a rudimentary mapping of the socioeconomic dimensions. Major criticism of IAMs include missing feedback loops and not integrating a functioning social system or an insufficient consideration account of human behaviour. Environmental Macroeconomic models feature a very detailed mapping of economic dimensions. Their theoretical model structures are carefully calibrated to provide coherent representations of historical statistical data sets from official national accounts statistics and to project these data sets into the future. The so achieved depth of detail in the depiction of socio-economic interdependencies is, however, accompanied by a fading out of biophysical interdependencies. As a subset of Macroeconomic models, the dynamics captured by General Equilibrium models (CGEs) are determined by neoclassical theory. Macro-econometric Input-Output models, another subset of Macroeconomic models, do not draw exclusively on theoretical considerations when projecting future dynamics of the socioeconomic system. Instead, empirically observed economic dynamics, quantified, and evaluated by applications of Econometric methods, are explicitly considered by the parametrised causalities. For a reliable mapping and assessment of the interactions between SDGs (which have been shown to vary significantly between different societies), macro-econometric IO models therefore appear more adequate than CGEs. However, it is ultimately an empirical question to what extent these advantages can be exploited. If no sufficient empirical observations are available for model calibration, the dynamics mapped by macro-econometric models will also be governed by theoretically derived specifications.

Finally, System Dynamics models emerged from our analysis as well-established tools to assess SDG interactions. Their flexibility in terms of type and scope of the represented system interrelationships, their case specific applications and involved opportunities for applications of participatory modelling approaches mark advantages of SD models that are frequently mentioned in the scientific literature. Based on the generic insight that any system under analysis needs to be analyzed as a system, SD approaches can be generally characterized by their fundamental consideration of complex long-term interdependencies between various stock and flow variables. The four key elements that are of particular relevance is this regard (feedback, accumulation, delay and non-linearity) will be discussed in the following.

In SD feedbacks can be understood as links between variables and if the connections are circular rather than linear (e.g. variable A causing an effect in variable B, which again impacts A), it is called a feedback loop. This is especially relevant when looking at a problem from a system perspective, because one variable can affect several other variables and at the same time be affected by several other variables. Feedback loops can either lead to a balancing (i.e. oscillating, goal seeking) or reinforcing (i.e. growth or decay) behavior over time. In fact, many reinforcing feedbacks exist within the climate system. For example, the warmer it gets, the more the permafrost melts, which releases more CO_2 and again leads to higher temperatures, which again leads to additional melting of permafrost etc. In social systems feedbacks also exist. However, in applied modelling studies these can be easily missed due to neglected mappings of relevant system dynamics or an incomplete consideration of relevant interactions between respective subsystems. Rebound effects, i.e. social developments in which initial technical efficiency gains are offset by economy-wide cost and income effects, mark prominent examples for respective social feedback processes. To illustrate just one example in this regard, we may consider the case of an assumed technical efficiency gain in rail traffic. Retaining all other framework assumptions constant, this initial effect will directly reduce the overall energy demand for train services. However, as soon as it is considered that higher efficiency leads to lower cost per km which encourages people to make use of train services more frequently and to travel longer distances by train, the initial energy saving effects diminish. This may even lead to a situation where, compared to the initial situation, respective behavioral responses ultimately induce a higher energy demand. Considering social feedbacks as an essential component of macrosystem therefore enables researchers to map the implied system's dynamics more thoroughly.

This insight is of course also shared by economists. Appropriate dynamic economic modelling will therefore always be characterized by an inclusion of relevant rebound effects. However, while SD analyses are virtually geared towards mapping corresponding feedback relationships from the outset, not every economic modelling approach actually does facilitate an appropriate mapping of respective feedbacks. Accounting for feedbacks and resulting feedback loops leads to non-linear behavior of system simulations.

In any computational model, the relationships between the modelled variables are parametrised as equations. As SD places great emphasis on the simultaneous mapping of stocks and flows, differential equations will usually represent the elementary mathematic building blocks of SD models. This matters as stocks can set limits to the system as well as they cause delays in the system, which again leads to non-linear behavior. The simulated effects of an action present today may therefore impact even rather distant future projections, like it is the case with many educational interventions.

Hence, SD offers an approach for understanding the structure of a system, which is necessary if we want to understand synergies and trade-offs between targets rather than just univariate effects of interventions from individual impact variables on one selected target variable. Simulation results are also often visually represented by depicting stocks, flows and feedbacks. This makes it easier for stakeholders to understand the general structure of the model/system without in depth knowledge of the underlying mathematical parameters. An important aspect of SD modelling is the graphic nature of the models, as this does not only make model structure transparent from a visual perspective, but also allows non-modelers to more easily engage with and understand the model and the interlinkages between the different environmental, social and economic elements.

In terms of our research interests, it was especially appealing to see that many references stress the ability of system dynamics models to assess biophysical, economic and social interactions related to sustainable development simultaneously. In particular, the iSDG model – a successor of the T-21 model – was identified as most frequently applied dynamic model for national level SDG interaction analysis and policy support. As respective assessments had already been carried out by applying iSDG in both developing and industrialised countries, we therefore decided to parameterise this model for Germany and test its suitability for mapping German SDG developments in ex ante transformation studies. The preparatory adjustments to the original iSDG assessment framework required for this modelling case study are summarised in the following section. The simulation results from our applications of the adapted assessment framework for Germany will then be presented in Chapter 4.

3 Applied assessment framework

3.1 Fundamentals of the general iSDG assessment framework

The iSDG assessment approach is based on a methodical platform that allows for the integrated recording of SDG interactions within a country and has already been extensively documented in the international scientific literature. See for example (Pedercini et al. 2019; Pedercini et al. 2018b; Collste et al. 2017). Since the iSDG model is based on the Threshold 21 model, it can refer to a development history of more than 30 years with independent applications for national policy analyzes in more than 40 countries (Pedercini 2011; Pedercini et al. 2018b). A detailed model description and documentation can be found online (https://isdgdoc.millennium-institute.org/en/). The most important characteristics for our applications are described in the following.

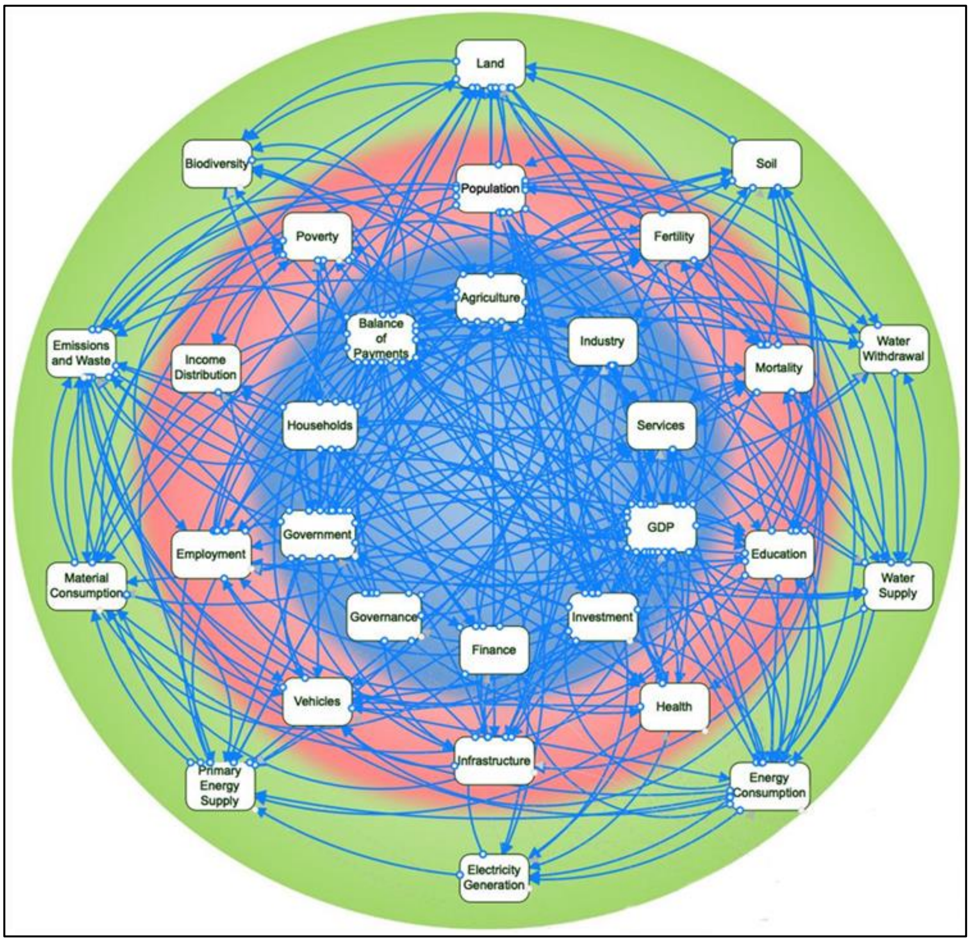
The iSDG has been designed to support national development planning, with a special focus on enabling analysis for medium- and long-term development issues at a national level, which is especially important when talking about sustainable development. iSDG is conceived to complement budgetary models, sectoral models, and other short- to medium-term planning tools by providing a comprehensive and long-term perspective on development.

As shown in Figure 16, the model integrates into a single framework the **economic (blue), social (red), and environmental (green) aspects** of sustainable development. The projected developments are simulated by 30 interacting modules. Whereas these modules are in general not directly related to economic sectors, it is common practice amongst iSDG modelers to refer to these as sectors.

As the model covers all the SDGs, it supports a better understanding of the interconnections of the goals and targets to develop synergetic strategies to achieve them. In the initial model set up, this is done through a parametrization process that focuses on SDG interaction. This standardized procedure allows for a fast adaptation to national contexts, such as the German case, as it largely relies on internationally available datasets. The iSDG model simulates the fundamental trends for SDGs until 2030 under a business-as-usual scenario, and supports the analysis of relevant alternative scenarios. The latter is especially supported by the nature of the iSDG's degrees of freedom in the parametrization and flexible structural design, which allows for the integration of context (e.g. national) specifications. The model can also trace the trends beyond the SDGs' time span all the way up to 2050. Hence, the iSDG is useful at four levels for SDG planning.

First, it allows analyzing how – under business as usual (BAU) conditions – the country would progress towards each of the 17 SDGs. Such analysis provides an initial overview of the areas that require more attention from policy makers. Second, the high level of interconnectedness among goals in the model allows for building a shared understanding among stakeholders of how development in each area affects (and might be necessary for) developments in other areas. Such an understanding provides important insights on the fundamental leverage points in the system – i.e. points of intervention that can lead to rapid and positive change. Third, the model supports the simulation of a variety of policies addressing each of the 17 Goals, in isolation and in combination with others, to understand their relevance and possible synergies.

Figure 16: Key action areas covered by the iSDG model



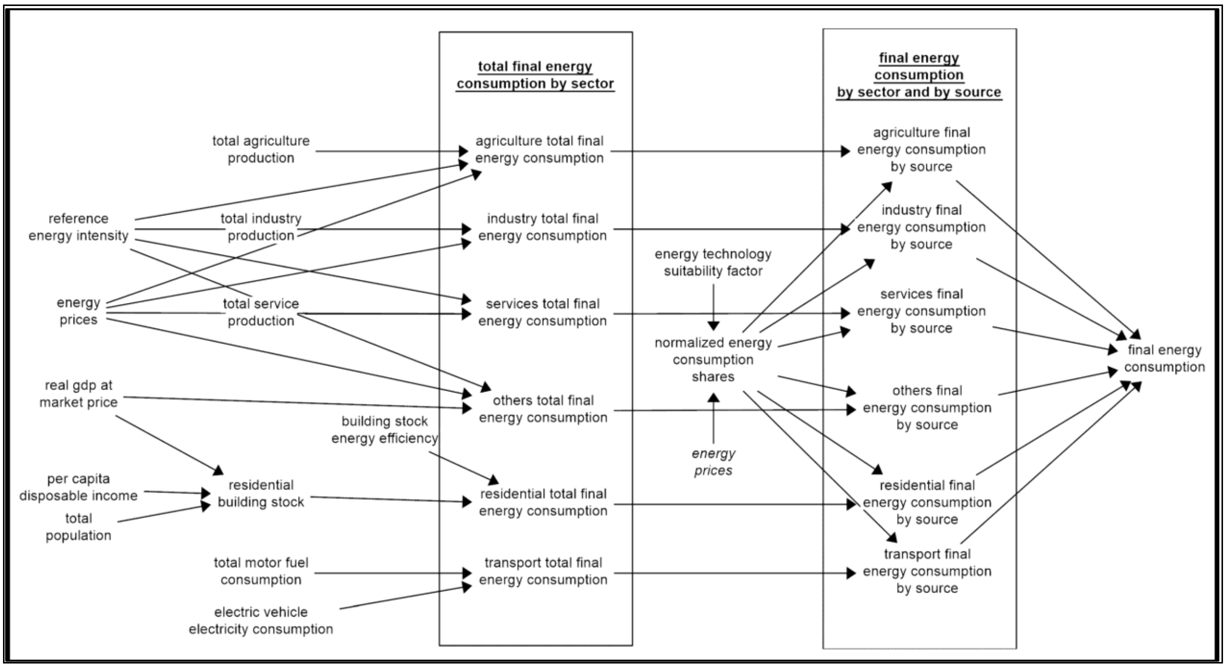
Source: Millennium Institute (2021)

A key characteristic of the iSDG, which is related to the SD nature of the model, is that a user interface provides an easy visual access to model structures and simulation results. This facilitates an in-depth review of scenario elements also by non-modelling experts, like, for example decision-makers. The user interface can also be used to educate a broader audience about the interactions between the SDGs and potential future scenarios.

3.2 Coverage of action fields from the RESCUE-study

3.2.1 Energy

Figure 17: Simplified CLD of the energy consumption's dynamics



Source: Own calculations

In the energy supply module primary energy supply of gas, oil, coal, biomass, and electricity is calculated. Biomass energy supply calculations are based on crops production and forest products as outlined in Hoogwijk et al. (2003). The model follows a demand driven approach, which means the main drivers of primary energy supply are final energy consumption and electricity generation.

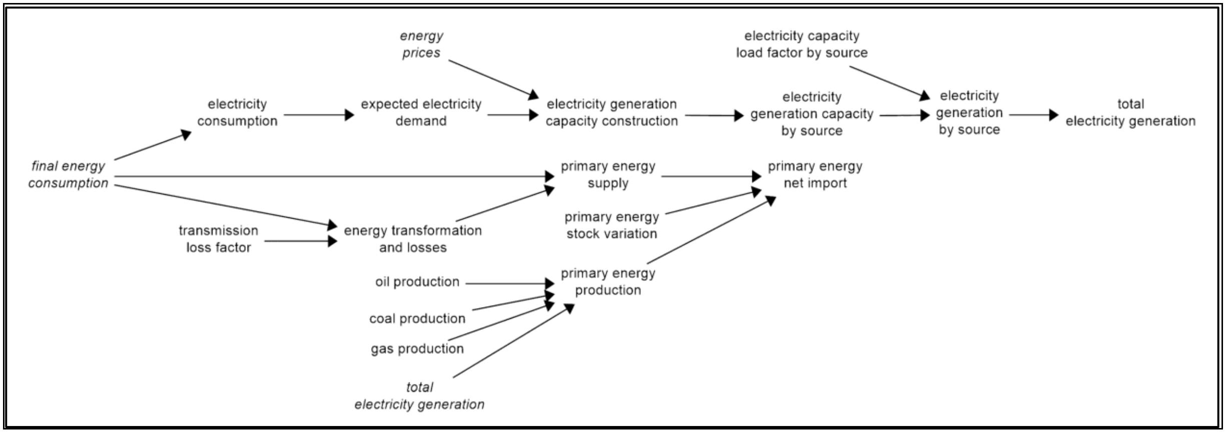
Figure 17 shows how energy consumption is calculated in the iSDG. This also includes energy consumption components that fall within other sectors as defined in this report. The choice of energy source is mainly influenced through energy prices, which are exogenous input parameters and the energy technology suitability factor, which is calibrated based on historical trends. Additionally, to replicate policies that target for example the phase out of fossil heating systems or fossil fuel use in the industry sector, a parameter called target normative consumption share can be adjusted accordingly, which influences final energy consumption by consumption sector (i.e. agriculture, industry, services, other, residential and transport) and by source (i.e. oil, gas, heat, electricity, bio, heat).

Based on the difference between primary energy production and primary energy supply, imports are calculated.

Exogenous inputs to this module are electricity generation efficiency by source, other transformation losses factor, transmission loss factor and primary energy stock variant.

In the electricity generation module total electricity production from fossil fuels, nuclear, hydropower and other renewable sources (i.e. wind and solar) is calculated. Figure 18 presents how the electricity generation is calculated in the iSDG.

Figure 18: Simplified CLD of the electricity generation's dynamics



Source: Own calculations

In this sector the installed capacity is estimated and captured. Future expected electricity demand is driving electricity capacity expansion. Electricity generation capacity (i.e. nuclear, coal, oil, gas, heat, solar, wind, hydro, bio) expansion happens through construction of additional plants. The choice of additional capacity by type is based on levelized cost of electricity and can be influenced by targeted private or government investment in specific technologies. Power plants are generally decommissioned when their average lifetime has been reached. To be able to capture normative fossil phase-out policies that are not market based, the option of early decommissioning of fossil fuel power plants has been introduced through adding the parameter "normative and exogenously defined electricity capacity decommissioning fraction".

3.2.2 Government

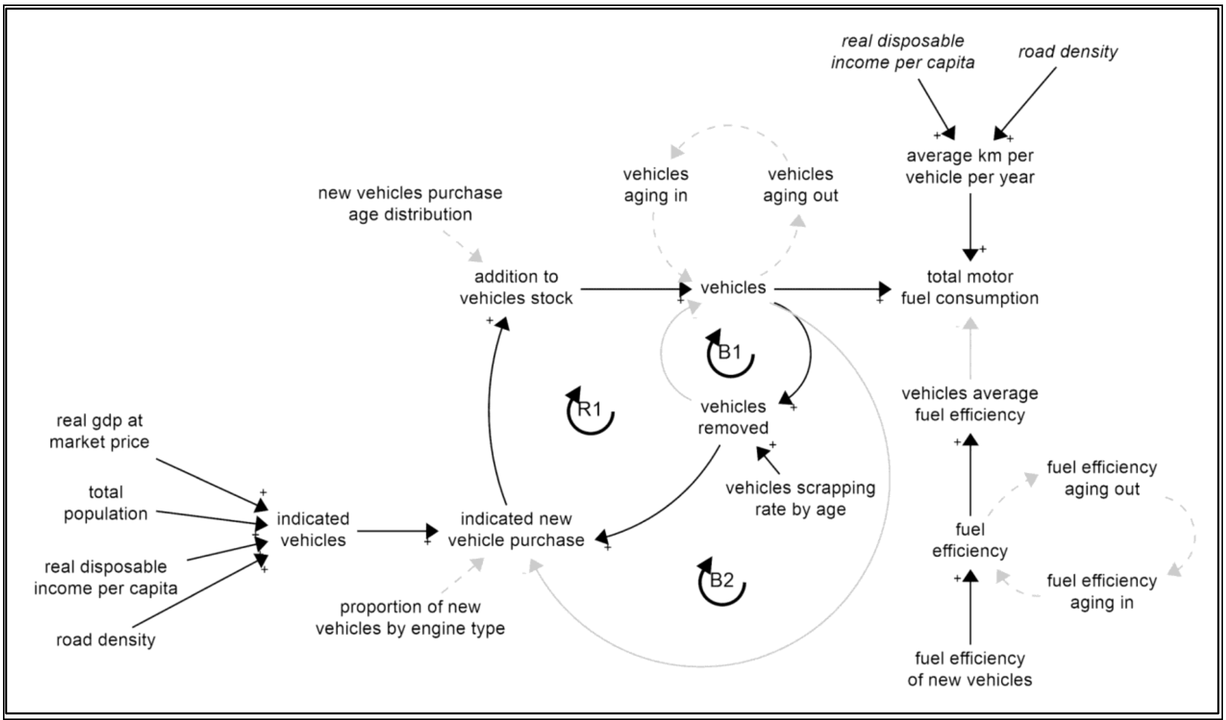
This sector accounts for government revenue and total government expenditure, which is allocated different categories, according to macroeconomic and functional classifications. The latter includes a number of categories, which are used for defining government expenditure policies. Funds allocated to "administrative and other expenditure" only have a macroeconomic effect in the model. The following categories are relevant for the context of this project:

- Government expenditure as share of GDP by main category [energy expenditure]
  - Government expenditure share of energy expenditure for large scale photovoltaic
  - Government expenditure share of energy expenditure for large scale wind power
  - Government expenditure share of energy expenditure for household energy efficiency
  - Government expenditure share of energy expenditure for industry energy efficiency
- Government expenditure share of agriculture expenditure for training

The amount of expenditures for each of these categories represent major policy variables that can be defined as desired percentage of GDP. This sector also encompasses the main structure related to energy and carbon taxes. For the purpose of this project, a simplified carbon tax structure was implemented. It works through an exogenous parameter that is defined as carbon fee (€/ton CO_2), which is based on the carbon content of respective energy sources. Changing this parameter leads to higher cost of fossil fuels and thereby, influences energy prices of fossil fuels, which affect electricity generation fuel consumption and final fuel consumption as outlined in the electricity generation and energy supply modules' description.

3.2.3 Mobility

Figure 19: Simplified CLD of the vehicles sectors' dynamics



Source: Own calculations

Calculations regarding mobility are split between two modules in the iSDG, namely infrastructure and vehicles. The supply chain approach applied in the infrastructure module allows to model the dynamics of transportation infrastructure, including construction, maintenance, and decay. This makes it possible to explicitly consider the effect of time lags in transportation infrastructure development, and on the rural access index. Currently the following infrastructure elements are considered: paved and unpaved roads, and railways. If necessary, others can be added. Transportation infrastructure funding is first allocated to maintenance. Funds remaining after maintenance are allocated to construction start-ups, a capital cost per kilometer of infrastructure (Lambert and Huh 2004; Rioja 2003). An important factor influencing construction quality and use of transport infrastructure, infrastructure life and maintenance cost is governance (Kenny 2012). For this project, there was no model module available to map developments in public transport or air traffic.

Additionally, intensity and frequency of natural disasters and their impacts on infrastructure, health and private capital are encompassed in this module. Beyond this, transportation infrastructure influences many other modules including education, agriculture, industry and services. This module has no exogenous inputs. Additional investment in infrastructure is one of the policy interventions possible in this module.

The Vehicles module follows the dynamics depicted in Figure 19 and tracks the number of passenger and commercial road vehicles (internal combustion engines and electric) and the emissions these vehicles produce (fine particulate matter, PM 2.5). Through setting a target proportion of new vehicles, policies encouraging uptake of electric vehicles can be implemented. The model explicitly accounts for the replacement of old vehicles by new and the factors affecting decisions concerning the level of fuel efficiency of new vehicles, including public expenditure (subsidies). By capturing the vehicles and replacement dynamics, related delays become explicit. The transition process takes time as households are assumed to replace their current vehicles after a few years and that the electric vehicle market is not mature enough to cope with a radical change in demand. Hence, the transition time is not a parameter that is exogenously determined but rather a result of the underlying model structure.

The parameter passenger vehicles per capita[46] defines the number of vehicles per person and is calibrated based on historical data. By changing the target value for the number of vehicles per person a shift away from motorized individual transport can be simulated. Vehicles relate to the material sector through fossil fuel consumption; other materials necessary for vehicle construction or alternative engines are not considered.

Regarding connections to other sectors, vehicle emissions contribute to the aggregate emissions in the Emissions and Waste module and also link to health as vehicles contribute to particulate emissions through fuel combustion and through tire, brake, and road dust (Klimont et al. 2002). There are no exogenous model inputs to this module, but it is affected by calculations in other modules, such as income and road density as they affect purchase of vehicles (Greenspan and Cohen 1999; Litman 2015).

3.2.4 Industrial production

The modelling of the industry sector is based on an extended Cobb-Douglas (CD) production function (Cobb and Douglas 1928). Basically, a CD function derives industrial production from the amounts of inputs of the production factors capital and labor.

In the iSDG an extended CD is employed. Factor productivity is influenced by drivers from other modules, such as: education (average years of schooling used as proxy) (Barro 2001; Nelson and Phelps 1966; Romer 1990); health (life expectancy used as proxy) (Bloom et al. 2001; Howitt 2005; López-Casasnovas et al. 2005); infrastructure (including roads and irrigation infrastructure) (Calderón and Servén 2004; Canning 1999); access to electricity (Calderón and Servén 2004); level of governance (Kaufmann et al. 2002); macroeconomic stability (inflation rate used as proxy) (Bruno and Easterly 1998; Fischer 1993); climate change (Burke et al. 2015); energy prices (Arezki and Blanchard 2014; Jiménez-Rodríguez and Sánchez 2005; Peersman and van Robays 2012); female participation in the workforce (Loko and Diouf; Cuberes and Teignier 2012) and openness to trade (Edwards 1998; Yanikkaya 2003).

Production growth is driven by an increase in available production factors or by an increase in respective productivities. This implies that demand factors are not considered in the calculation of production, that the quantities produced are fully used, and prices are exogenous to the model. This means that the models industry sector is supply driven and does not consider demand as a driver of production but only the aforementioned production factors. This production-side determination of macroeconomic development pathways represents a standard approach to long-term growth modelling. It is therefore well justified from the long-term focus of the iSDG model. In the model the production factors are used in unit-consistent form, using normalized values. A similar approach is used to normalize the drivers of productivity. The overall effects of variations in available production factors and drivers of productivity are combined in a multiplicative form, assuming Hicks-neutral technological change, meaning that only the effectiveness of production is influenced but the balance of labor and capital stay the same. Elasticity ranges of production factors are based on literature and calibrated for Germany based on historical data.

Total industry production is one of the three components (together with agricultural and service production) determining real GDP at factor cost. The production of industry sectors of chemical

[46] In the model, the variable is referred to as total vehicles per thousand people.

manufacturing, construction and mining and quarrying determine material consumption of metal ores and non-metallic mineral consumption. The material consumption efficiency can be changed exogenously, which also positively affects productivity.

3.2.5 Agriculture and land use

The agriculture module includes crops production, fishery production (separating fish catch and harvest - aquaculture), livestock production and forestry production. Beyond the linkages to modules that are relevant to the production factors (i.e. land, labor and capital) and influence factor productivity, such as investment, balance of payment (openness to trade), education, employment (female participation in the labor market), government expenditure, governance, health, infrastructure (transportation infrastructure), climate and energy prices, this module is also linked to the following modules: land, biodiversity, soil and water supply.

More specifically, crops production is influenced by the harvested area, and soil nutrition (with the availability of macro-nutrients Nitrogen, Phosphor and Potassium represented), precipitation, irrigation, which along with total factor productivity affects the actual yield. Production factors are combined as in a Cobb-Douglas production function. More specifically, an increase in the production factors or their productivity reduces the difference between actual and attainable yield. Crop production is divided between cereals and other crops.

Livestock production is affected by the same factors described above. However, in the case of livestock, production per unit of land does not converge to a maximum attainable yield, but its growth is determined directly by growth in driving factors and the corresponding elasticity parameters. Elasticity ranges of driving factors are based on literature and calibrated for Germany based on historical data as described in Kleemann et al. (2022).

As it is the case for industry the same holds true here and in the production functions, growth in production is driven by an increase in available production factors or by an increase in their respective productivities. This implies that demand factors are not considered in the calculation of production, that the quantities produced are fully used, and prices are exogenous to the model.

Additional to price, the following parameters of this module are exogenous to the model: crop intensity index, crop production value per ton, livestock value added per ton, fish catch production, fish harvest production, forestry production, other agriculture input cost per ton of production and effect of change in type of crop yield. Again, in the model the production factors are used in a unit-consistent form, using normalized values. A similar approach is used to normalize the drivers of productivity. The interplay of available production factors and respective productivities is again combined in a multiplicative form, assuming Hicks-neutral technological change.

As agricultural production, like production in all economic sectors covered in the iSDG, is also supply driven, a reduction in meat consumption can currently only be implemented as a change in the profitability of livestock production by changing a parameter called output shock by sector. Through investments in sustainable agriculture[47], captured in the government module, agricultural practices can be shifted towards more sustainable ones, decreasing fertilizer use.

In the land use module land use for different purposes is tracked. It includes four classifications of land agricultural land, settlement land, forest land and other land. Agriculture land is further divided into arable land and permanent crops, and pasture land. Other land accounts for all land

[47] Sustainable agriculture is rather generically parameterised in the model as farming methods relying on fertilizers from nitrogen-fixing plants. In the model, sustainably managed agriculture is more labor-intensive. Further specific requirements, as for instance defined by different eco labels, are not mapped explicitly in the model.

that is not for agriculture, settlement, or forest, and also works as an intermediate stage in the transformation between land uses. With the levels of the different types of land change, the land module ensures that total amount of land is always conserved. The land use module does currently not consider land use for wind or PV.

The purpose of the soil module is to determine soil nutrients balances and their long-term impact on soil organic matter. Flows of the three major soil macro-nutrients (Nitrogen, Phosphorous, and Potassium) are considered as they relate to agricultural activities. More specifically inflows are nutrients addition through fertilization (both mineral fertilizer and manure), biological fixation (symbiotic, non-symbiotic, chemoautotrophic, and from scattered trees), and deposition. Outflows consider nutrient use (uptake from crops and crops residuals removed) and losses (leaching and gaseous losses). Finally, the gap emerging between nutrients inflows and outflows is drawn from soil organic matter. This representation is fundamentally based on FAO's nutrients balance work. Exogenous model inputs in this module are fertilizer consumption, nutrient uptake proportion and US fertilizer price per ton of nutrient.

3.2.6 Construction and housing

No explicit construction or housing sector existed in the iSDG. However, components of it were covered in other sectors, such as material consumption, land and infrastructure.

Material consumption is treated as a separate sector as it accounts for all material flows across all sectors and also includes waste. It is strongly linked to economic activities in the other sectors. In our applications, this module derived projections for domestic extractions and domestic material consumption (DMC). DMC is income-driven and part of it is construction material consumption and cement demand, which is modeled explicitly.

As outlined above in the land sector settlement land is estimated and in the infrastructure roads and their construction are captured.

To also be able to capture building sector dynamics additional structure was added to the model. The building stock structure captures the buildup, maintenance and destruction of the building stock for commercial and residential buildings. Buildup is a function of the population and the space demand per person. The share of cement and wood in buildup and renovation activities can be altered. Through this the cement consumption, which feedbacks to the material sector, can be changed. Energy heating demand of residential buildings is calculated as a function of energy efficiency, which is captured through the U value (i.e. thermal transmittance parameter) dynamics. Additionally, heating degree days, depend on average temperature, which is dependent on the exogenous climate change assumptions.

3.3 Adapting and calibrating the framework to German developments

3.3.1 Data work

To adapt the structures of the iSDG model for an analysis of German interdependencies, approximately 200 german data sets of social, economic and environmental indicators had to be integrated into the model database. For this purpose, the Millennium Institute first applied long-established data collection procedures, which import the required observations from internationally renowned databases (World Health Organisation-WHO, United Nations-UN, World Bank, World Food Organisation-FAO, International Energy Agency-IEA).

However, many of the international data sources assessed under the standard procedure lacked required data sets or reported insufficient or unreasonable data for Germany. In some cases, respective data gaps could be filled by information sets published by Eurostat or Destatis. But unfortunately, most required data sets could not be retrieved directly from these sources either. This led to more intensive data collection and adjustment efforts. Since a complete overview of all time series used for model parameterisations (including respective reference sources) was handed over to UBA at the end of the project as a separate Excel file, the preparatory data work activities are not documented in more detail here.

3.3.2 Model adjustments

To ensure the iSDG captures the German system structure correctly, some adjustments were made. Additionally, changes in the model structure were made to be able to also capture some dynamics relevant to the Green Supreme scenario of the RESCUE study. While a number of adjustments could have been made, due to the scope of the project, not all of them were feasible. The decision on which adjustments to make were based on feasibility in terms of data availability, expert judgement (including workshop results and expert meetings) and time required to implement the changes compared to the value of the additional insights.

Adaptations included numerical as well as structural adjustments (e.g. disaggregation of industry modules, building module). The adjustments in the industry module are discussed in the following:

Disaggregation of the industry sector

The Green Supreme scenario of the RESCUE study covered the industry sectors listed below:

a) Iron/Steel
b) non-ferrous metals
c) lime
d) cement
e) food
f) wood/paper
g) chemistry
h) glass

When disaggregating industries in the iSDG several connections to other modules need to be considered to maintain consistency. The minimum requirements in terms of data items for each industrial sector are: value added and employment. Based on the data explored and experience it was not advisable to disaggregate below ISIC-Rev. 4 level 1 (OECD.Stat). Following ISIC, this led to the disaggregation of industry below:

1) VB: Mining and quarrying
2) VE: Water supply, sewerage, waste management and remediation activities
3) VF: Construction
4) V10-12: Manufacture of food products, beverages and tobacco products
5) V16-18: Manufacture of wood and paper products: printing
6) V20: Manufacture of chemicals and chemical products
7) Other industry

The additional data sets required for the economic modelling of these industry sectors (value added and employment time series) were extracted from the Eurostat DataBrowser by project partner GWS.[48]

3.3.3 Model calibration

After a successful data collection and model adaptation process, the iSDG baseline for Germany was developed. For this the model, meaning the numerical values of and relationships between variables, were calibrated based on the data collected in the previous step. The basic model was validated by systematically assessing the development of the endogenous indicators represented by the model with the historical developments previously recorded. At the model level, 204 variables are included in the calibration process are averaged to aggregate the statistics. In some cases, due the too few data points, some statistics are not able to be calculated for those variables. This is why the total variables (population column) included in calculations changes. Of these 204 variables, approximately 89.34 percent are covered by historical data for the period of the model calibration. As outlined above, in some cases, data coverage was sparse, while in others all years of the simulation have a corresponding historical data point.

Table 13 shows an overview of the calibration results for the main variables. A comprehensive Calibration Report documenting detailed parametrization results has also been handed over to the UBA. As a technical manual, this report has not been made public. However, it can be made available on request from the authors. To assess the model's fit to historical data, five statistical measures are usually assessed by the model authors: R-Squared, Root Mean Square Percent Error, and the Theil Statistics for error decomposition.

R-Squared, (R^2) or the coefficient of determination, in this case, compares the correlation between the simulated series and the historical series. With a metric scale ranging from 0 to 1, this statistic measures for a time series under inspection, how much of the historically observed variations is captured by the simulated values. The Root Mean Square Percent Error (RMSPE) builds on the previous statistic, in that it indicates the percent error between the historical and simulated values. In most cases, these statistics share an inverse relationship; the lower the RMPSE, then the higher the R^2.

Identifying size of error is necessary to improve goodness-of-fit, however the origin of that error, is also important to identify how it impacts the interpretation of the model. The three Theil Inequality Statistics; Bias (UM), Variation (US), and Co-variation (UC), enable unpacking the source of the error (Theil 1966). This approach has long been a best practice within the field of Econometrics and System Dynamics in order to determine error based on the purpose of the model (Sterman 1984). Thiel Statistics are measured between 0 and 1, and when combined should sum to 1; essentially providing a percentage of residual error due to each source.

[48] The DataBrowser can be accessed via https://ec.europa.eu/eurostat/databrowser/explore/all/all_themes (retrieved on April 24, 2024)

Table 13: Calibration summary statistics

	Population	Mean	Median	Minimum	Maximum	Standard Deviation
N	204	17.87	20.00	3.00	20.00	5.31
Data Coverage	204	0.89	1.00	0.15	1.00	0.27
R^2	192	0.66	0.84	0.00	1.00	0.35
RMSPE	203	0.15	0.08	0.00	2.83	0.26
U_m	201	0.43	0.32	0.00	1.00	0.35
U_s	201	0.16	0.10	0.00	0.86	0.18
U_c	192	0.43	0.41	0.00	0.99	0.32

Source: Own calculations

Regarding all goodness-of-fit statistics, the model performs well overall, with some data consistency issues causing outliers in the error levels (two standard deviations above the mean): Averaged across all variables, R^2 indicates that two third of all historical development dynamics are captured by the simulations. The mean RMSPE of the model is 0.15, which indicates a low average error value, while the standard deviation is 0.26, representing a narrow distribution of error around the mean. For most variables RMSPE falls below 0.41, with few outliers skewing the distribution model.

In assessing the source of the error described in the RMSPE, there is a concentration of variables between 0 and 0.43 (mean) for error due to bias, while fewer variables have error greater than 0.5. Regarding error due to variation, there is, generally, low error due to variation, with few variables above 0.5. Last, the distribution of UC shows much of the error that exists in the model can be seen is due to co-variation (0.43). Overall, the average error is at acceptable levels and the error is concentrated in UC. This shows that the error of the model is non-systematic, indicating a strong connection between the model output and the medium to long-term trends embedded in historical data series.

3.4 Baseline results

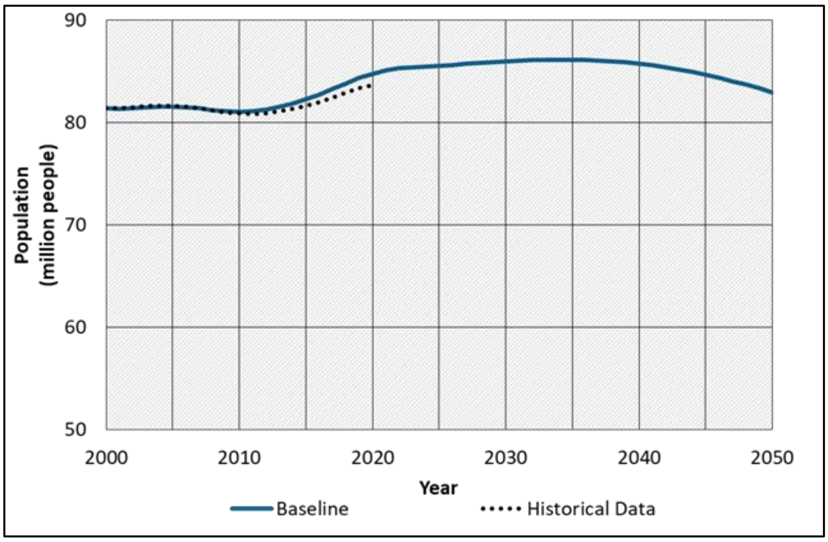
An application of the calibrated and validated iSDG base model without additional scenario assumptions generates the results of the baseline scenario. These serve as a reference for assessing the achievement of the SDG goals, also under assumed altered development trajectories. For the baseline scenario as well as all alternative policy simulations, all underlying global scenario assumptions refer to the Shared Socio-Economic Pathway (SSP2) (van Vuuren et al. 2017a). An application of the calibrated and validated iSDG base model without additional scenario assumptions generates the results of the baseline scenario. These serve as a reference for assessing the achievement of the SDG goals, also under assumed altered development trajectories. For the baseline scenario as well as all alternative policy simulations, all underlying global scenario assumptions refer to the Shared Socio-Economic Pathway (SSP2) (van Vuuren et al. 2017a). It is important to point out that the structures of a system dynamic model are not developed to predict future developments of individual variables. (For example, to analyze the effects of introducing good taxes on plastic products). Rather, applications of system dynamic models serve to depict the development dynamics of complex systems over time. In this sense, they serve to exploratively depict the "further" effects of, for example, "broad" social developments or macroeconomic innovations. The main results of the baseline for population, GDP (real GDP growth rate), Emissions (CO_2 emissions) and Resources (domestic material consumption) are discussed below. In the iSDG all of these indicators are endogenous, meaning that developments of population and GDP depend on other variables in the model and are not only set based on exogenous assumptions. In the RESCUE study population and GDP were exogenous inputs.

3.4.1 Population

In the iSDG, population is a function of fertility, mortality and migration. Fertility and mortality rates are influenced by socio-economic development, such as GDP, education and access to health services, and environmental factors, such as emissions and natural disasters. In the baseline scenario population peaks around 84 million in 2025 and declines to roughly 82.9 million in 2050 (see Figure 20). This is in line with the UN population scenarios for Germany[49] , which range from around 72 million in 2050 to slightly more than 85 million in 2050 with a growing trend until 2100. The median scenario peaks at approximately 83.5 in 2021 and decreases to roughly 79 million in 2050. In the RESCUE study population is an exogenous driver and assumed to decline after 2020, leading to a population between 67 and 76 million people in 2060, which was aligned with the "Continuity with weaker immigration" of the 13th Coordinated Population Projection that estimates around 71.9 million people in 2050 (Pötzsch and Rößger 2015).

[49] https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/276 (retrieved on April 24, 2024)

Figure 20: iSDG projection: Total population in Germany



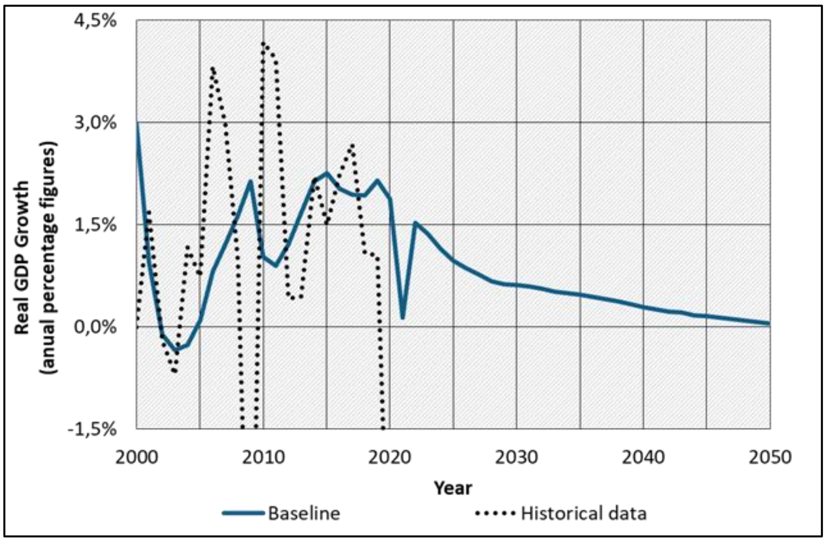
Source: Own calculations

3.4.2 Real GDP

In the baseline scenario, the real GDP market price growth rate decreases constantly but never becomes negative. Total real GDP at market price keeps growing to approximately 3.74 trillion in 2050. As population also follows a downward trend, real GDP per person keeps growing at a faster pace. The share for the GDP growth rate in the iSDG projection drops clearly till 2050 (see Figure 21).

In the RESCUE GreenSupreme scenario GDP is also an exogenous driver and assumed to be 0.5 % between 2010 and 2030 and zero from 2030 to 2050. In the iSDG GDP is endogenously calculated as aggregate production of all sectors. Production is calculated as an extended Cobb-Douglas (CD) function (Cobb et al. 1928). Generally, the production factors include capital and labor. Capital can be subject to damage through extreme events. Factor productivity is influenced by drivers from other sectors, such as education, health, infrastructure, access to electricity, level of governance, macroeconomic stability, climate change, energy prices, female participation in the workforce and openness to trade. Individual sector deflators and the overall GDP deflator are exogenous to the model.

Figure 21: iSDG projection: GDP growth rate in Germany

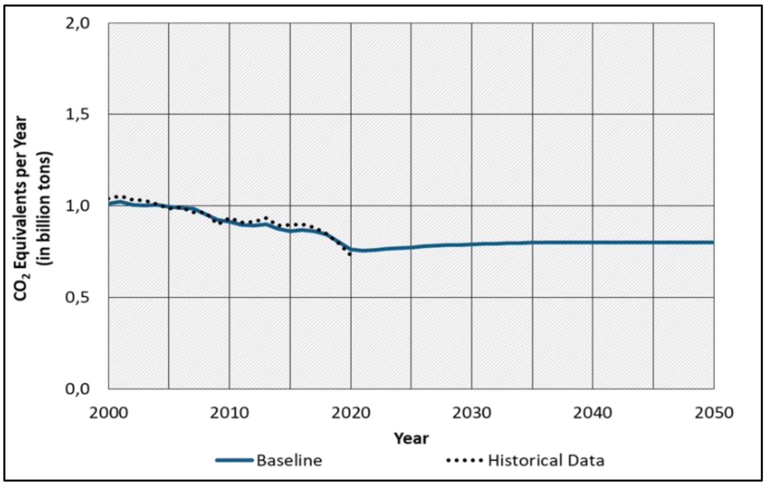


Source: Own calculations

3.4.3 GHG Emissions

In the German version of the iSDG total GHG emissions are captured as CO_2 equivalents. The emissions only grow slightly in the beginning and level off almost completely until 2050. As the population degrows, the emissions per person grow slightly more than total emissions. In line with the EU accounting scheme, the GHG emissions in the iSDG refer to fossil fuel, non-energy related agricultural (based on the level of activity), waste management and industrial production emissions. The iSDG projection for total GHG emissions shows that the tons of CO_2 equivalents/year will increase from 2020 to 2050 (see Figure 22).

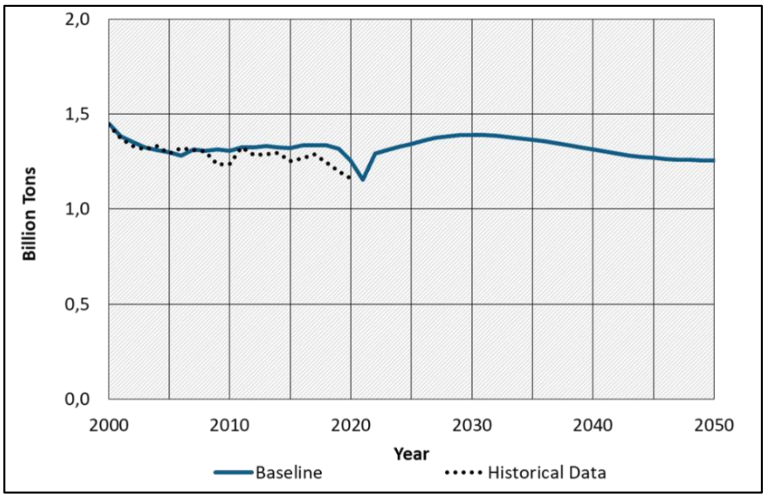
Figure 22: iSDG projection: Total domestic GHG emissions in Germany



Source: Own calculations

3.4.4 Domestic material consumption

Figure 23: iSDG projection: Total Domestic Material Consumption (DMC) in Germany



Source: Own calculations

Figure 23 shows that the total domestic material consumption in the iSDG projection decreases overall with fluctuations from 2000 to 2050.

3.5 Approaches to parameterising policy scenarios

The iSDG is a long-term policy planning tool, which focuses on understanding synergies and trade-offs, rather than providing sectoral details. In general, several options of parameterizing policy scenarios within the iSDG exist through including different types of interventions that affect SDG outcomes. The different types of interventions that can be assessed include: **(re)directing investments, setting targets, fiscal policies and taxation, law and order as well as subsidies and transfers as distributional measures**.

In the case of **(re)directing investment flows**, in the public sector exogenously defined shares of GDP for a specific functional expenditure category are defined. In the current study, this intervention type was implemented for several expenditures related to the energy and agricultural system. Changes in private investment were not explicitly investigated.

Implementing **normative targets** to achieve certain goals, as for example in the case of electric vehicles, can be used when a government strategy is not implemented as a law or investment.

Law and order policies are generally implemented by driving exogenous variables that drive the behaviour of a certain element/variable (e.g. through setting rates or defining shares) in the model in the desired direction as was for example done in the case of defining a renovation rate.

Fiscal measures and taxes are instruments that can be tested in the iSDG. The current structure captures taxes on different income groups but also related to the energy system (see above).

Transfers and subsidies only relate to redistribution policies for households and subsidies for energy efficiency increases are classified as expenditures in the respective category.

As the model does not have a vast demand side structure, strategies that concern behavioural change and are not reliant on economic incentives can be implemented in two ways:

1) By setting a target value for a specific variable as it is assumed that the official communication of a target in combination with information and education campaigns influences behaviour.
2) Driving the behaviour of certain variables exogenously as for example in the case of livestock reduction.

4 Application of the iSDG assessment framework for Germany: Policy scenarios

To understand potential synergies and trade-offs of climate and resource pathways, a number of different scenarios were defined varying in the resource and climate policies considered. On the one hand policies that consider already existing policies and on the other hand policies that are more closely aligned to the GreenSupreme scenario of the RESCUE study are analyzed. Following the logic of the RESCUE Green Supreme action fields and the iSDG model structure as outlined above. They encompass:

► Baseline

The Baseline scenario is the result of model calibration. Hence, the effects of policies that have been in place for an extended time period are captured (e.g. high push for renewables) but policies that have only been implemented recently (e.g. carbon tax) are not. Hence, the Baseline is not the same as what is often referred to as a scenario with existing measures.

► Energy System

In the RESCUE study many of the interventions concern fossil fuels. Through this, aspects of energy supply or demand, spanning a wide range of sectors and action fields are concerned. For this study the Energy System scenario encompasses all energy system changes that are not encompassed in any of the action fields (Industry, Building and housing, Mobility, Food and agriculture) as outlined in the scenarios below. Hence, the Energy System scenario encompasses policies mainly concerned with energy supply and governmental regulation of the energy system. It is combining the following three scenarios:

- Energy consumption

  Energy consumption moves energy consumption away from fossil fuels in those energy consumption sectors that are not covered by an individual policy package. These include services and other (as residual) by setting the target normative consumption shares of fossil energy carriers to zero.

- Carbon tax

  In accordance with existing national implementations, the carbon tax is modelled without any direct compensation in the form of a climate fee. The tax is levied on everyone (without exception) who sells fossil fuels. The effects of the resulting funds on national budgets have not been mapped in the simulations. In the implementation in the model, this essentially means that commodity prices for fossil fuels are increased by the assumed tax rate. The carbon tax simulations assume a tax rate (in real local currency units, i.e., € per tonne of CO_2) that increases from 30 € per tonne of CO_2 in 2022 to 400 € per tonne of CO_2 by 2030 and 500 € per tonne of CO_2 by 2050.

- Electricity generation

  In line with the ambitious GreenSupreme scenario of the RESCUE study, our transformation scenario assumes a complete phase-out of coal, oil and nuclear energy carriers in electricity generation by 2030. This is done by decommissioning fossil and nuclear fueled power plants and accompanied by additional public investments in renewable energy generation capacity (wind and solar) to achieve, in line with current climate protection targets of the German government, an 80 % share of renewable energy sources in electricity generation by 2030. By 2050, this share of renewables in electricity generation increases further to 88 %. Just as in the GreenSupreme scenario, gas plays an important role as a bridging technology in electricity generation. As a result of the decommissioning of fossil and nucelar fuels, the share of gas in electricity generation increases to just over 17.9 % by 2030. For 2050, a remaining gas share of 11.7 % in electricity generation is simulated.

Some key long-term targets of the Green Supreme scenario (like, for example, a 97 % share of renewables in 2040) are apparently not covered by our parametrizations of transformations in the energy system. To this, we would like to note that our integrated dynamic simulations project economy-wide electricity generation to deviate significantly from corresponding reference values of the Green Supreme scenario. As will be shown in the detailed presentation of simulation results for the energy sector in section 4.3.4, all of our assumed transformations result in a massive overall increase in electricity demand. In our model simulations, the assumed year 2050 electricity generation volumes of the RESCUE Green Supreme scenario are already reached in 2030 and roughly doubled by 2050. As these projections result from the mapped system characteristics of the iSDG, we consider this a cautionary indication of optimistic assumptions for respective transformation pathways of the RESCUE study.

► Industry (incl. Circular Economy)

The industry scenario combines energy and Circular Economy policies with the goal of reducing resource consumption and emissions directly targeted at the industrial sectors laid out in section 3.3.2.

In line with the GHG-emissions reduction goal set by the German government, the target normative energy consumption was set to phase-out fossil fuels and shifting to electricity. The share of energy expenditure for industry energy efficiency is adjusted so that the rise in electricity consumption is dampened by technological upgrade (using more efficient equipment and capital). Through a change in non-energy related production emissions per unit of output, industry emissions can be halved.

To cover Circular Economy policies, which are a key in the RESCUE study, material- and water consumption efficiencies are assumed to increase exogenously (0.5 % p.a. increase in material efficiency). This is not tied to investments, but rather seen to result from regulation. The value added effects resulting from these efficiency improvements drive industrial output in the respective simulations.

► Building and housing

Public investments directed at households regarding electricity efficiency are implemented so that the rise in electricity consumption is dampened by technological upgrade (using more efficient equipment and capital), and through increases in renovation rates also the heating efficiency is improved.

Additionally, the share of building manufacturing (construction or renovation) which use wood products is increased. This policy increases the proportion of buildings which are either being renovated or in construction to use wood instead of traditional construction materials.

The growth rate of building stock expansion is reduced through an exogenous change in the elasticity of income to building rate, which can either be interpreted as a change in people's mindsets or a constraining policy. This very far-reaching assumption implies a significantly slower expansion of residential building space: In the building and housing simulations, the residential building stock (in square metres) is reduced by approximately 12.1 % by 2050 compared to baseline reference projections.

► Mobility

The mobility policy package includes electrifying the vehicle fleet so that the transport fuel consumption drops drastically. This is achieved by setting a target value for the share of new electric vehicle purchases that assures all new vehicles are electric by 2050 (passenger and commercial).

The shift away from individual motorized transport assumed in the RESCUE study is implemented through dampening the increase in per capita vehicles by exogenously changing the number of per capita vehicles, which can be interpreted as a shift towards other modes of transport. However, this shift is not explicitly covered.

► Food and agriculture

To align this part of the iSDG with the measures presented in the RESCUE study, a reduction in livestock production is implemented. The reduction gradually halves the production levels of 2020 by 2050. Assuming the absence of any substitutional meat imports, this would drive national meat consumption closer to the recommended amount per day according to the German Nutrition Society (DGE)[50].

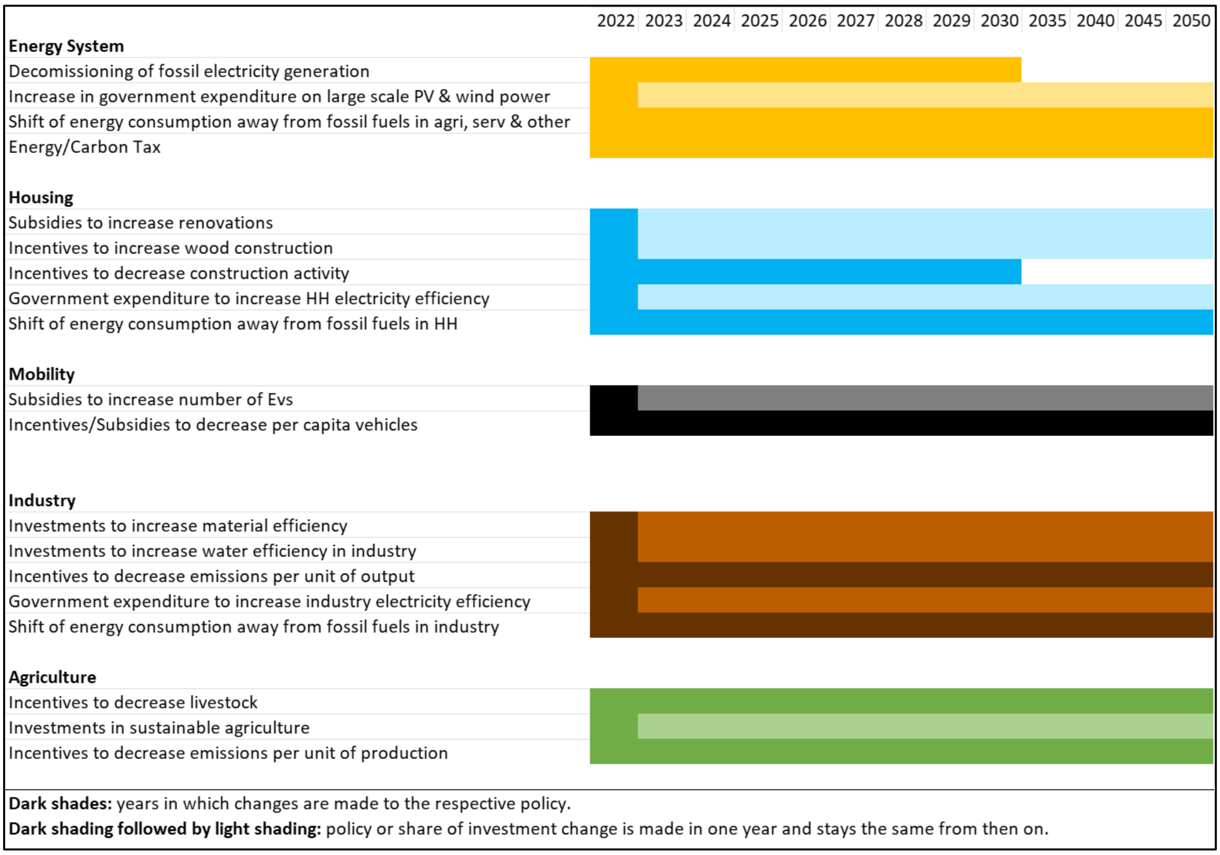
The increase in governmental expenditure for sustainable farming enables more farmers to practice sustainably which has three direct effects: (1) soil's nitrogen balance is restored and maintained, (2) non-energy related emissions from the agriculture sector decrease at a faster rate than in the past, and, (3) agricultural employment does not decrease as fast as historically given the larger need for labour force under sustainable agriculture (compared to conventional) as represented in the model structure.

► Policies

The policies scenario combines all the above-mentioned scenarios. The timing of policies in the individual scenarios as well as in the combined scenario are depicted in Figure 24. Dark shades represent years in which changes are made with regards to the specific policy. If a dark colour is followed by a light one, it means that a policy or share of investment change is made in one year and stays the same from then on.

[50] For corresponding nutritional recommendations, see for example: https://www.dge.de/presse/meldungen/2024/gut-essen-und-trinken-dge-stellt-neue-lebensmittelbezogene-ernaehrungsempfehlungen-fuer-deutschland-vor/ (retrieved on June 26, 2024)

Figure 24: Timing of policies in the scenarios



Source: Own calculations

4.1 KPI developments for individual policy scenarios

The three main Key Performance Indicators (KPIs) chosen for summarizing the overall development dynamics under individual model parametrizations are GDP, domestic material consumption and GHG emissions (Figure 25). While in the RESCUE study GDP was exogenously specified, respective economy-wide development dynamics are endogenously derived by the iSDG. Hence, GDP does not only influence economic, social and environmental developments in the model but is also influenced by developments and interventions within the different dimensions of the model.

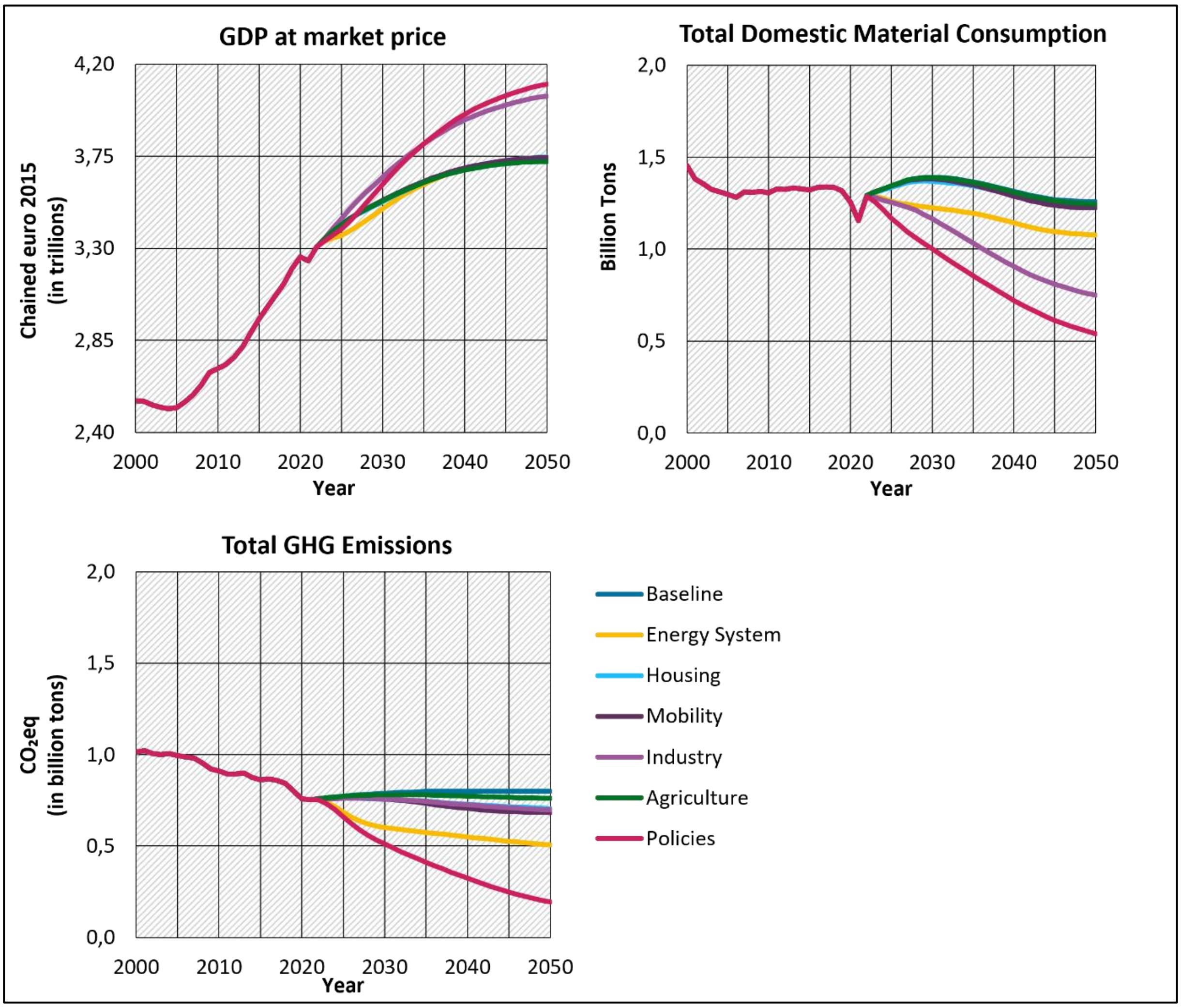
GDP at market price is increasing in all the scenarios, including the Baseline. No differences compared to the Baseline in the Housing, Mobility and Agriculture scenarios can be observed. In the Energy System scenario, GDP is moderately lower in the first ten years compared to the Baseline as a result of higher government expenses. Indeed, as the government expenses go up, debt rises which halts the increase in economic capital investment given the redirection of financial flows. With capital increasing at a slower rate, economic production also slows down. The Industry scenario is the only scenario that individually yields better results than the baseline. In this scenario, GDP increases significantly as productivity rises induced by the Circular Economy framework. Although in the beginning a combined policy approach performs slightly less well, synergies stemming from the combination of all policies in the Policies scenario, lead to the highest GDP in the long-run.

Total domestic material consumption reduces most in the Policies scenario due to the combined effects of the Industry and Energy System policies (note that the material footprint was not estimated in this study as changes outside of Germany related to imports and exports were not considered). The Industry scenario leads to the most significant changes due to material efficiency measures, which cause the domestic material consumption to decrease by 40 % compared to the Baseline scenario. The major impact comes from the reduction in the non-metallic and metal consumption. The energy consumption only contributes modestly to the overall changes. In the Energy System scenario, a notable decrease in total material consumption due to the radical decrease in fossil fuel energy consumption occurs. However, the trajectory does not result in a significant enough decrease to be considered alone. While policies affecting electricity generation and the carbon tax lead to a decrease of fossil fuel consumption and thereby reduce material consumption, in the case of the energy consumption policies the improvements due to fossil fuel reduction are compensated by an increase in non-metallic and metal ores consumption.

Compared to these projections, we do not observe any significant deviations from baseline domestic material consumption projections in cases of the Building and Housing scenario, the Mobility scenario, and the Agricultural scenario. For the Agricultural scenario, this observation can be attributed to the fact that, on the demand side, no detailed dietary changes were modelled. Hence, as far as material flows are considered, only supply-side effects can be observed in this scenario.

Considering the Building and Housing scenario, this observation can be attributed to the still somewhat preliminary reporting scope of the newly created Building and Housing module. As a matter of fact, the modelled building stocks are currently not disaggregated by individual material categories. This implies that the model does currently not track individually, which materials flows have been historically triggered for building and renovation activities by the construction industry. Consequently, projected material flows currently cannot be derived bottom-up from individual demands for, for example, traditional construction materials (non-metallic minerals) and biomass-based construction materials.

Figure 25: KPIs time series development (policy comparison)



Source: Own calculations

In the Housing scenario, dampened material demand by the construction industry for investments in newly established buildings (modelled via a lowered elasticities of per capita living space to income) is therefore largely offset by an increased material demand by the construction industry for renovating the existing building stock (modelled via surging renovation rates). Furthermore, as all material efficiency improvements are part of the Industry scenario, the respective effects are not visible when considering the other scenarios individually.

Emissions perform better in all scenarios compared to the Baseline. In 2010, Germany set the goal of reducing GHG emissions by 80 to 95 % compared to 1990 levels in compliance with the 2 degree target. This equals a reduction between 1000 and 1188 million tons of GHG emissions in CO_2 equivalents, meaning that emissions should range between 250 and 62.5 million tons of CO_2 equivalents in 2050. Since October 2023 the new goal is greenhouse gas neutrality by 2045 (Die Bundesregierung 2024).

As neither carbon capture nor carbon dioxide removal were considered in this modelling exercise, greenhouse gas neutrality is not achieved. However, in the Policies scenario gross domestic emissions are at around 250 million tons in 2045 and 194 million tons in 2050, not considering carbon capture and storage. For 2050, this translates into a 84 % reduction compared to 1990 levels is achieved, which is within the range of the target set in 2010. The biggest improvements again occur in the combined Policies scenario.

Individually, the Energy System scenario yields the best results, with significant decreases until 2050 due to changes in (1) the electricity generation mix, and (2) the energy consumption mix. The major break in the trend is associated with the decommissioning of coal in the electricity generation mix, which ensures fast results but levels off after. Then continuous improvements are mainly caused by the changes in the energy consumption of targeted economic sectors (all except industrial and residential). Net zero is not achieved because (1) the vehicle stock is not fully electric, (2) the residential and industrial energy sector are addressed in a different scenario policy package, and (3) non-energy related emissions are not addressed.

In the Industry scenario, moderate but continuous decreases until 2050 happen due to the phase-out of fossil fuel energy consumption in the industrial sector, and efficiency measures to reduce the non-energy related emissions of the industrial sector. These changes have a mild impact on total greenhouse gas emissions given the small share that industry represents in the total emissions. Hence, all policies need to work together to achieve large reductions, even if they only lead moderate to minor improvements individually.

Moderate but continuous decrease until 2050 occur in the Mobility and Building and Housing scenarios. In the latter this is a result of residential energy consumption. Indeed, the renovation and efficiency improvements lead to a decrease in residential energy consumption, specifically fossil fuel-based energy consumption. In the case of mobility, the increasing share of electric vehicles leads to reductions as households tend to choose electric vehicles over internal combustion cars, the fossil fuel transport energy consumption is drastically reduced.

In the Food and Agriculture scenario, minor decreases in emissions also happen because of small changes in non-energy agricultural emissions. These changes have a mild impact on total greenhouse gas emissions given the small share that agricultural non-energy related emissions represent in the total. In the RESCUE study all scenarios managed to achieve a reduction of more than 90 % compared to 1990 levels. The difference in the total GHG emission reductions on the one hand stems from the higher population in this scenario but more importantly also from the assumption a faster switch to alternative fuels (most importantly green hydrogen), which is not modelled in the iSDG.

Overall, it becomes apparent that the Policies scenario performs best economically as well as environmentally, with Industry and related Circular Economy measures and Energy System measures playing the largest part.

4.2 Analysis of SDG performance

The lens of analysis and the SDG performance are measured through the 17 SDG performances based on the official Sustainable Development indicators (SDi - (United Nations 2023)) that are incorporated into the iSDG (also see Table 14).

In the iSDG, each SDG encompasses a subset of indicators based on the international SDG indicators. Based on this, the SDG indicator attainment level is measured based on a ratio of (1) the difference between the indicator's value and the "zero level" (which can be understood as the "worst performance" in an international setting) and (2) the difference between the "target level" (defined based at international level) and the "zero level", as can be seen in the following equation:

SDG Indicator Attainment = (Indicator Performance-Zero Level)/(Target Level-Zero Level)

For a concise overview of the "target levels" and "zero levels" applied in individual indicator assessments, we refer to the model documentation available online.[51] In the following sections overall SDG performance in the different scenarios are presented and the main dynamics in the three sustainability dimensions (i.e. environmental, social and economic) are described. For each SDG the unweighted average of the indicators determines the overall SDG performance level.

4.2.1 Overall SDG performance in baseline and combined policy scenarios

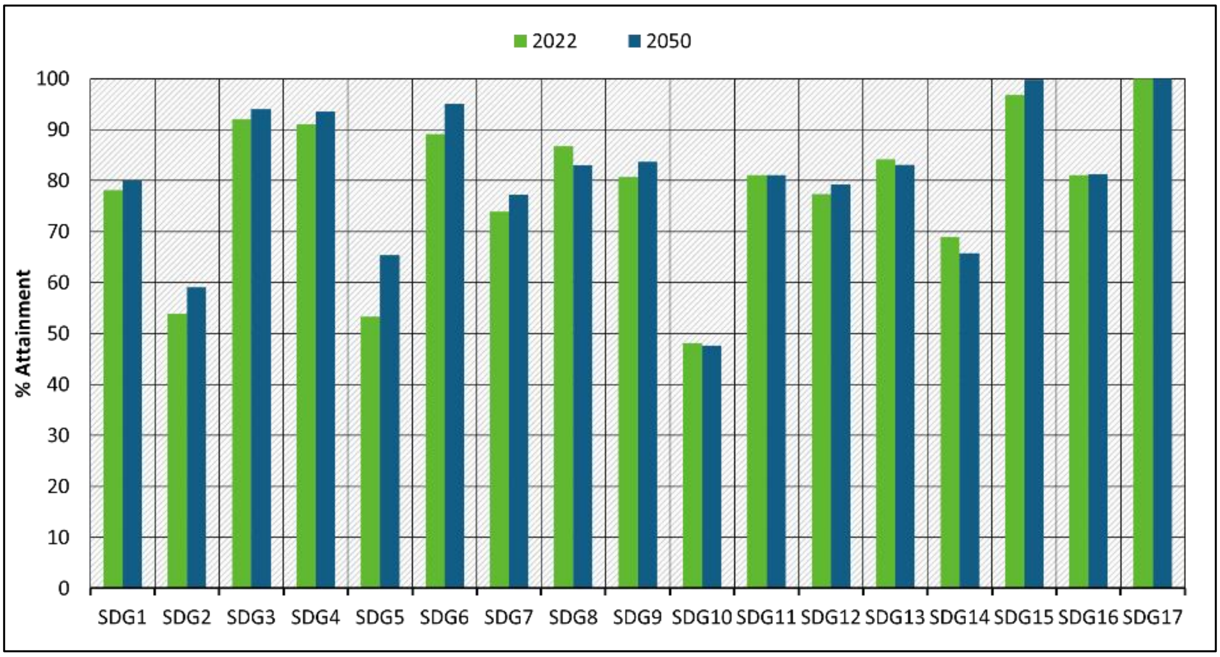
In this section, overall SDG performance and sector specific performance today, in the baseline as well as in the combined policy scenarios are presented. The contribution of each policy is discussed in more detail below.

In the Baseline scenario overall SDG attainment starts relatively high for Germany (see Figure 26), with an overall SDG performance of 78 % and none of the SDGs performing below 50 % with the exception of SDG10. In particular, SDGs 3 (Good Health and Wellbeing), 4 (Quality Education), 6 (Clean Water and Sanitation), and 17 (Partnership for the Goals) are already close to full attainment. On the other hand, for SDG 2, 5 and 10 the averaged attainment levels appear rather low for a high-income country like Germany. This observation is largely attributable to the international established definition of the mapped indicators. Taking SDG 10 (Reduce inequality within and among countries) as an example, a major driver of the averaged results is the "growth rates of household income per capita among the bottom 40 per cent of the population". As a matter of fact, it is usually the case that corresponding growth rates are considerably higher in less developed but rapidly catching-up countries (like, for example, Serbia, Albania or Croatia) than in more developed countries (like Germany or also France or Switzerland). Hence, the respective observations for SDG 10 should not be misinterpreted as significant changes with regards to inequality. (In all further evaluations of respective results, this insight was considered by also analysing the Gini coefficient as a measure for inequality effects.)

[51] https://isdgdoc.millennium-institute.org/en/ (retrieved on April 23, 2024)

4.2.1.1 SDG performance of today & in baseline

Figure 26: Baseline SDG Attainment in 2022 and 2050



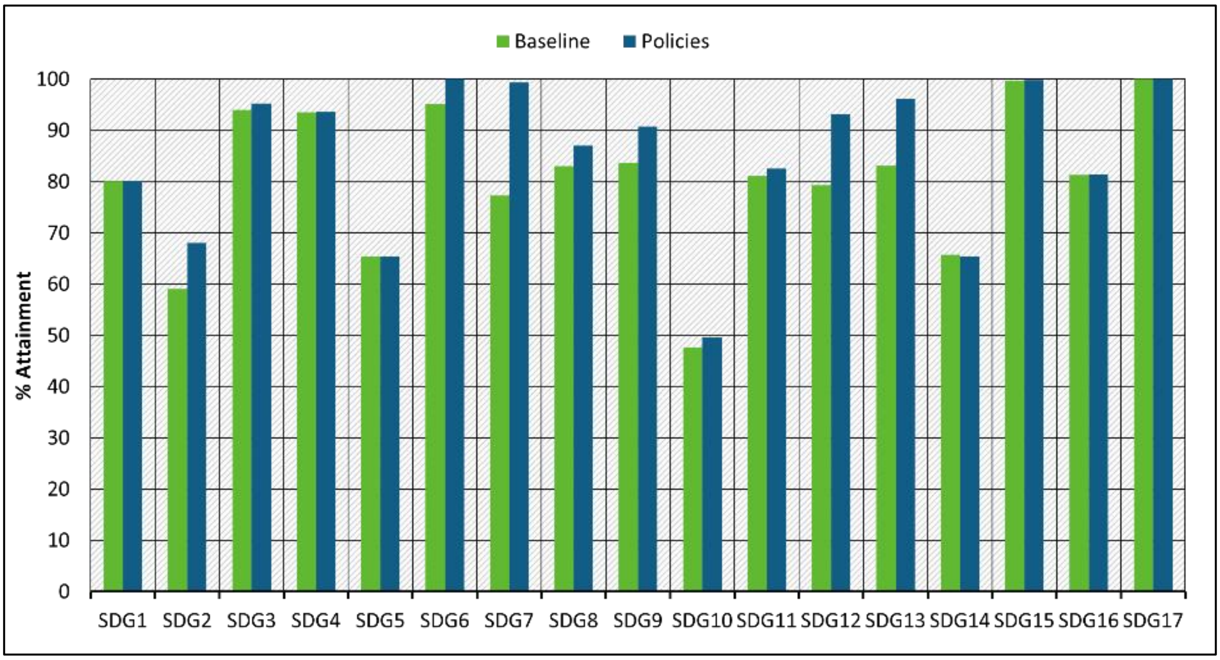
Source: Own calculations

When comparing the attainment levels of 2022 and 2050, one can see in Figure 26 that most the trends lead to higher attainment. However, for some SDGs trends are going in the wrong direction and performance is worsening (see SDG 8, 13, and 14). For SDG 8 – Decent work and economic growth, the trend worsens majorly because the GDP has a hard time growing at its historical rate given the change in demographics (see section 3.4.1). Indeed, as population growth starts stagnating and declining, the service sector grows at a much slower rate than historically which causes overall economic production to slow down.

Looking at the positive trends, SDG 5, which touches on gender equality, sees relatively high improvements (12 % increase from 2022 to 2050). This development is caused by the continuation of education for all genders. Indeed, women's participation in the education system and its highest level (tertiary education) has been growing. This leads to a change in their employment positions as well as their place in society (politically, socially, economically). Moreover, SDG 2, relating to agriculture and nourishment, also sees its SDG attainment level improve. The five percent increase observed from 2022 to 2050 is mainly caused by the improvements in the proportion of harvested area sustainably managed, which continues on its historical trend and reaches 35 % by 2050.

4.2.1.2 SDG performance in baseline & combined policy scenarios

Figure 27: Baseline & Policies SDG Attainment in 2050



Source: Own calculations

When looking into the 2050 SDG attainment of the Policies scenario, one can observe in Figure 27, major improvements from Baseline for SDG 2 (9 % higher, 14 % increase since 2022), SDG 7 (22 % higher, 25 % increase since 2022), SDG 12 (14 % higher, 16 % increase since 2022), and SDG 13 (13 % higher, 12 % increase since 2022) while minor improvements are measured for SDG 6 (5 % higher, 11 % increase since 2022), SDG 8 (4 % higher, no increase since 2022), and SDG 9 (7 % higher, 10 % increase since 2022). Moreover, based on our analysis, the Policy scenario doesn't significantly and negatively affect the performances of SDGs. A detailed description of the reasons for these improvements is presented below.

Table 14 ranks overall SDG improvement by SDG according to the three categories: none, small and significant and shows which indicators were considered for calculating SDG performance. These categories are based on qualitative judgements relating to the changes of indicators and their relevance in changes of overall SDG performance. Whether an indicator drove (✓) or did not drive (X) the development of overall SDG performance over time is indicated in the contribution to SDG column. Some indicators only contributed to the indicator change to a "small" extent.

Table 14: SDG and SDG indicator performance

SDG	SDG Indicators	Overall SDG improvement	Contribution to SDG attain-ment
SDG1	Proportion of population below international poverty line	none	X
	Proportion of population below national poverty line		X
	Proportion of households with access to basic services		X
	Disasters human impact index		X
	Economic damage due to natural disasters as share of GDP		X
SDG2	Prevalence of undernourishment	significant	low
	Prevalence of stunting		X
	Prevalence of wasting		X
	Agriculture output per worker		✓
	Proportion of harvested area sustainably managed		✓
SDG3	Maternal mortality ratio	significant	low
	Average access to basic health care		X
	Under five mortality rate		X
	Neonatal mortality rate		X
	Premature non communicable disease mortality		low
	Death rate due to road traffic injuries		✓
	Proportion of women of reproductive age (15-49 years) who have their need for family planning satisfied with modern methods		X

	Adolescent birth rate		X
SDG4	Proportion of population age 20 to 24 that has completed secondary school	none	X
	Primary and secondary average completion rate		X
	Proportion of population age 15 to 24 that is enrolled in education or has completed tertiary education		X
	Gender parity index for average years of schooling		X
	Average adult literacy rate		X
SDG5	Proportion of women in managerial positions	none	X
	Contraceptive prevalence		X
SDG6	Average access to safely managed water source	significant	X
	Average access to safely managed sanitation facility		X
	Water use efficiency		✓
	Water resources vulnerability index		✓
SDG7	Average proportion of population with access to electricity	significant	X
	Renewable share in total final energy consumption		✓
	Energy intensity measured in terms of primary energy and GDP		✓
SDG8	**Annual growth rate of real GDP per capita**	small	✓
	Annual growth rate of real GDP per employed person		✓
	Material footprint index		low
	Domestic material consumption index		low

	Unemployment rate		X
SDG9	Rural access index	significant	X
	Industry production index		low
	Industry employment as share of total employment		X
	GHG emissions per unit of value added		✓
SDG10	**Growth rates of household income per capita among the bottom 40 per cent of the population and the total population**	small	✓
	Proportion of population below half median income		✓
	Average labor share		X
	Redistributive impact of fiscal policy		low
SDG11	Land consumption index	significant	X
	Disasters human impact index		X
	Economic damage due to natural disasters as share of GDP		X
	Proportion of urban waste collected and disposed		X
	Pm 25 mean annual exposure		✓
SDG12	**Material footprint index**	significant	✓
	Domestic material consumption index		✓
SDG13	Disasters human impact index	significant	X
	GHG emissions per capita		✓
SDG14	Proportion of fish stocks sustainably exploited	small	X
	Proportion of marine areas effectively protected		✓

SDG15	Change in forest cover	small	X
	Proportion of terrestrial areas effectively protected		low
	Red list index		X
SDG16	**Conflict-related deaths per 100,000 population**	small	✓
	Bribery incidence		X
	Normalized governance index		X
SDG17	Domestic revenue as share of GDP	none	X
	Proportion of domestic budget funded by domestic taxes		X
	Interest on public debt as share of export		X

Source: Own calculations

4.2.2 Aggregated results for key sustainability dimensions

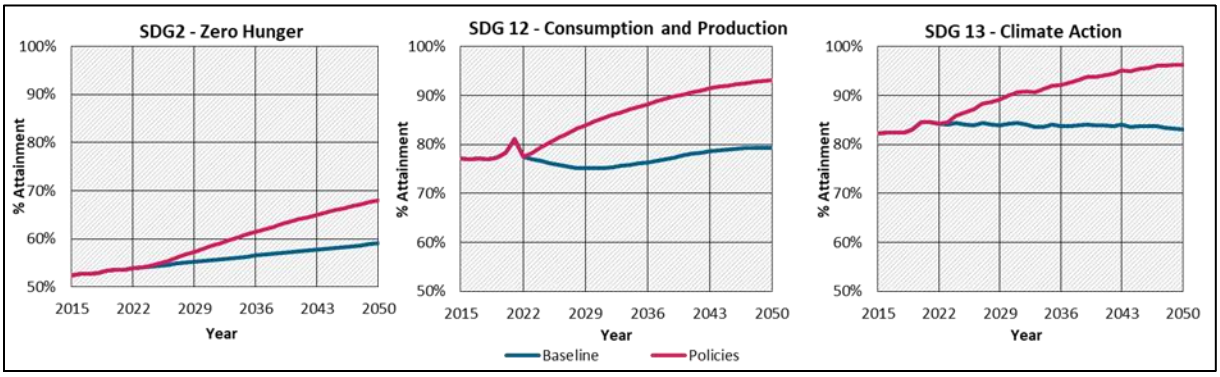
The results above show that the integrative approach of a combined policies scenario contains many potential positive spill overs. The cause of this development is analyzed in the following sub sections through the three dimensions of sustainable development: environmental, social and economic.

4.2.2.1 Environmental SDG performance

When looking at the Policies scenario and the range of interventions, three major environmental dimensions are thought to be addressed: GHG emissions, Domestic Material Consumption, and Soil's health. To analyse these three dimensions, SDG 2, 12 and 13 were selected.

As can be observed in Figure 28, SDG 2 trajectory clearly deviates from the Baseline's trajectory. Increasing sustainable agricultural practices improves overall performance of SDG 2. However, halving the livestock but negatively impacts on SDG 2 as it reduces the volume of production per labour unit in the agricultural sector. The growing proportion of harvested area sustainably managed has two major effects: (1) decrease in non-energy related agricultural emissions and (2) revitalised soil nutrient balance. However, the analysis suggests that great attention needs to be put on the source of nutrient input. Indeed, as manure application decreases (given the decrease in livestock production), the use of artificial fertilizer might be prioritised over natural solutions which could have negative consequences over time.

Figure 28: Environmental SDGs time series development



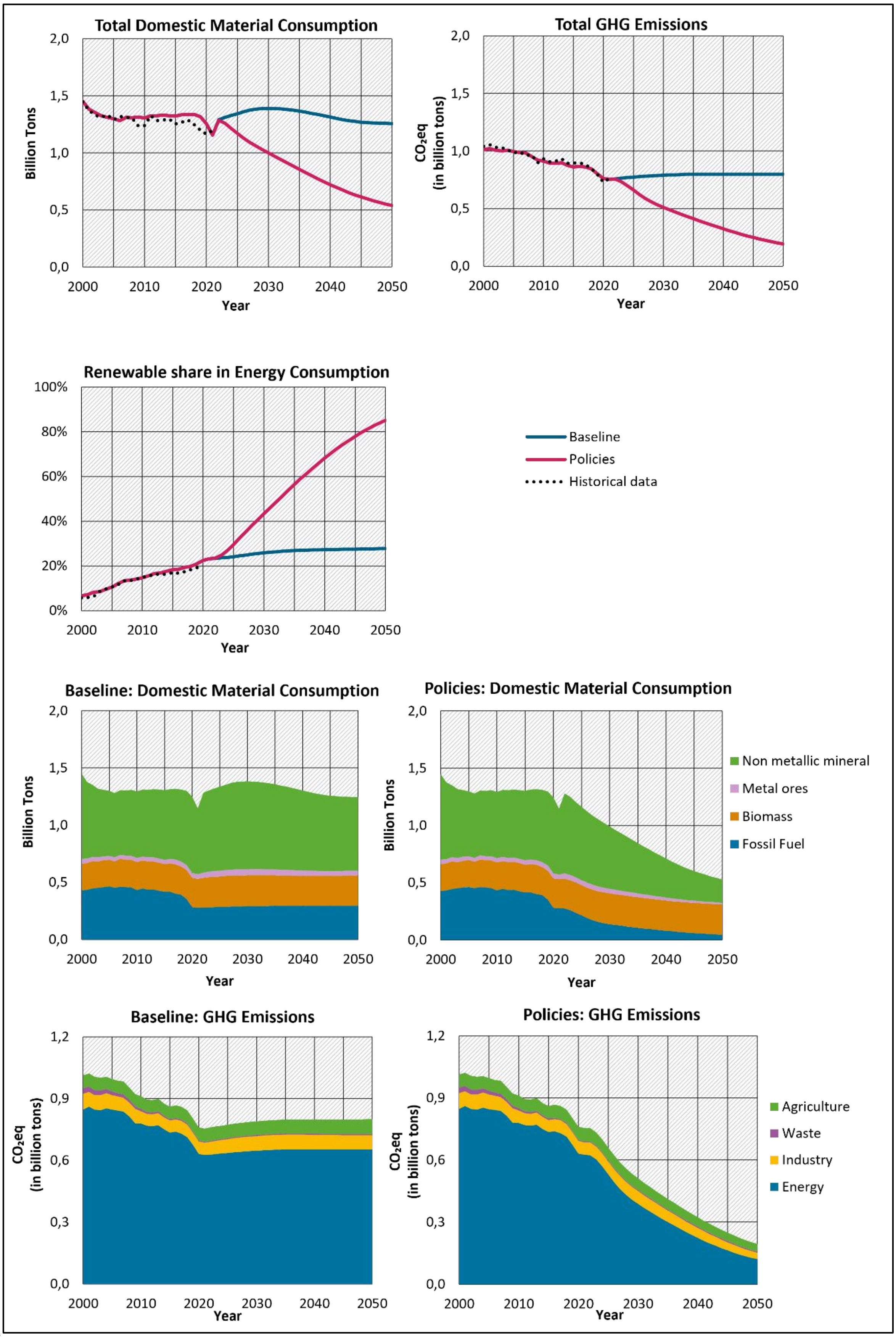
Source: Own calculations

Concerning SDG 12, which relates to responsible consumption and production, Germany's main affair refers to material footprint and consumption. Due to the missing coverage of global contexts, the material footprint is only superficially derived from projected national income developments. Domestic Material Consumption (DMC, shown in Figure 29) is calculated as the sum of biomass consumption, construction and other material consumption, fossil fuel consumption and metal ores, which are the result of the endogenous dynamics of each sector captured in the model.

As can be observed in Figure 29 the fossil fuels and non-metallic minerals represent the largest share of material consumption, therefore, on the one hand, the radical change entailed by the combination of the energy related policy packages (Energy Consumption, Building and Housing, Mobility) causes fossil fuel material consumption to drastically decrease. On the other hand, the material related policy package (Industry) causes the non-metallic mineral consumption to drastically decrease too. These two components cause the overall domestic material consumption to decrease by 55 % from 2022 to 2050.

Regarding SDG 13, which relates to climate action and in particular to GHG emissions, the Policies scenario has a high impact on SDG attainment. Most of the impact is caused by changes in energy consumption. Indeed, as can be seen in Figure 29 the majority of GHG emissions are related to combustion of fossil fuels, which are depicted as energy emissions and include energy related emissions in all sectors (the energy sector itself, residential, transport, industry, services and agriculture). Note that this scenario is line with the "Fit for 55" EU legislative framework which aims at reducing of 55 % GHG emissions by 2030 compared to 1990. For Germany, this can be translated to a reduction of 688 million tons of CO_2 equivalent (from 1 251 to 563 million tons of CO_2 equivalent). Total GHG emissions are continuously declining from 760 million tons in 2020 to 195 million tons (equals a reduction of 85 % compared to 1990 levels) in 2050. While this reduction is achieved for 2030 (511 million tons), the 2050 goal of climate neutrality is not achieved for two major reasons: (1) the inherent time delays that occur when seeking to change key energy dynamics (housing and transport), and (2) the technical limitations in non-energy related emissions (agriculture, waste, industrial processes). This observation encourages taking other measures in addition to the ones suggested in the Policies scenario. In particular, the analysis suggests measures related to climate adaptation, which is related to the global developments (i.e. SSP2 scenario) in which the German scenarios are embedded in.

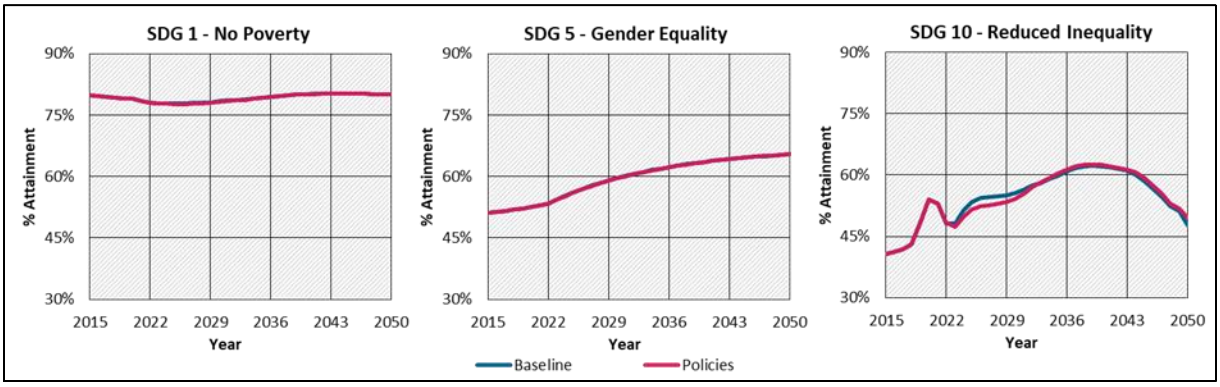
Figure 29: Environmental indicators time series development



Source: Own calculations

4.2.2.2 Social SDG performance

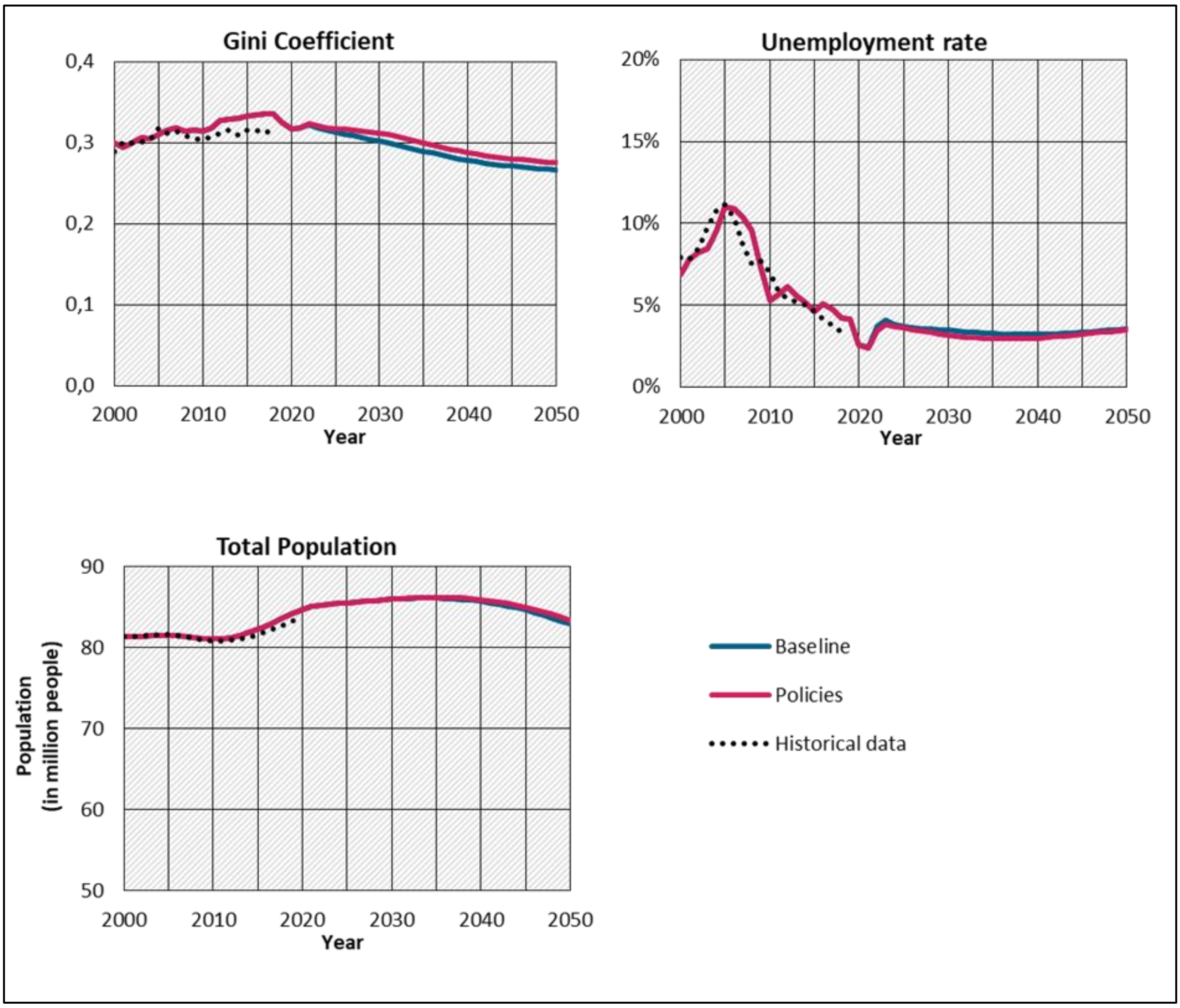
Figure 30: Social SDGs time series development



Source: Own calculations

For the social sectors, the analysis suggests no significant impact or spillovers across social SDGs. This is mainly due to two elements: (1) Germany's SDG attainment is already quite high when it comes to social indicators (also compare Sachs et al. (2023)), and (2) the interventions defined in the Policies scenario aren't directly aimed at achieving social benefits. As can be seen in Figure 30 SDGs 1, 5, and 10 don't have major changes in development compared to the Baseline scenario. For SDG 10 this is partly due to the way the indicators for this SDG are defined (see definition of indicators in the Annex and discussion of indicators below). Moreover, when looking at more specific indicators in Figure 31 we see no major changes in the development of unemployment or population. While a difference exists when looking at income distribution through the Gini Coefficient, the trend is the same. More details will be developed when looking at each policy package separately but the reason behind this performance comes from the Carbon Tax policy. Indeed, the assessment of the Carbon Tax policy hints at a higher impact on low income revenue which could potentially lead to other social disruptions if not managed collectively (as it has been in France).

Figure 31: **Social indicators time series development**

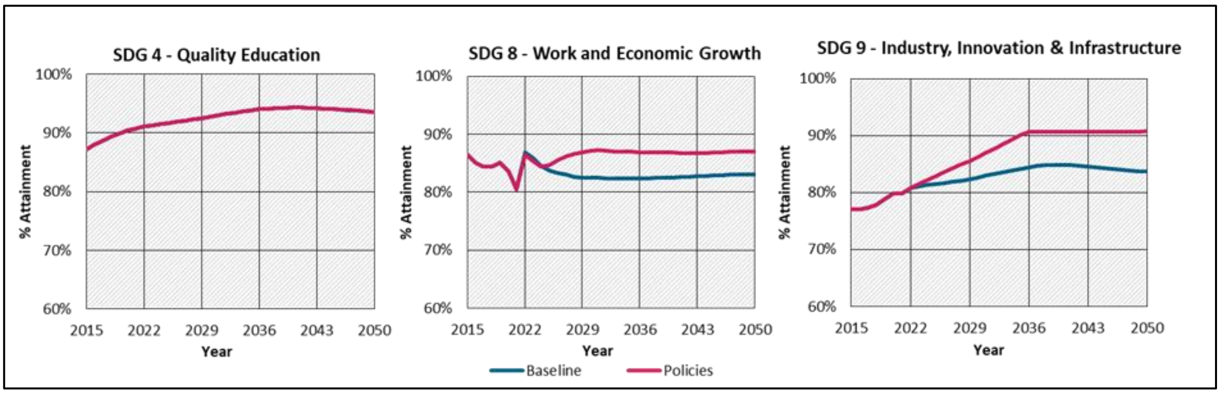


Source: Own calculations

4.2.2.3 Economic SDG performance

Similarly, to what the social sectors analysis suggested, economic sectors are not majorly impacted by the Policies scenario. As sought, the decoupling of environmental impact and economic production is achieved seamlessly. One can see in Figure 32 that SDG 8 and 9 achieve higher levels of attainment under the Policies scenario. The reasons behind this development are the following: (1) the Circular Economy framework in the industry policy package does increase productivity whilst reducing environmental impact, and (2) the change in energy consumption doesn't impact negatively the fundamental dynamics of economic capital but does have major impact on the dynamics of GHG emissions. As can be observed in Figure 33, GDP at market price evolves at a higher level than in the Baseline scenario. This is mainly due to (1) the increase in industrial production and (2) the changes in financial flows related to energy. Cause (1) will be further analysed when analysing the Industry policy package. When looking into cause (2), the main dynamics that unfolds goes back to the changes in energy consumption.

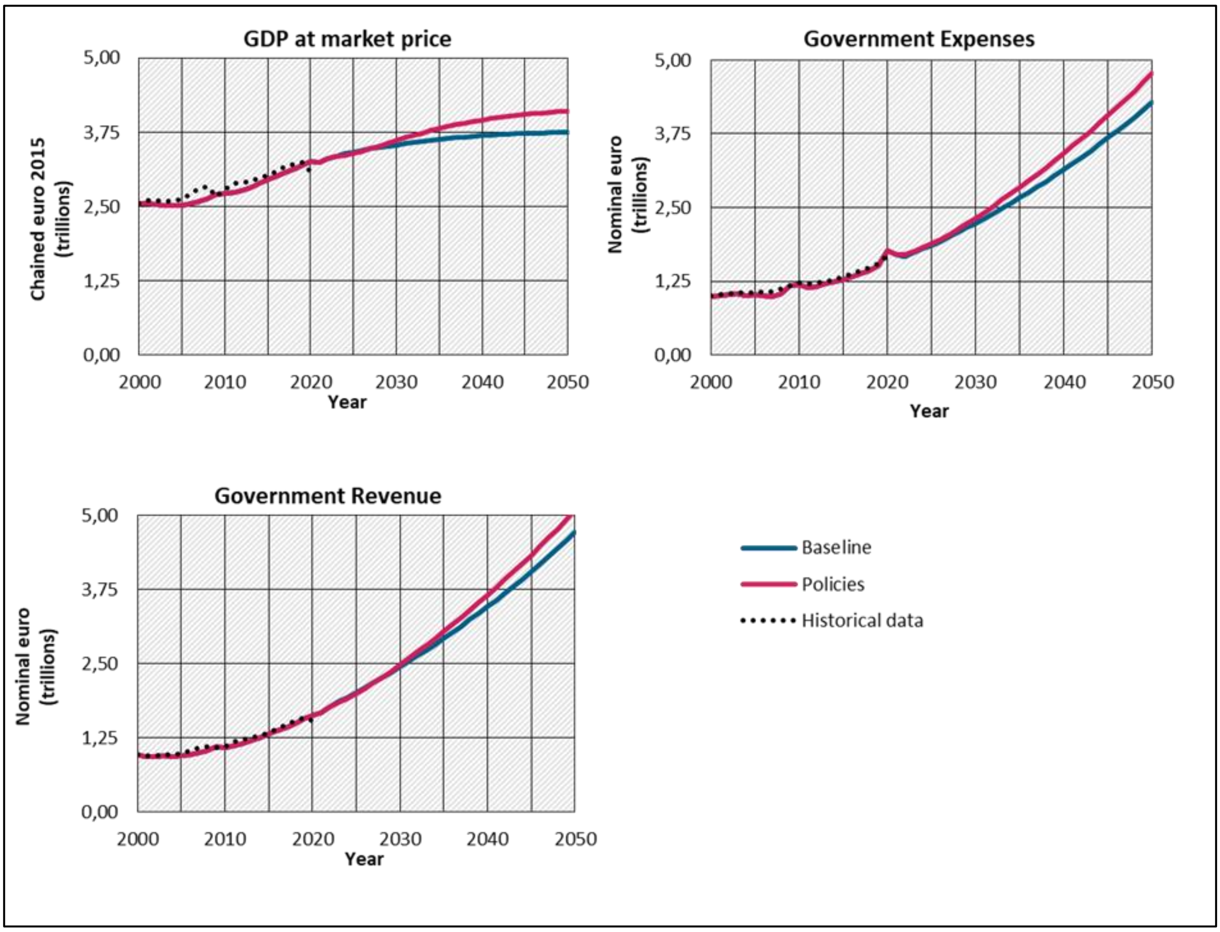
Figure 32: Economic SDGs time series development



Source: Own calculations

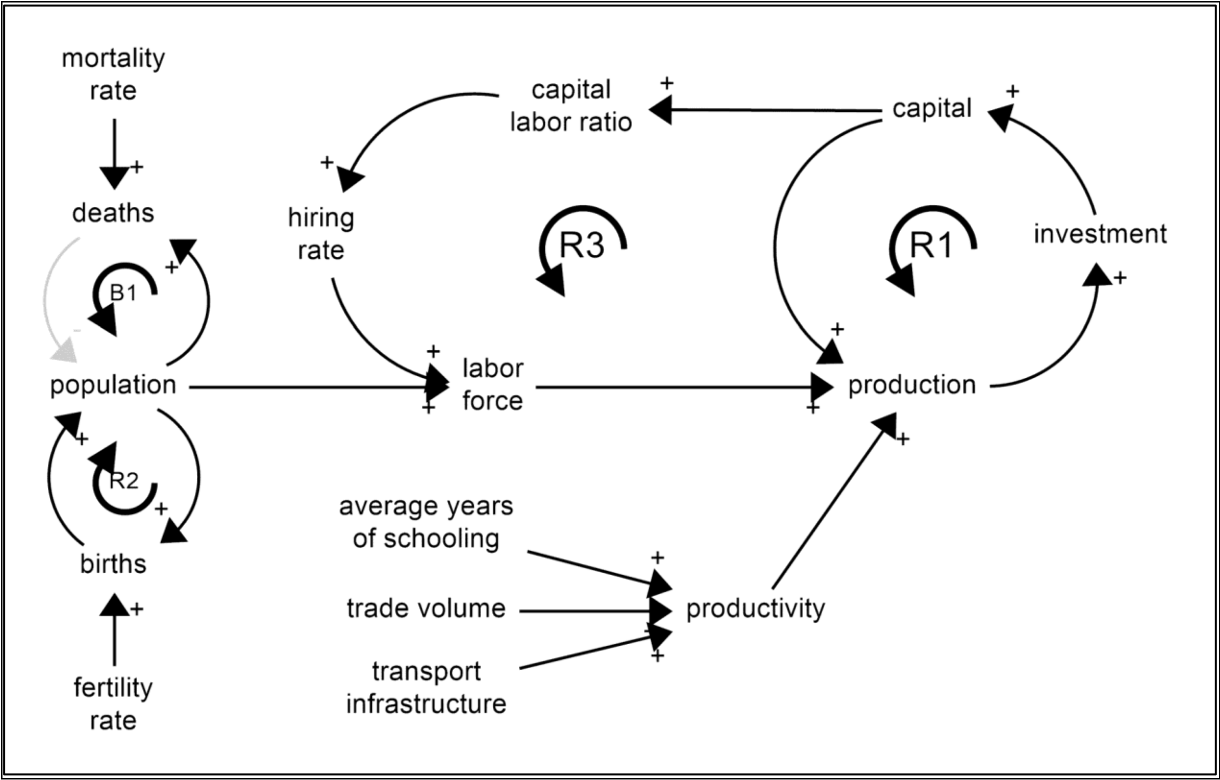
Phasing out of fossil fuels entails reducing the dependency to foreign energy imports. Combined with a larger volume of domestically generated electricity, Germany increases its energy resilience. This translates into a higher positive trade balance for the country, which positively impacts total factor productivity. This leads to a growth in value added which again, increases government (through the different levels of taxation) and private revenues which overall enables the increase in expenditures.

Figure 33: Economic indicators time series development



Source: Own calculations

Figure 34: iSDG Economic Dynamics



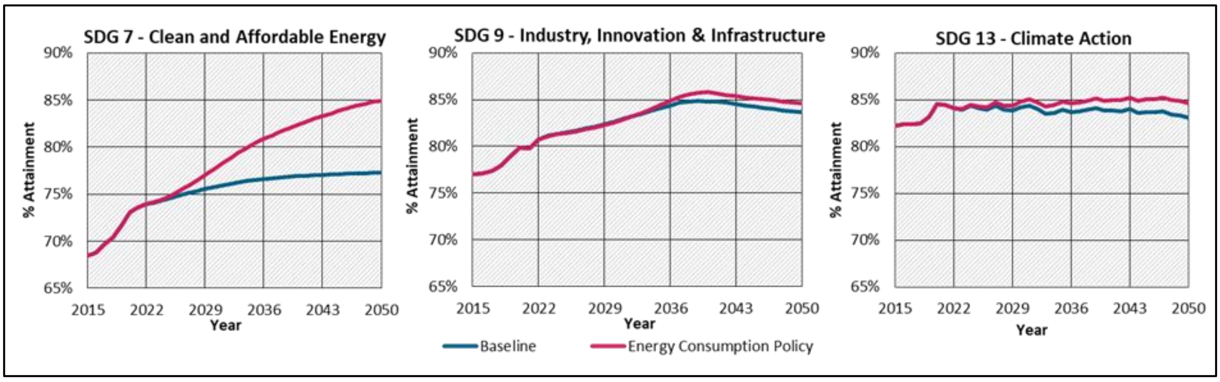
Source: Own calculations

Figure 34 displays the main dynamics relevant for understanding economic developments in the iSDG. The relationships between the economic modules include many effects. Over the short-term, investment in sectors forms new, more productive, capital, which stimulates employment demand and output. Output is then either consumed domestically, or, when there is a surplus, it is exported. In the long term, output is dependent on the levels of the factors of production (capital, labor, and total factor productivity). Private investment is allocated between the sectors. At an aggregate level, the relationships between economic sectors can be understood as a feedback relationship between firms producing output based on capital, labor, and total factor productivity. This affects consumption and saving, which is the proportion of the value added that is then reinvested. The reinvestment then leads to a change in capital, which indicates employment demand and drives changes in hiring.

4.3 Detailed SDG analysis for individual policy packages

4.3.1 Influence of energy consumption policies on SDG performance

Figure 35: Energy concumption: SDG development over time of concerned SDGs



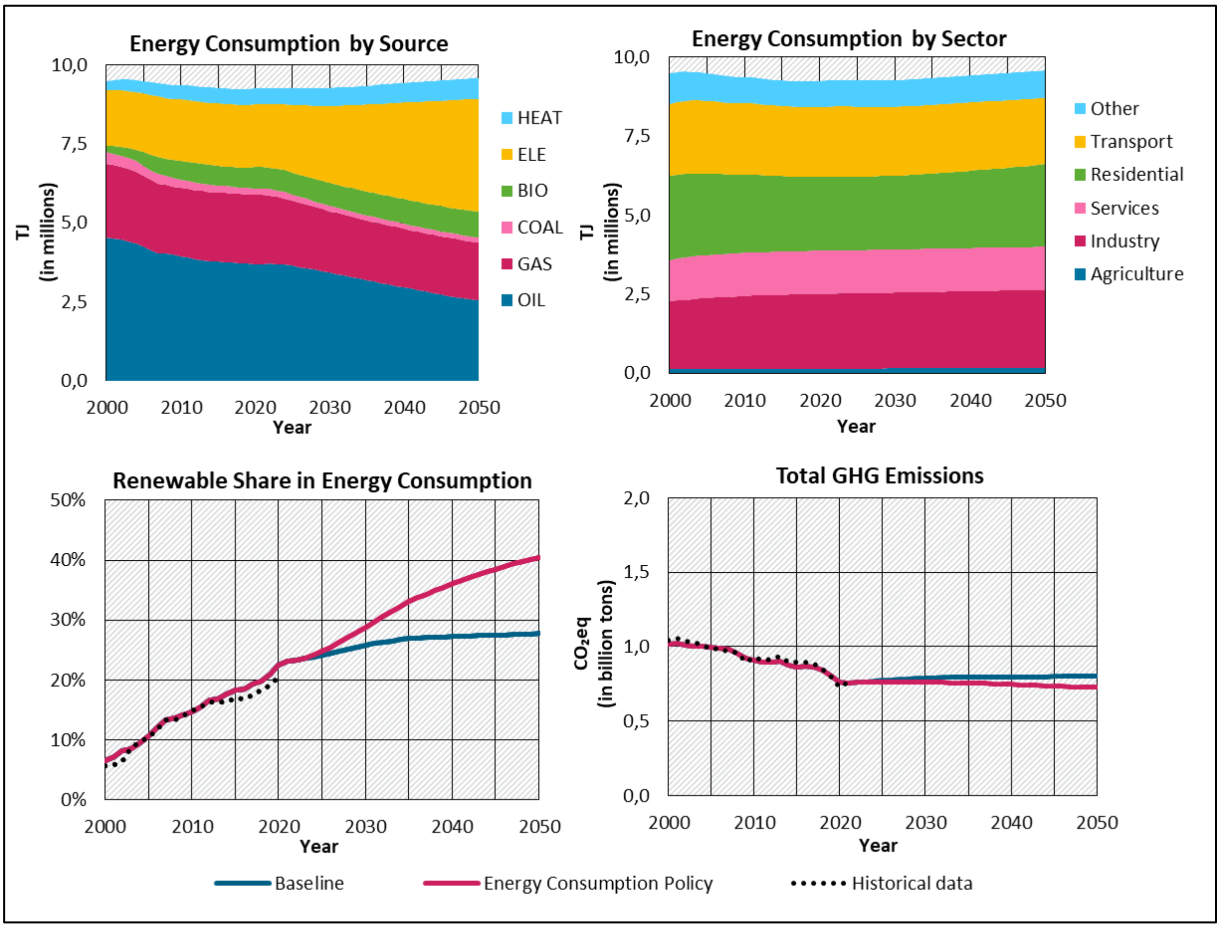
Source: Own calculations

In the pursuit of sustainable development partially illustrated in the Energy System policies, the Energy Consumption policy package crafts a scenario focusing on energy consumption transformation across diverse economic sectors, making significant strides toward SDGs. The following analysis offers a comprehensive evaluation of the outcomes and implications within the German context. In this scenario, Germany commits to a pivotal shift in energy consumption, targeting a transition to cleaner sources across all economic sectors, with the notable exceptions of industry, households, and transport. By the year 2050, these economic sectors, encompassing agriculture, services, and others as residual category (which does not include industry), cease their consumption of fossil fuels and instead increase their reliance on electricity. The main impacts of this policies concern SDG 7, 9 and 13 as displayed in Figure 35.

Concerning SDG 9, Germany demonstrates high attainment, reaching 84 % by 2050. This accomplishment is underpinned by modest yet noteworthy improvements in SDi 9.4.1, which tracks CO_2 emissions per unit of value added. These improvements, while seemingly minor, carry significance, given the relatively low share of services, agriculture, and other economic sectors (excluding industry and households) in the total energy consumption, which stands at less than 25 %. However, the discernible reduction in fossil fuel-based energy consumption within these sectors has a cascading effect, resulting in a modest decrease in greenhouse gas emissions. It is this combination of increased production and reduced emissions that facilitates SDG 9's achievement.

The pursuit of SDG 13 in Germany also demonstrates significant progress, reaching an impressive 84.5 % attainment by the year 2050. This progress can be attributed to sustained improvements in SDi 13.2.2, which gauges per capita GHG emissions in CO_2 equivalent. The pivotal alteration in energy consumption results in an 11 % reduction in fossil fuel emissions compared to the Baseline scenario by 2050. However, this reduction is dampened when looking at the total GHG emissions (see Figure 36). Only minor improvements can be observed (9 % lower than the Baseline scenario). The energy consumption of other sectors is not considered in this scenario. Therefore, the GHG emissions from energy consumption shown only reflect the reductions in the sectors outlined above.

Figure 36: Energy Consumption indicators time series development



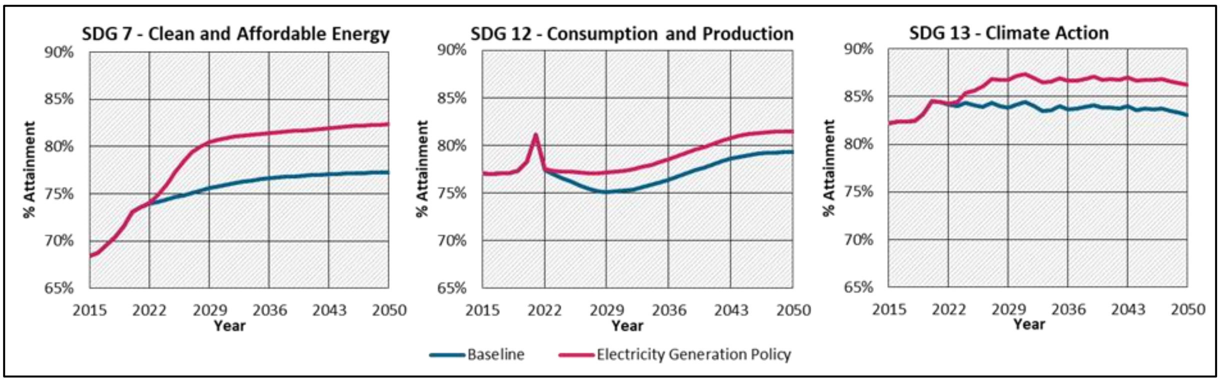
Source: Own calculations

Finally, in the context of the Energy Consumption scenario, we observe a notable achievement of high attainment in SDG 7. By the year 2050, Germany achieves an 85 % attainment of this goal. This strong performance is directly attributable to SDi 7.2.1, which monitors the renewable share in total final energy consumption.

A pivotal change in the energy consumption mix is the cornerstone of this endeavor. In 2050, an impressive 40 % of final energy consumption is derived from renewable sources, a substantial leap compared to the mere 27 % projected in the Baseline scenario. The primary driver behind this progress is the deliberate reduction of fossil fuel-based energy consumption within the services sector, representing 13 % of the total final energy consumption. As can be observed in Figure 36 most of the current final energy consumption is fossil fuel based (26 % gas, 40 % oil and 2 % coal). With the Energy Consumption policy package this share drops significantly (18 % gas, 26 % oil and 2 % coal). The major share of the remaining oil consumption occurs in the transport sector, as it is not explicitly targeted under this policy package but in the mobility policy package. For coal and gas the share stays the same for household and industry as this is not addressed in this policy package. The shift away from fossils is a shift towards higher electricity consumption, which even without additional electricity policies leads to a higher share of renewables in energy consumptions as Germany benefits from an expanding share of renewable electricity generation. This effect occurs because Germany benefits from historical and price developments that lead to a growth in renewables even without additional public investments (as can be seen in Figure 36). However, this effect is larger when electricity generation is targeted as described below.

4.3.2 Influence of electricity generation policies on SDG performance

Figure 37: Electricity generation: SDG development over time of concerned SDGs



Source: Own calculations

In this scenario, Germany's approach to electricity generation capacity has undergone a pivotal transformation in the scenario presented. The following analysis provides an intricate examination of the impact on Sustainable Development Goals (SDGs) and other Key Performance Indicators (KPIs) within the German context. In this envisioned scenario, Germany boldly takes two major steps to redefine its electricity generation landscape (see previous section for details). Firstly, a firm commitment is made to phase out fossil fuel-based electricity generation entirely by the year 2030. Secondly, substantial investments are directed towards bolstering the deployment of renewable energy sources, with a pronounced focus on solar and wind energy. This innovative approach is designed to align with the SDGs and channel efforts towards a greener and more sustainable energy future. This major transition of the electricity generation system mostly impacts SDG 7, 12 and 13 as displayed in Figure 37.

The progress made in the realm of SDG 7, which encompasses affordable and clean energy, reflects high achievements. By the year 2050, Germany attains a notable 83 % adherence to SDG 7, primarily driven by continuous advancements in two critical indicators: SDG Indicator (SDi) 7.2.1 – Renewable Share in Total Final Energy Consumption and SDi 7.3.1 – Energy Intensity Level of Primary Energy. For SDG 7, key insights from this scenario analysis include:

- Increased Renewable Energy Share: By altering the composition of its electricity generation mix, Germany successfully elevates the share of renewable energy sources in its final energy consumption. In 2050, a substantial 85 % of the nation's final energy consumption is derived from renewable sources, a significant leap from the 27 % observed in the Baseline scenario. It reflects the high share of renewable energies in the electricity mix, which is around 90 % in 2050. This achievement aligns with Germany's commitment to reducing carbon emissions and fostering a sustainable energy ecosystem and is close to the findings of the RESCUE study, in which all scenarios reach a renewable share of 90 % or higher, with the exception of the GreenLite scenario.
- Early Impact: Notably, a considerable portion of the improvement is realized well before the year 2030. This early transformation can be attributed to the systematic phase-out of fossil fuel-based electricity generation from coal and oil capacity, a pivotal step in curbing carbon emissions and promoting cleaner energy sources. This is also aligned with the RESCUE study, in which all coal fired power plants are decommissioned until 2030.
- Pre-existing Advantages: It is important to recognize that Germany starts from a favourable vantage point, with an already high proportion of its population having access to electricity

(SDi 7.1.1). This pre-existing infrastructure advantage serves as a strong foundation for the ambitious sustainability goals set forth in this scenario.

- Holistic Approach Required: While the scenario yields impressive progress in SDG 7, it is imperative to acknowledge that achieving even higher levels of attainment demands a more holistic approach. The transformation of the electricity generation sector must be complemented by parallel efforts to modify energy consumption patterns and sustain economic production. To further enhance SDG 7 outcomes, a comprehensive strategy, such as the one underlying the combined Policies scenario, that addresses all aspects of the energy system is indispensable.

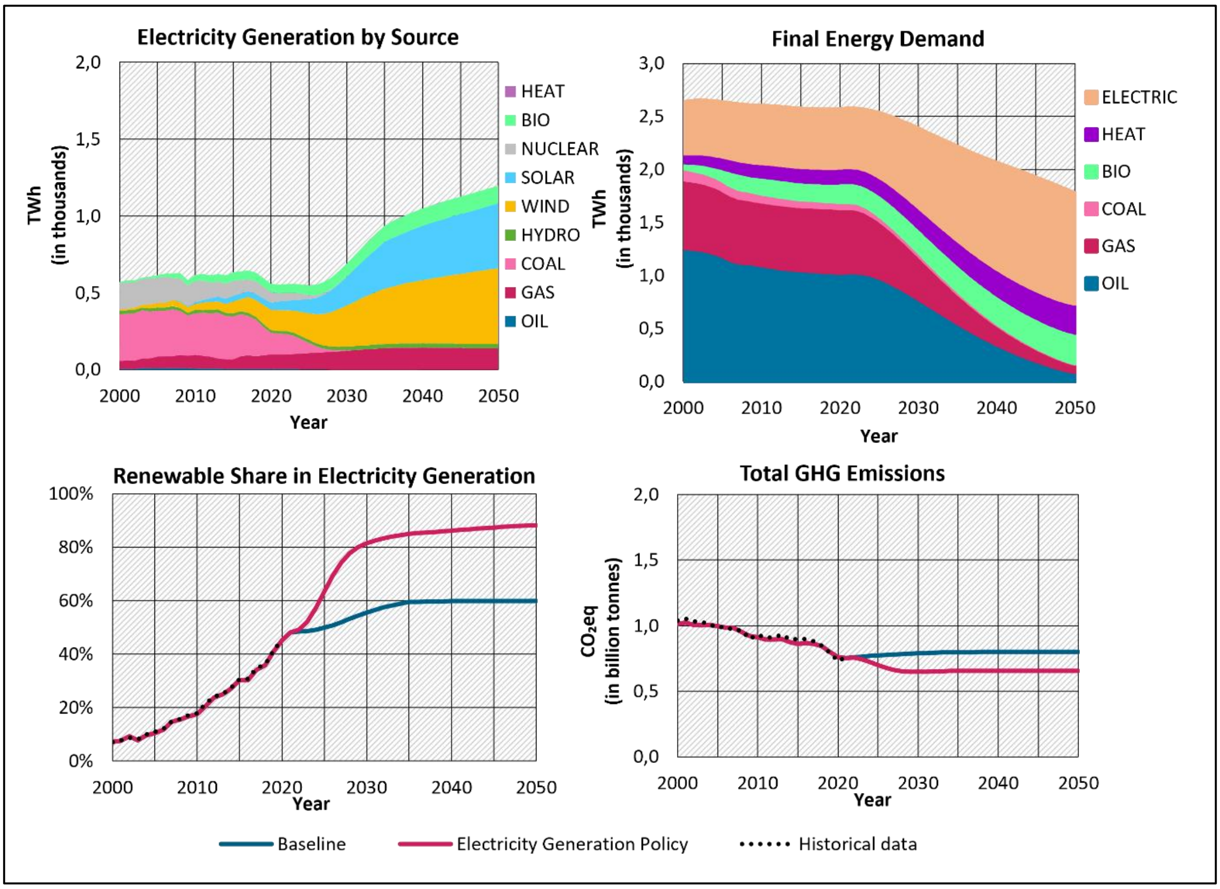
The analysis of SDG 12 reveals a substantial progress towards high attainment, with a projected achievement of 81 % by the year 2050. This notable advancement can be largely attributed to a series of continuous improvements concerning SDi 12.2.1, which pertains to the material footprint as the consumption of fossil fuels (one its components) is reduced, and SDi 12.2.2, focusing on domestic material consumption. As of 2050, Germany has successfully decreased its fossil fuel material consumption by an impressive 40 % when compared to the Baseline scenario. It is important to note that the most significant gains in this regard are realized prior to 2030, aligning with the phased decommissioning of fossil fuel-based electricity generation. This strategic transition underscores the critical role of the energy sector in achieving the desired targets for SDG 12.

To further enhance the prospects of achieving higher levels of attainment for SDG 12, it is imperative to adopt a holistic approach that amalgamates changes in electricity generation with comprehensive modifications in energy consumption and material efficiency across various sectors. This approach is essential to curtail domestic material consumption of fossil fuels, and to extend the benefits to other key components, such as non-metallic minerals, metal ores, and biomass. The synergistic alignment of these efforts holds the potential to drive significant reductions in material consumption and a concomitant decrease in environmental impacts.

The pursuit of SDG 13 has also yielded progress, with an anticipated high attainment of 86 % by the year 2050. This achievement can be primarily attributed to the continuous improvements observed in SDi 13.2.2, focusing on per capita greenhouse gas (GHG) emissions in CO_2 equivalent. A key driver of this progress is the transformation of the electricity generation mix, which, by 2050, has led to a substantial 22 % reduction in fossil fuel emissions when compared to a Baseline scenario. Notably, the majority of these reductions occur prior to 2030, in line with the phased decommissioning of fossil fuel-based electricity generation.

However, to further advance towards higher attainment of SDG 13, it is imperative to adopt an integrated approach that goes beyond changes in electricity generation. This comprehensive strategy should encompass shifts in energy consumption, industrial emissions, and agricultural emissions. Only through this multifaceted approach can the ambitious goal of achieving net zero GHG emissions by 2050 be realized, underlining the critical need for systemic changes in various sectors to combat climate change effectively.

Figure 38: Electricity generation indicators time series development



Source: Own calculations

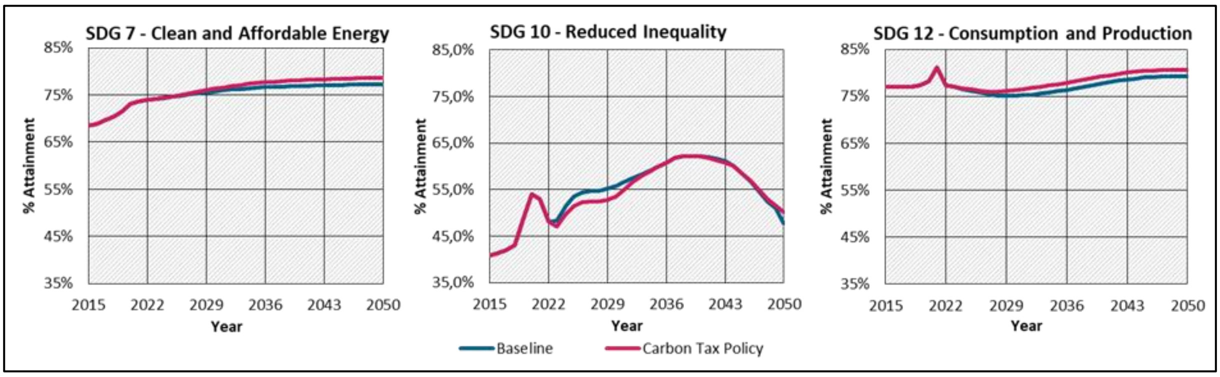
Moving away from formal SDG indicators, one can observe in Figure 38 that under the Electricity Generation package, the electricity generation mix radically changes:

- oil and coal are not part of the mix,
- gas only represents a small share of the total electricity generation (11 % in 2050),
- both solar and wind gain significant shares in the mix due to increase in investment,

all of which drives upwards the proportion of electricity from renewable sources. Indeed, by 2050, 90 % of electricity is generated from renewable sources. The remaining 10 % can mostly be attributed to gas. In this scenario, also nuclear energy is almost entirely phased out due to the dynamics resulting from the fossil phase out with the exception of gas and the strong push for renewables. The most significant share of this progress is attributed to the decommissioning of oil and coal as we see that between 2020 and 2030, we nearly double the proportion of electricity from wind, solar and hydro (from 44 % to 82 %). This is also the main driver for the drop in emissions as we see that no significant progress is made once the decommissioning phase is over. As previously stressed, changes in electricity generation are not sufficient enough to achieve emissions neutrality.

4.3.3 Influence of a carbon tax on SDG performance

Figure 39: Carbon tax: SDG development over time of concerned SDGs



Source: Own calculations

Still under the Energy System policy, the Carbon Tax scenario embarks Germany on a consequential scenario, focusing on the implementation of a progressive carbon tax. This scenario holds critical implications for SDGs, and the ensuing analysis provides an in-depth evaluation within the German context. In this scenario, Germany incrementally escalates carbon pricing, directly affecting the taxation of fossil fuels used in electricity generation and final fuel consumption. This initiative yields two notable effects: firstly, an increase in the cost of fossil fuels, and secondly, a tempered growth in household revenue, influenced by changes in private transfers.

Unlike the other policies, the carbon tax influences not only energy and environment related SDGs but also SDG 10, which is about inequality and thereby, most importantly the social dimension of sustainable development (see Figure 39).

To understand the developments influencing the dynamics of those SDG performances, Figure 39 displays individual indicators. Germany attains a 79 % adherence to SDG 7 by the year 2050, signifying moderately high progress towards achieving affordable and clean energy. This accomplishment is underpinned by modest improvements in SDi 7.2.1 – Renewable Share in Total Final Energy Consumption and SDi 7.3.1 – Energy Intensity Level of Primary Energy. The analysis of SDG 7 outcomes in this scenario is presented as follows:

- **Substantial Reduction in Gas and Coal Consumption:** The impact of the carbon tax on fossil fuel usage is particularly evident in the substantial reductions observed in gas and coal consumption. By 2050, gas consumption is reduced by 10 %, while coal consumption experiences a remarkable 75 % decrease in comparison to the Baseline scenario. These reductions are indicative of the tax policy's efficacy in steering energy production and consumption towards cleaner and more sustainable alternatives.
- **Increased Share of Renewables:** As carbon pricing takes effect and fossil fuel prices rise, a small shift occurs in the energy landscape. By 2050, the share of renewables in the energy mix increases by 2 % in comparison to the Baseline scenario (see Figure 40). This shift is crucial for reducing carbon emissions and promoting clean energy sources. However, the increase in share is not more pronounced, largely due to limitations in the modelling approach, as discussed in the limitations section.
- **Diminished Total Energy Consumption:** A main effect of the carbon tax policy is the overall reduction in total final energy consumption. However, it is relatively small as displayed in Figure 41.

Concerning SDG 10, the examination of results reveals an intriguing pattern, as illustrated by the Gini Coefficient (see Figure 40). In the Carbon Tax policy scenario, the Gini Coefficient is higher than in the baseline but still continuously decreases into the future, even if it is at a slower rate than in other scenarios. This distinctive trend calls for an exploration of the underlying factors and the financial flows that shape these outcomes. These factors are presented as follows:

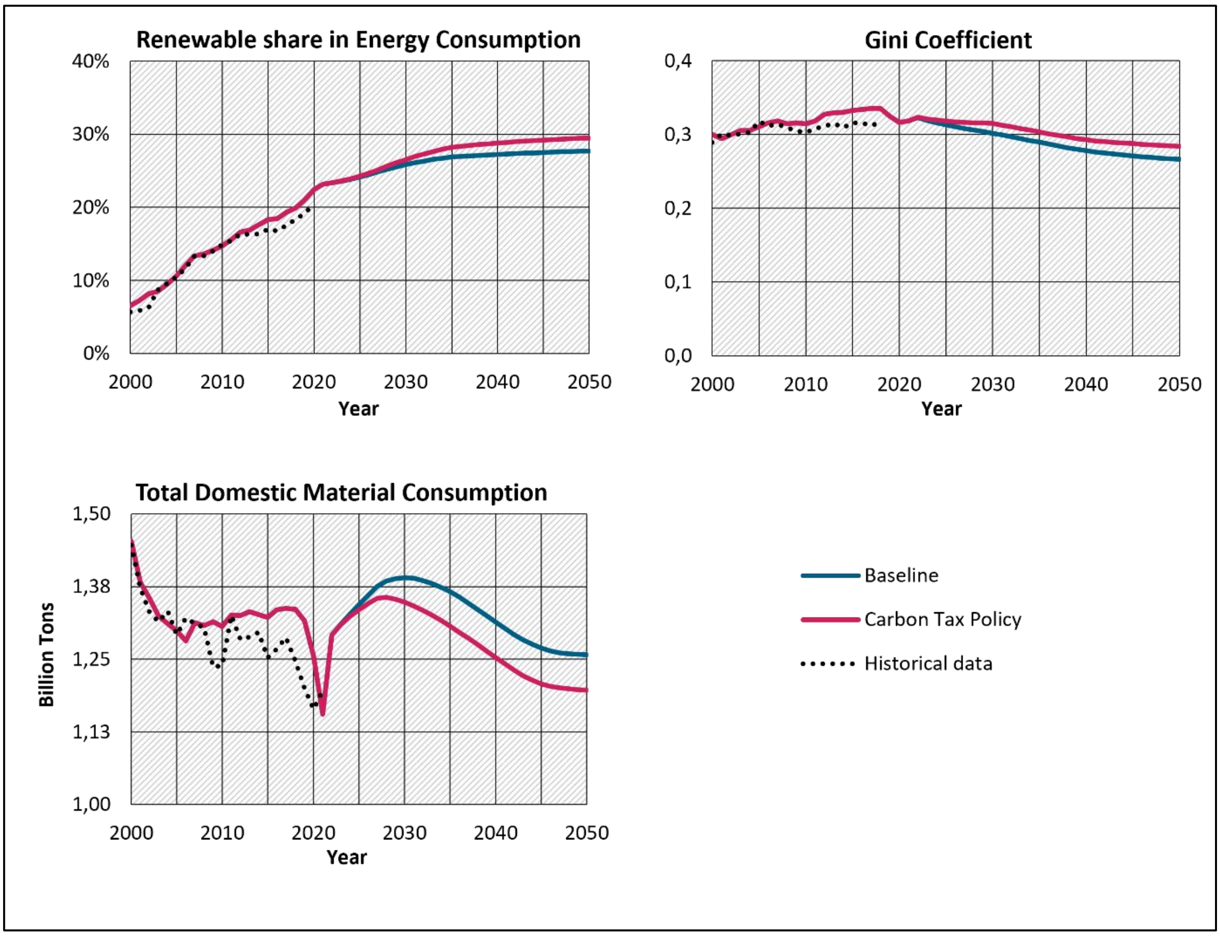
- **Impact on Household Costs:** The impact of the carbon tax policy on household revenues contributes to the observed effect. As households face increased costs due to the rise in fossil fuel prices, particularly in energy and fuel consumption, it has a noticeable effect on their financial well-being. This shift in the financial landscape exerts a substantial influence on income inequality within the nation.
- **Disproportionate Impact on Low-Income Households**: Notably, the impact is more pronounced among low-income households. For individuals and families with limited financial resources, managing the necessity of increased private consumption, influenced by the carbon tax policy, poses considerable challenges. The forced increase in private consumption exerts a more substantial strain on low-income households, as it represents a more significant proportion of their income.
- **Mitigating the Impact:** Conversely, high-income households experience a comparatively insignificant increase in consumption costs relative to their income. Their financial capacity to absorb these changes without significant disruptions to their overall well-being is considerably greater.

Germany's strategic pursuit of sustainable development yields high attainment in SDG 12, with an 80 % compliance by the year 2050. This achievement is underpinned by continuous improvements in two key indicators: SDi 12.2.1 – Material Footprint and SDi 12.2.2 – Domestic Material Consumption (see Figure 40). In this regard two major observations are to be noted:

- **Reduction in Fossil Fuel Material Consumption:** Another outcome of the carbon tax policy is the reduction of fossil fuel material consumption by 10 % in 2050 when compared to the Baseline scenario (see Figure 40). This reduction not only represents a positive step in curbing carbon emissions but also aligns with the overarching goals of responsible and sustainable resource utilization.

Pursuing Higher Attainment: To aspire to even higher levels of attainment in SDG 12, it is imperative to implement a multi-faceted strategy. While the carbon tax policy is effective in desensitizing fossil fuel consumption, more radical changes in energy consumption are required. These changes should encompass not only shifts in energy sources but also alterations in electricity generation methods and material efficiency improvements in non-energy-related material consumption. This holistic approach aims to foster a deeper reduction in domestic material consumption of fossil fuels, while also addressing the resource consumption patterns of other vital components such as non-metallic minerals, metal ores, and biomass.

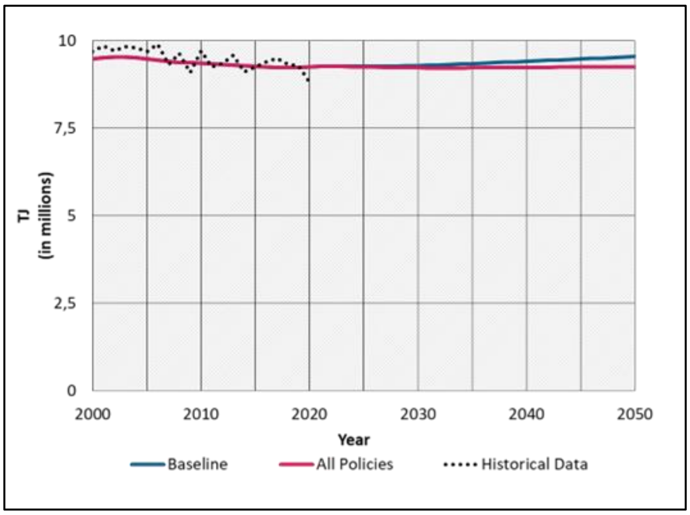
Figure 40: Carbon tax indicators time series development



Source: Own calculations

In essence, the analysis of the Carbon Tax policy scenario offers valuable insights into potential developments in Germany's pursuit of SDGs, specifically SDG 7, SDG 10, and SDG 12. While this scenario serves as an experimental exploration of what could transpire rather than a definitive projection, it underscores the nation's commitment to advancing these critical SDGs. The scenario indicates that if Germany would increase the cost of carbon emissions it would moderately help achieve clean energy, reduce carbon emissions, and foster sustainable consumption and production patterns. While not a direct blueprint of the future, this scenario prompts policymakers to consider the intricate balance between environmental sustainability and social equity and the multifaceted strategies required to drive progress in these SDGs.

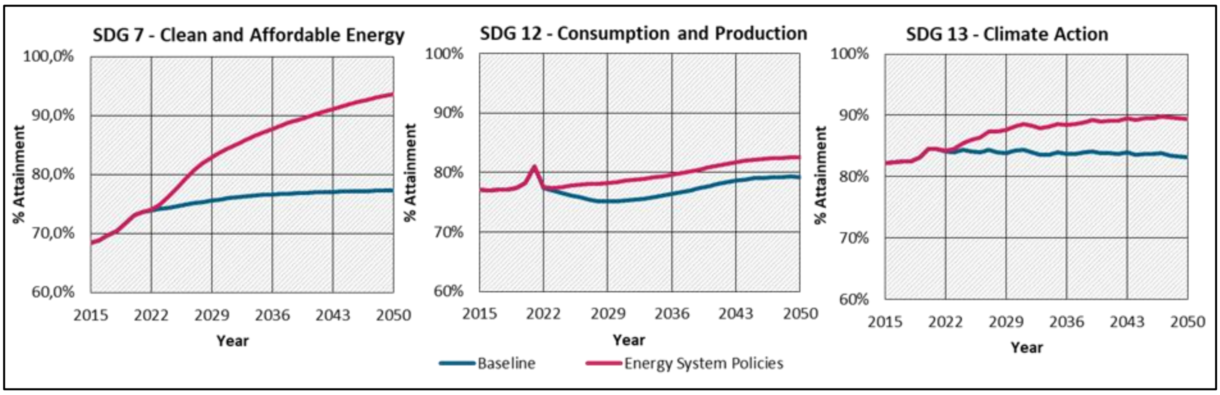
Figure 41: Total Final Energy Consumption in Carbon Tax policy



Source: Own calculations

4.3.4 Energy System policies

Figure 42: Energy system: SDG development over time of concerned SDGs

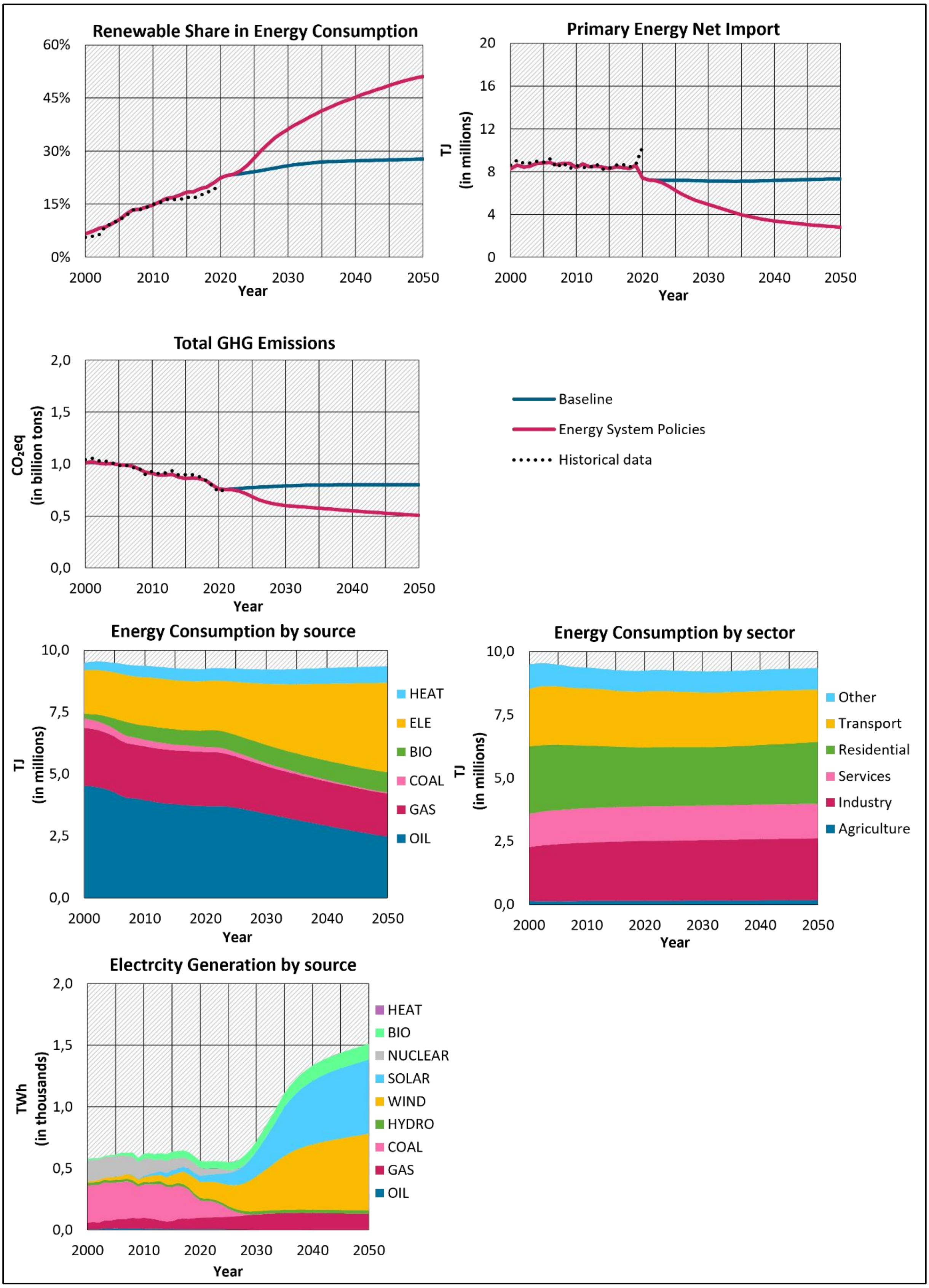


Source: Own calculations

The three policy packages described above can be seen as Energy System policies, which aim at transforming the energy system landscape and do not specifically concern the residential, industry or transport sector. The main SDGs of interest when implementing the Energy System policies are SDG 7, 12 and 13. As can be seen in Figure 42, significant attainment levels are achieved. The causes behind the development of each of these SDGs were analysed for each policy package and compared to each other to truly distinguish which impacts can be attributed to which policy.

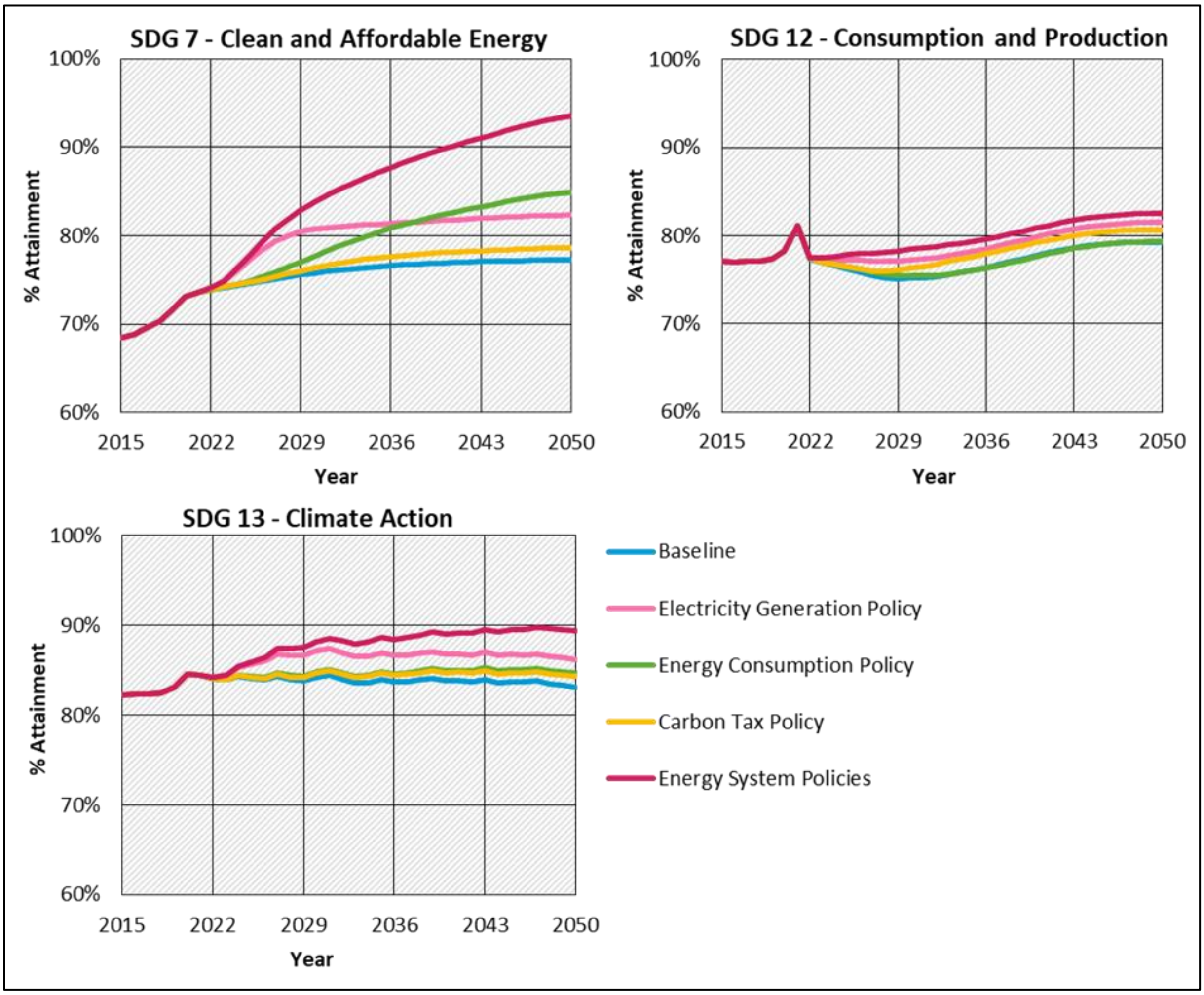
Figure 43 shows the overall major dynamics in the Energy System policies scenario of individual indicators related to the SDGs and SDG indicators as such. The overall dynamics and contribution of the separate policy packages are described below.

Figure 43: Energy system indicators time series development



Source: Own calculations

Figure 44: SDGs time series development (Energy System policy comparison)



Source: Own calculations

This sub-section aims at (1) identifying which policies in the Energy System policy package serve as accelerators and (2) describe where synergies can be harvested. By looking at Figure 44, and in particular SDG 7, one can observe that the Electricity Generation policy enables sharp increase in attainment before 2030 compared to the other policy packages.

This is caused by the decommissioning phase, however, once the decommissioning phase is over, the attainment level is quickly caught up by the attainment level of the Energy Consumption policy package which reaches the highest attainment out of all three policies. In other words, the Electricity Generation policy package has short term impacts on SDG 7, while the Energy Consumption policy package has longer term impacts. In addition, the analysis of synergies (expressed in Table 15 and Table 16) suggest that the combination of the policy packages enable greater results than the sum of its parts.

Table 15: SDG Attainment net difference between Baseline and policies in 2050

	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17
Energy System	0 %	0 %	0 %	0 %	0 %	0 %	16 %	1 %	3 %	2 %	1 %	3 %	6 %	0 %	0 %	0 %	0 %
Electricity Generation	0 %	0 %	0 %	0 %	0 %	0 %	5 %	0 %	1 %	0 %	0 %	2 %	3 %	0 %	0 %	0 %	0 %
Energy Consump-tion	0 %	0 %	0 %	0 %	0 %	0 %	8 %	0 %	1 %	0 %	0 %	0 %	2 %	0 %	0 %	0 %	0 %
Carbon Tax	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	2 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %

Source: Own calculations

Table 16: SDG Attainment net change from 2022 to 2050 by scenario

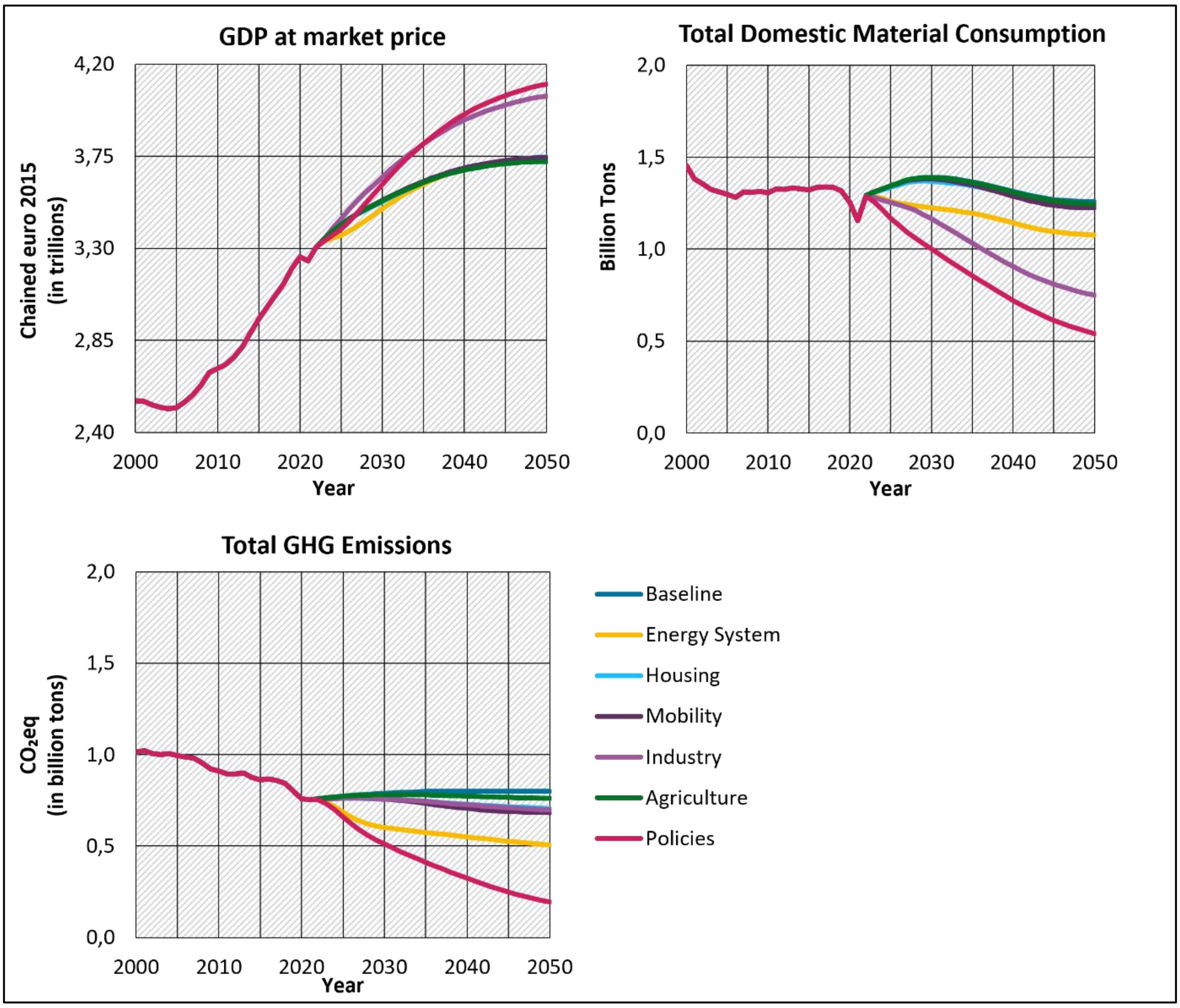
	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17
Energy System	2 %	5 %	2 %	2 %	12 %	6 %	20 %	-3 %	6 %	2 %	1 %	5 %	5 %	-3 %	3 %	0 %	0 %
Electricity Generation	2 %	5 %	2 %	2 %	12 %	6 %	8 %	-3 %	4 %	0 %	0 %	4 %	2 %	-3 %	3 %	0 %	0 %
Energy Consumption	2 %	5 %	2 %	2 %	12 %	6 %	11 %	-4 %	4 %	-1 %	0 %	2 %	1 %	-3 %	3 %	0 %	0 %
Carbon Tax	2 %	5 %	2 %	2 %	12 %	6 %	5 %	-4 %	3%	2%	0%	3%	0%	-3%	3%	0%	0%

Source: Own calculations

Indeed, when looking at the difference of attainment level in 2050 between the Baseline and the policies (Table 15), one may observe that the sum of the three policies would enable a 14 % increase in SDG 7 attainment, against a 16 % increase when policies are combined. This positive synergy and the magnitude of the attainment achieved can be explained by the combination of the changes in Electricity Generation and Energy Consumption policy packages. Whilst energy consumption gradually shifts from fossil fuels to electricity, the electricity generation capacity is changing towards renewable sources. Therefore, the proportion of energy consumption from renewable sources increases more significantly than if these were implemented separately. In the case of separate implementation, transitioning out of fossil fuel consumption leads to an increase in electricity generation which without changes in electricity generation capacity will still be carbon intensive. The other way around, transitioning the electricity generation capacity doesn't increase the electricity consumption. This later represents a minority share in total final energy consumption which therefore limits the impact on SDG 7.

Concerning SDG 12 and 13, the most impactful policy is the Electricity Generation package (as can be seen in Figure 44). The major difference for this performance, compared to other policy packages, is in the decommissioning of coal electricity power plants. The single act of decommissioning reduces the fossil fuel material consumption of 40 % and fossil fuel emissions by 20 % (both compared to 2022, see Figure 45). In addition, the historical decreasing trend of mining and quarrying production continues for all policies which leads to higher SDG 12 attainment in all cases. As opposed to the analysis made for SDG 7, the synergy analysis of SDG 12 and 13 isn't as encouraging. Indeed, the sum of the impacts are equal to the combined impact (see Table 16).

Figure 45: KPIs time series development (policy comparison)

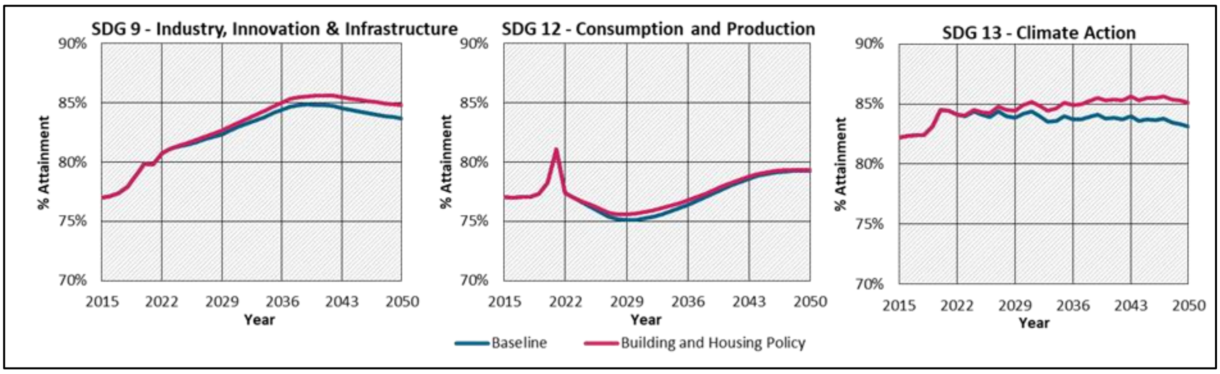


Source: Own calculations

Finally, if looking at the overall economic performance of the different policies (through GDP at market price, see Figure 45), the analysis suggests that all policies end up within a range of 2 % of the GDP achieved in the Baseline. In other words, with the set of energy scenarios no major changes are to be expected in the overall economy. However, it’s noteworthy to rank qualitatively the highest to lowest GDP achievement policies: (1) Energy Consumption, (2) Baseline, (3) Energy System, (4) Electricity Generation, (5) Carbon Tax.

4.3.5 Building and Housing

Figure 46: Building and hoursing: SDG development over time of concerned SDGs



Source: Own calculations

The Building and Housing scenario in Germany involves four key policies: promoting the energy efficiency of household electrical appliances, increasing the renovation rate of existing buildings, boosting wood-based construction, and discouraging building stock expansion (see precious section for details). These measures impact industrialization, consumption, and climate resilience as represented by SDGs 9, 12 and 13 displayed in Figure 46, these elements are the core focus of the analysis that follows.

The respective parametrisations impact overall SDG attainment under SDG 9: The implementation of the scenario results in an impressive 84 % attainment of SDG 9 by 2050. These achievements can be attributed to minor yet notable improvements in two key indicators: SDi 9.2.1 – Industry Production Index and SDi 9.4.1 – CO_2 Emissions per Unit of Value Added. The analysis of SDG 9 outcomes in this scenario is presented as follows:

- **Significant Impacts of Building Reforms:** The construction and renovation activities cause an increase in the construction component of industrial production in the model.
- **Residential Energy Consumption:** The acts of renovation and efficiency enhancements have a far-reaching effect on energy consumption patterns. This leads to a notable 30 % reduction in residential energy consumption compared to the Baseline scenario (see Figure 47). This decrease in energy consumption not only enhances energy efficiency but also plays a pivotal role in curbing greenhouse gas emissions.
- **Balancing Production and Emissions:** The enhanced attainment of SDG 9 stems from the combination of increased production, driven by building and renovation activities, and decreased emissions due to reduced energy consumption. This interplay results in a scenario that outperforms the baseline. To seek higher levels of attainment in SDG 9, the building and housing reforms must be integrated with broader energy consumption and Circular Economy efforts as they are assumed in the Energy System and Industry scenarios. This comprehensive strategy is pivotal in further boosting industrial production and continuing the downward trend of emissions.

Expanding the analysis into the implications for SDG 12, we observe overall achievement levels that a rather similar to baseline projections. This outcome is largely attributed to the restrained expansion of the building stock. In the absence of this intervention, the policy scenario would result in notably lower attainment compared to the baseline. This underscores the significance of the building and housing reforms in maintaining a sustainable trajectory for consumption and production.

- **Renovation-Driven Industrial Production:** The increase in the renovation rate has a ripple effect on industrial production, particularly within the construction sector. This leads to a slightly higher consumption of materials.
- **Balancing Material Consumption:** As shown in Figure 47 the building stock in the Baseline is much higher than in the Building scenario but the total domestic material Consumption does not differ significantly. This is due to the high renovation rates and related material demand in the Building scenario. To address the offset resulting from increased construction production and its associated material consumption, it is imperative to integrate the building policy with material efficiency incentives as were implemented in the industry policy package, such as Circular Economy policies. This multifaceted strategy serves as a counterbalance to the growing resource consumption that accompanies the surge in construction activities. The material efficiency measures aim to enhance resource utilization, minimize waste, and reduce the environmental footprint associated with material extraction and production.

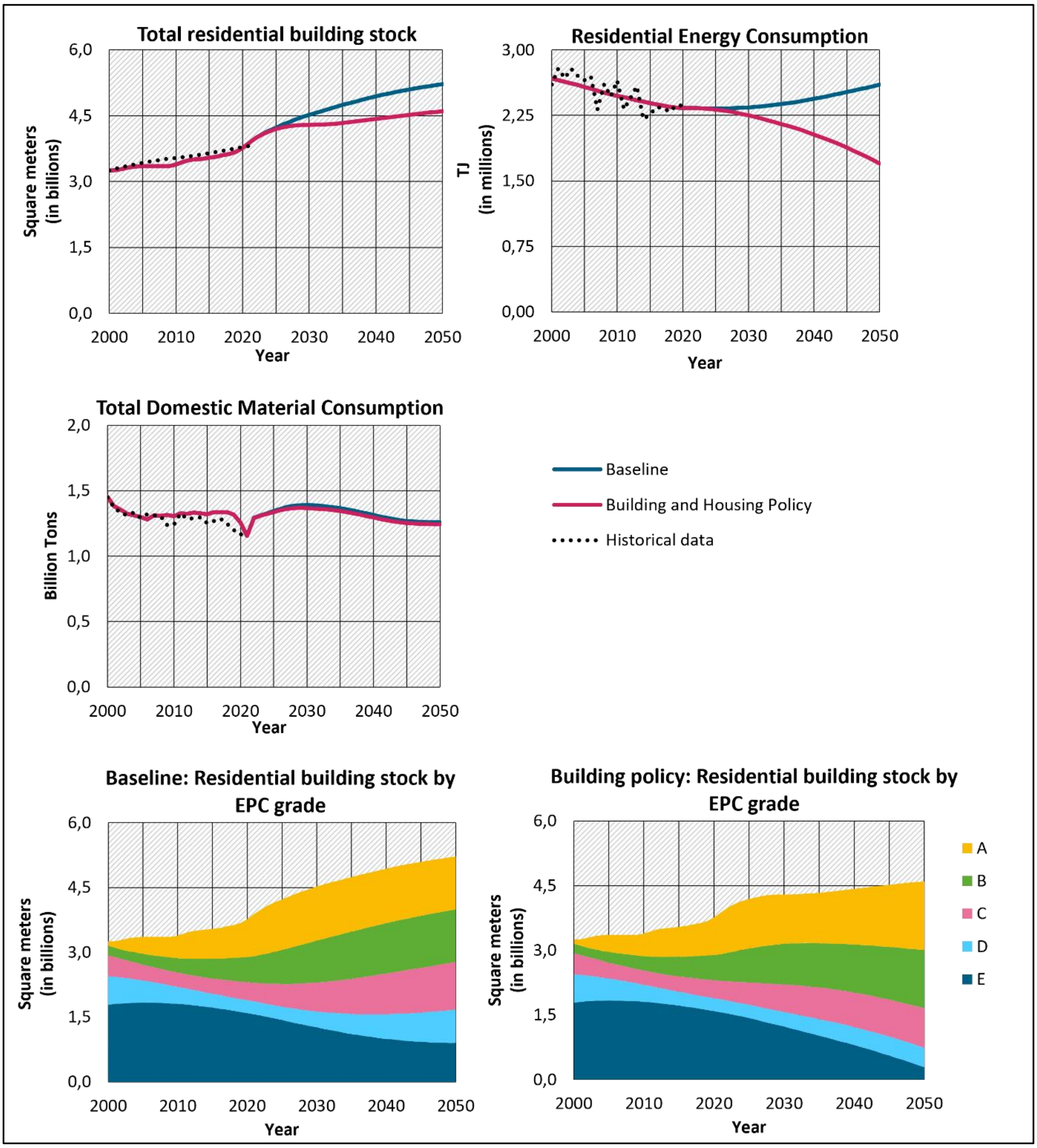
Extending the analysis to the implications for SDG 13 within Germany's building and housing reform scenario, we uncover the complex interplay between climate action and the nation's commitment to achieving a sustainable future. The implementation of the scenario results in an impressive 85 % attainment of SDG 13 by 2050, primarily driven by minor yet crucial improvements in SDi 13.2.2 – Per Capita GHG Emissions in CO_2 Equivalent. This achievement underscores Germany's dedication to curbing greenhouse gas emissions and addressing climate change.

- **Residential Energy Consumption and Emission Reduction:** The key driver of this high attainment lies in the substantial reduction in residential energy consumption, which has cascading effects. Lower energy consumption translates into a reduced dependence on fossil fuels, subsequently leading to a significant decrease in greenhouse gas emissions. This interconnectedness showcases the critical role of building and housing reforms in fostering a more sustainable and environmentally responsible energy landscape.
- **Striving for Higher Attainment:** To aspire to even higher levels of attainment for SDG 13, the building and housing efforts need to be complemented by more extensive changes in fossil fuel-related emissions. The reduction in residential energy consumption is a significant step, but to make further progress, holistic strategies are required to drive substantial reductions in emissions across multiple sectors.

In summary, the building and housing policy scenario in Germany provides a glimpse into the nation's potential commitment to advancing SDGs 9, 12, and 13. Although this scenario is speculative and not indicative of specific future plans, it underscores Germany's dedication to fostering industrialization, infrastructure improvements, responsible consumption, and reduced emissions. With impressive attainment levels of 84 % for SDG 9, and 85 % for both SDG 12 and SDG 13 by 2050, Germany demonstrates in this scenario manages to achieve a balanced approach that combines enhanced production, reduced emissions, and resource-conscious consumption.

Figure 47 presents a more detailed development over time of the indicators addressed in the dynamic description above.

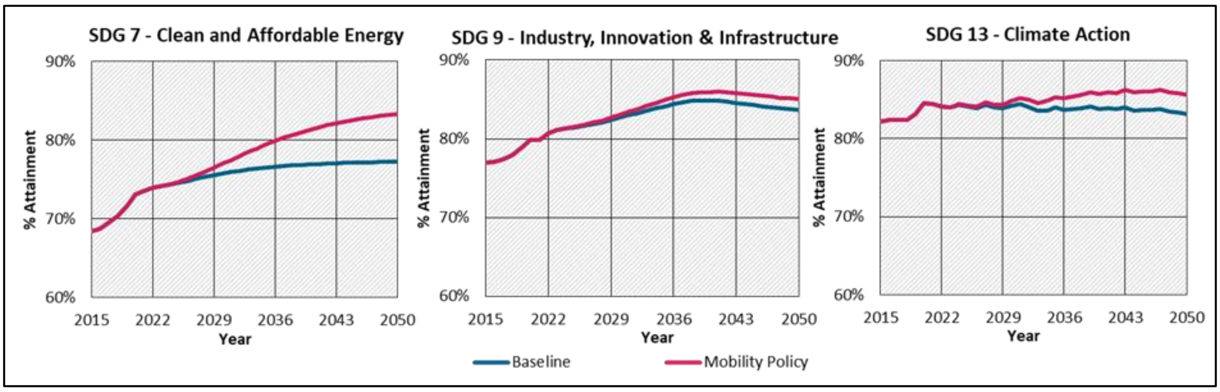
Figure 47: Building and housing indicators time series development



Source: Own calculations

4.3.6 Mobility

Figure 48: Mobility: SDG development over time of concerned SDGs



Source: Own calculations

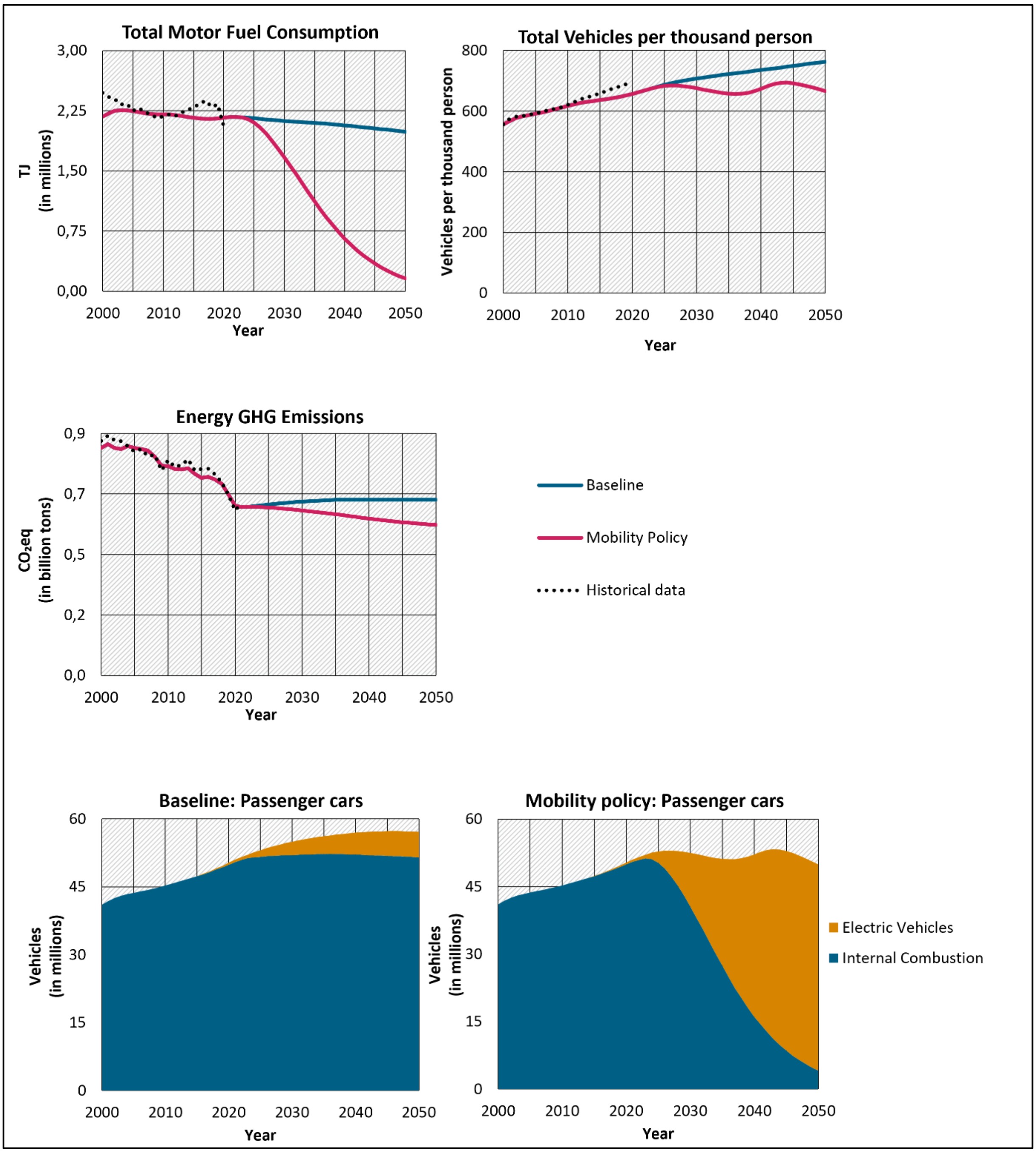
Germany's mobility policy package, focuses on electrifying the vehicle fleet and discouraging individual transport, which holds significant implications for SDG 7, 9 and 13 as displayed in Figure 48.

The implementation of the mobility scenario culminates in 83 % attainment of SDG 7 by 2050, primarily attributable to continuous enhancements in SDi 7.2.1 – Renewable Share in Total Final Energy Consumption. Germany's commitment to transitioning toward renewable energy sources underscores the nation's dedication to achieving affordable and clean energy.

- **Shift in Vehicle Fleet Energy Consumption:** By altering the energy consumption of the vehicle fleet, Germany achieves a notable transformation. In 2050, 36 % of final energy consumption originates from renewable sources, a significant increase from the 27 % in the Baseline scenario. This substantial improvement is primarily attributed to the phased reduction of internal combustion cars and reduction of total number of cars per person, which dominate the passenger car segment, decreasing from 98.8 % in 2020 to just 8 % in 2050 under the Mobility scenario (see Figure 49).
- **Impact of Electrification:** Electrifying the vehicle fleet contributes significantly to this shift, as electric vehicles increasingly displace traditional internal combustion engines. Moreover, Germany's transition to a greater share of renewable electricity even in the Baseline, as opposed to fossil fuel-based generation, supports this trend.
- **Pursuing Higher Attainment:** To enhance the positive effects of electrifying the vehicle fleet on SDG 7 and SDG 13, Germany's mobility efforts must be integrated with further changes in electricity generation. This is because electrifying the vehicle fleet makes most sense when electricity is produced from renewables instead of fossils. This way the shift actually is a shift away from fossil rather than from oil to electricity produced from fossils, leading to higher attainments in SDG 7 and SDG 13.

The mobility scenario has far-reaching implications for SDG 9. This analysis offers a nuanced view of the German context, underlining the nation's commitment to industrialization, infrastructure, and innovation, and its efforts to mitigate environmental impacts. Germany's mobility scenario results in an impressive 85 % attainment of SDG 9 by 2050, primarily attributable to minor yet crucial improvements in SDi 9.4.1 – CO_2 Emissions per Unit of Value Added.

Figure 49: Mobility indicators time series development



Source: Own calculations

This achievement underscores the nation's dedication to advancing industrialization and infrastructure improvements.

- **Fossil Fuel Reduction and Emissions:** The mobility reforms drive a significant decrease in fossil fuel-based energy consumption, resulting in slightly lower greenhouse gas emissions. While the improvements are modest, they are notable, given the substantial share of transport in total energy consumption (23 % in 2022). This shift in energy consumption not only aligns with the pursuit of cleaner and more sustainable transportation but also has direct implications for emissions (see Figure 49). However, assuming that the energy mix in electricity generation remains the same in this simulation, significantly lower emission reductions are simulated overall compared to the combined policy scenario.

- **Pursuing Higher Attainment:** To aspire to even higher levels of attainment for SDG 9, Germany's mobility reforms must be complemented by concerted efforts to reduce emissions in other sectors of energy consumption, such as residential, industrial, and various economic sectors. A comprehensive strategy is essential to further decrease emissions and continue the nation's trajectory toward more sustainable and environmentally responsible energy consumption.

Extending the analysis to the implications for SDG 13 within Germany's mobility scenario, we uncover the complex interplay between climate action and the nation's commitment to reducing greenhouse gas emissions. The mobility scenario culminates at an 85 % attainment of SDG 13 by 2050, primarily driven by continuous improvements in SDi 13.2.2 – Per Capita GHG Emissions in CO_2 Equivalent. Through subtle alterations in the energy consumption mix, the scenario results in a notable 17 % reduction in fossil fuel emissions compared to the Baseline scenario. This shift is instrumental in reducing carbon emissions and aligns with Germany's goals of reducing its carbon footprint. To aspire to even higher levels of attainment in SDG 13, Germany's mobility reforms must be integrated with broader changes in energy consumption patterns across various sectors, including industry, residential, and other economic sectors. Additionally, comprehensive strategies must address emissions sources beyond the transportation sector, such as industrial and agricultural emissions. Only through such multifaceted efforts can the ambitious goal of achieving net-zero emissions by 2050 be realized, aligning with the global commitment to combat climate change.

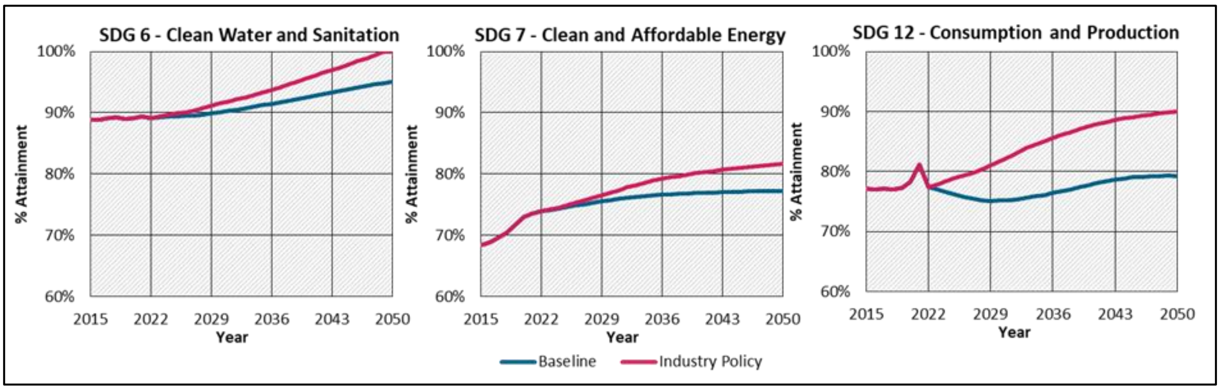
In summary, the scenario offers a glimpse into the nation's potential commitment to advancing SDG 7, 9, and 13. While this scenario is speculative and not indicative of specific future plans, it underscores Germany's potential. More detailed description of the main indicators affected in this scenario are shown in Figure 49.

4.3.7 Industry

The industry scenario comprises a comprehensive set of interventions aimed at enhancing industrial sustainability. This includes measures to increase material consumption efficiency, boost industrial productivity, reduce non-energy industrial emissions, improve energy efficiency, and shift industrial energy consumption to cleaner sources. These interventions have direct effects on domestic material consumption, water withdrawal, emissions, and energy consumption. The analysis of these policies explores their potential impact on sustainable industrialization, emissions reduction, and cleaner energy consumption in alignment with SDGs 6, 7, and 12 (see Figure 50).

In the context of the industry scenario, a comprehensive strategy is outlined, encompassing multiple facets that collectively contribute to the attainment of various SDGs. Germany achieves a remarkable 100 % attainment in SDG 6, emphasizing the nation's commitment to clean water and sanitation. This exceptional achievement is primarily driven by substantial improvements in SDi 6.4.1 – water use efficiency. Through the implementation of a Circular Economy framework within industrial sectors, Germany significantly reduces water withdrawal as value added increases. This strategic approach leads to a noteworthy 30 % improvement in water use efficiency, ultimately reaching full attainment. This dedicated focus on responsible water management aligns with Germany's broader sustainability goals, ensuring the preservation of this resource. Note that the industrial component of water withdrawal is critical as it represents 80 % of total water withdrawal in 2020 (as can be seen in Figure 51).

Figure 50: Industry: SDG development over time of concerned SDGs



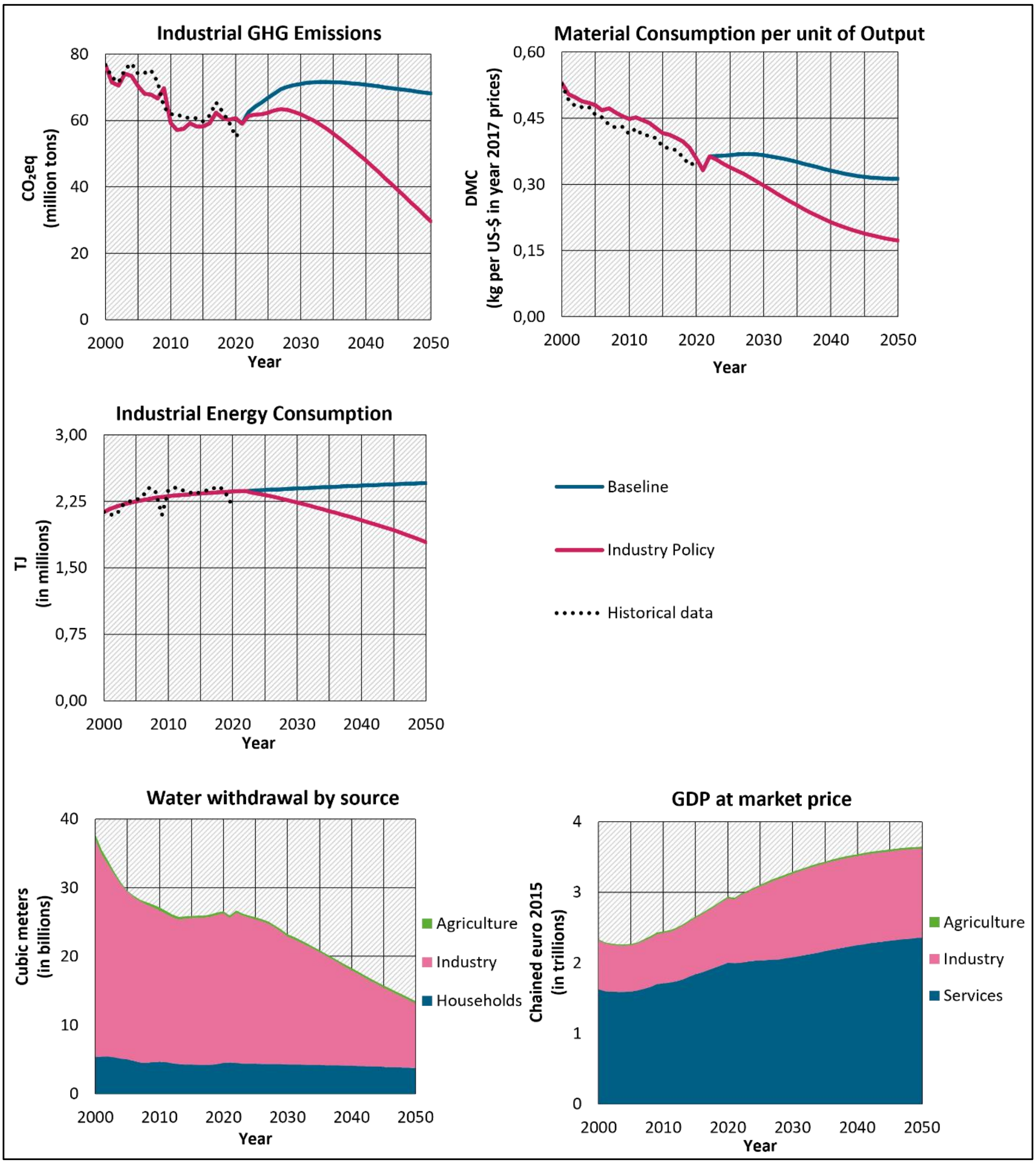
Source: Own calculations

Germany also attains a high level of 82 % in SDG 7, signifying the nation's dedication to affordable and clean energy. The focus here is on SDi 7.2.1 – renewable share in total final energy consumption. By reshaping the energy consumption within the industrial sector, Germany successfully increases the share of renewable energy sources to 32 % by 2050, compared to 27 % in the Baseline scenario. This achievement is a result of two key factors: the transition to cleaner energy sources and the implementation of efficiency measures. Notably, the shift of the industrial sector toward electricity consumption directly contributes to SDi 7.2.1, benefiting from Germany's growing share of renewable electricity. Furthermore, efficiency measures lead to a substantial 27 % reduction in total industrial energy consumption compared to the Baseline scenario (see Figure 51).

Germany achieves a high level of 90 % in SDG 12, supporting the nation's commitment to responsible consumption and production. This accomplishment is driven by continuous improvements in SDi 12.2.1 – material footprint and 12.2.2 – domestic material consumption. The framework employed not only stimulates higher economic output but also enhances efficiency in material consumption (as can be seen in the development of material consumption per unit of output of Figure 51). Consequently, this leads to a decrease in total domestic material consumption and footprint, with a significant 30 % reduction observed. It's essential to note that the improvements primarily relate to the metal ores and non-metallic mineral components of material consumption. Still, substantial efforts are both possible and necessary to achieve similar progress in reducing the fossil fuel and biomass components. This scenario's proactive approach aligns with SDG 12, emphasizing a commitment to resource-efficient and responsible consumption and production patterns.

In summary, Germany's Industry scenario exemplifies the nation's dedication to achieving multiple SDGs, addressing clean water and sanitation, affordable and clean energy, and responsible consumption and production. Through strategic policies that promote efficiency, responsible resource utilization, and clean energy adoption, Germany paves the way for a more sustainable and environmentally responsible future.

Figure 51: Industry indicators time series development

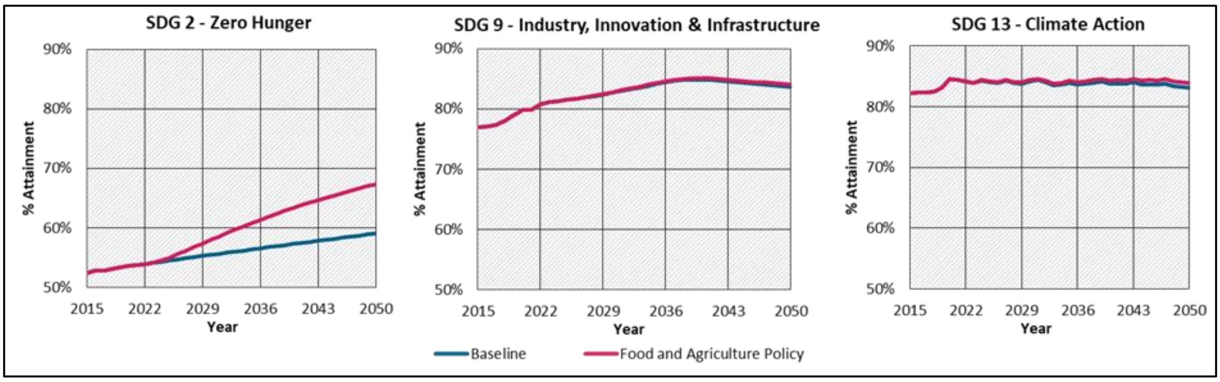


Source: Own calculations

4.3.8 Food and agriculture

In the Food and Agriculture scenario, Germany adopts a comprehensive strategy to address agricultural challenges and promote sustainability. Key measures include a gradual reduction in livestock production, sustainable agriculture training with increased government spending, and their associated benefits (see previous section for details).

Figure 52: Food and agriculture: SDG development over time of concerned SDGs



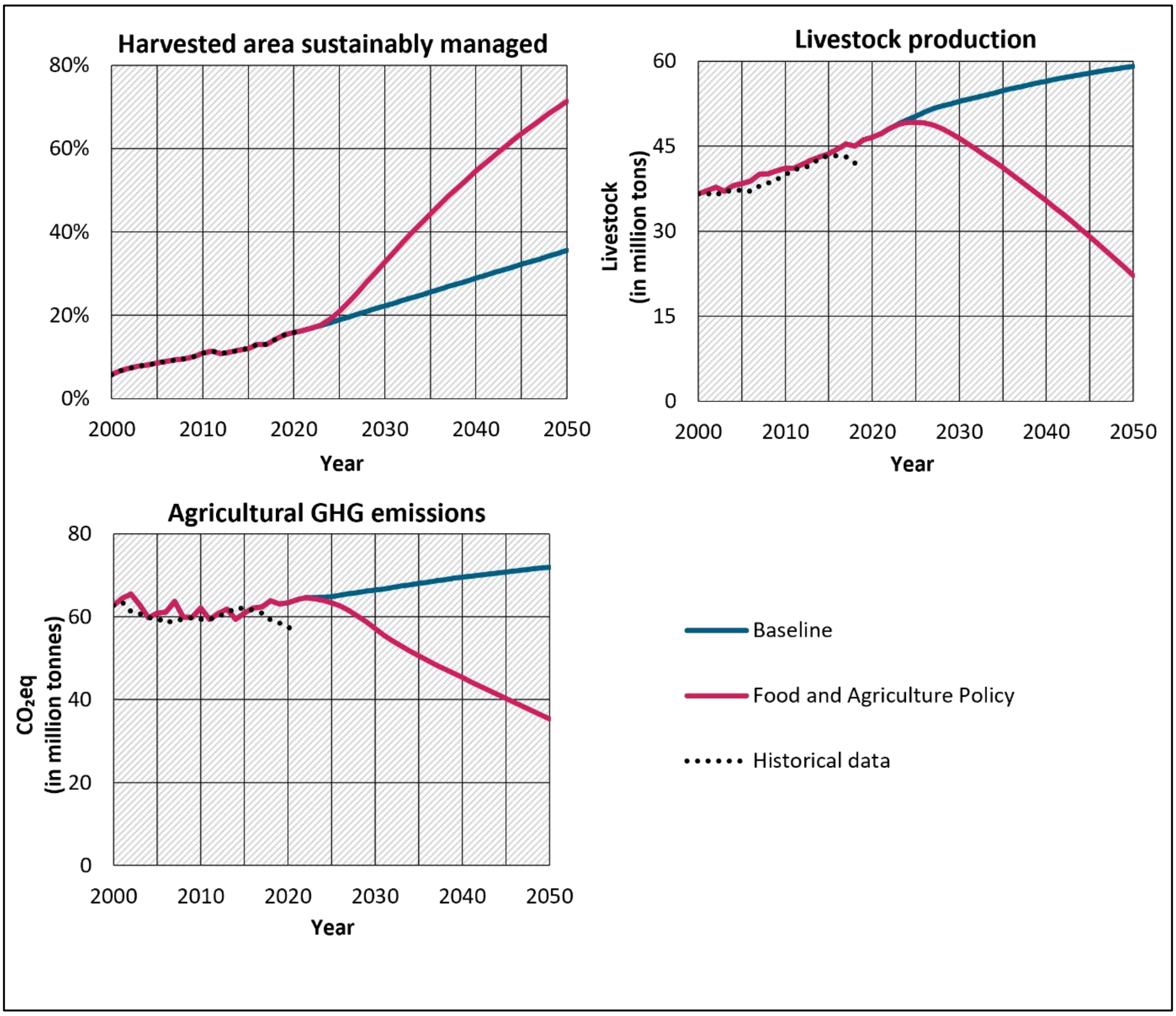
Source: Own calculations

These policies restore soil's nitrogen balance, accelerate the reduction of non-energy-related agricultural emissions, and stabilize agricultural employment due to the growing labour demand in sustainable practices. Figure 52 displays the related SDG dynamics.

In the context of the Food and Agriculture scenario, the nation demonstrates significant progress across multiple SDGs. In SDG 2, an attainment of 67 % is achieved in 2050, compared to 59 % in the Baseline scenario, primarily due to substantial improvements in SDi 2.4.1 – sustainable management of harvested areas (see Figure 53). This achievement is notable, considering a downward trend in livestock production, which impacts agricultural output per worker (SDi 2.3.1). The rise in sustainable agriculture training expenditure plays a pivotal role in transitioning agricultural practices toward less soil-intensive and lower non-energy-related emissions.

For SDG 9, Germany reaches a high attainment level of 84 % in 2050. This is driven by minor yet impactful improvements in CO_2 emissions per unit of value added (SDi 9.4.1). Notably, non-energy agricultural emissions decrease by 50 % compared to the Baseline scenario, contributing to the nation's environmental efforts (see Figure 53). However, given that non-energy agricultural emissions account for only 5 % of total GHG emissions in 2050, the overall impact on SDG performance remains relatively modest. To further enhance SDG 9 attainment, agricultural reforms must be integrated with broader energy consumption initiatives and industrial reforms to boost the industry production index (SDi 9.2.1).

Figure 53: Food and agriculture indicators time series development

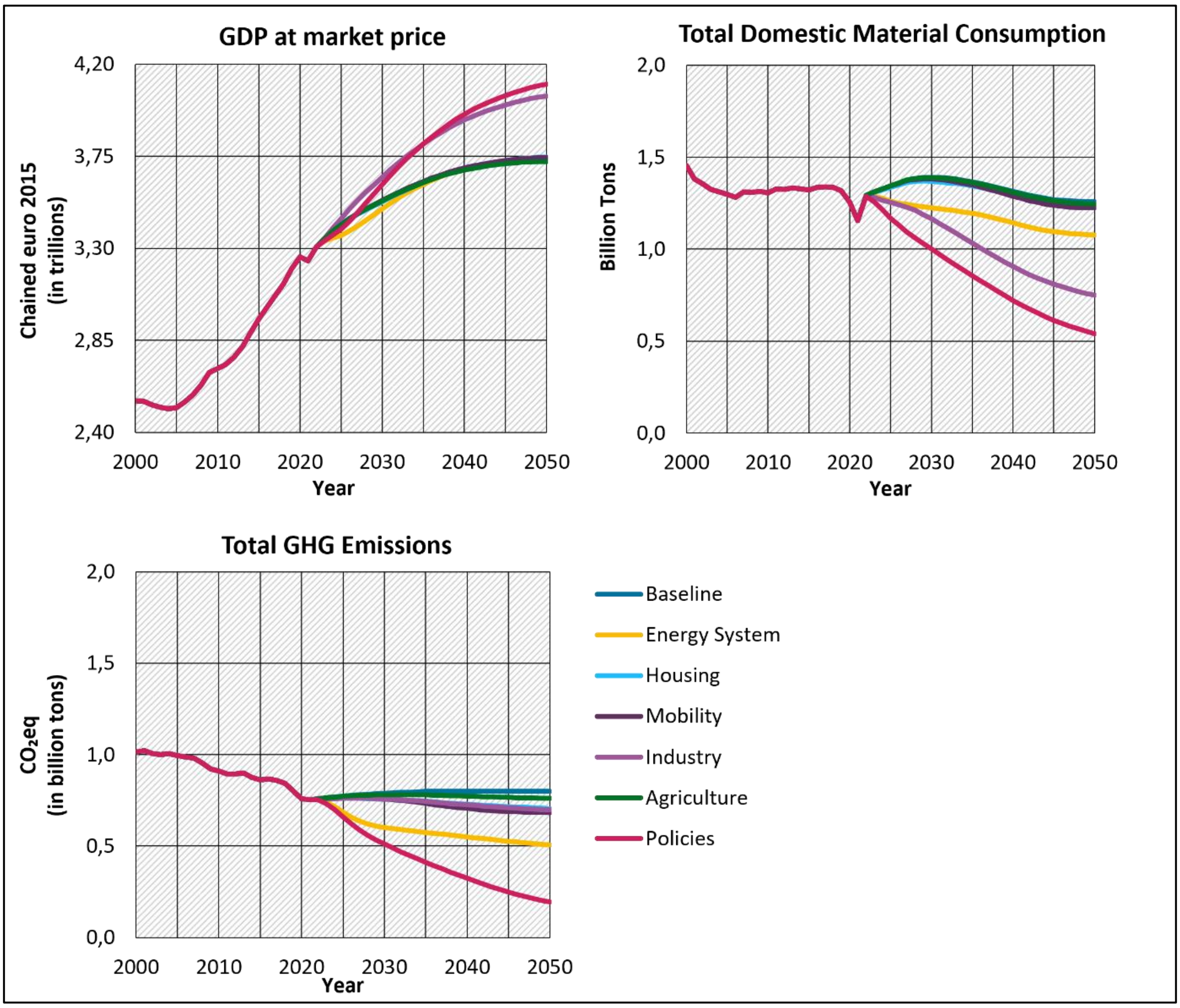


Source: Own calculations

In SDG 13, Germany also achieves high attainment, reaching 84 % by 2050, primarily due to minor improvements in per capita GHG emissions in CO_2 equivalent (SDi 13.2.2). However, to aim for even higher attainment, the agricultural sector's efforts must be complemented by measures addressing fossil fuel-related emissions and increased investment in adaptation capital to enhance resilience and reduce vulnerability, as highlighted by the disasters human impact index (SDi 13.1.1).

4.4 Accelerators, Synergies and Timing

Figure 54: KPIs time series development (policy comparison)



Source: Own calculations

As can be observed in Figure 54, the combination of policies enables higher results than any policies applied separately. Looking at GDP, we see that most of the achievements are achieved due to the Circular Economy framework put in place in the Industry scenario as all other scenarios don't have a major impact on the overall economy's output. Moreover, the Circular Economy framework allows Germany to extend its economic growth rate. A needed boost as it's being slowed down by the ongoing demographic transition. Concerning material consumption, we see that most of the implementation's results are due to the Energy System and Industry policies as all other scenarios don't have a major impact on the overall material consumption. Finally, with regards to GHG emissions, we see that most of the positive outcome of the Policies scenario are mainly due to the Energy System policies.

With respect to SDGs, one can see from Table 17 the achievements decomposition for each SDG. Regarding SDG 2, the only policy package contributing to the increase in achievement relates to the Agriculture scenario. In particular it's with the implementation of sustainable practices training that we see a significant increase in the proportion of harvested area sustainably managed.

Table 17: SDG Attainment net difference between Baseline and policies in 2050

	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17
All Policies	0%	9%	1%	0%	0%	5%	22%	4%	7%	2%	1%	14%	13%	0%	0%	0%	0%
Energy System	0%	0%	0%	0%	0%	0%	16%	1%	3%	2%	1%	3%	6%	0%	0%	0%	0%
Housing	0%	0%	0%	0%	0%	0%	6%	0%	1%	0%	0%	0%	2%	0%	0%	0%	0%
Mobility	0%	0%	1%	0%	0%	0%	6%	0%	1%	0%	1%	1%	2%	0%	0%	0%	0%
Industry	0%	0%	0%	0%	0%	5%	4%	3%	2%	0%	0%	11%	2%	0%	0%	0%	0%
Agriculture	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%

Source: Own calculations

Table 18: SDG Attainment net change from 2022 to 2050 by scenario

	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17
All Policies	0%	9%	1%	0%	0%	5%	22%	4%	7%	2%	1%	14%	13%	0%	0%	0%	0%
Energy System	0%	0%	0%	0%	0%	0%	16%	1%	3%	2%	1%	3%	6%	0%	0%	0%	0%
Housing	0%	0%	0%	0%	0%	0%	6%	0%	1%	0%	0%	0%	2%	0%	0%	0%	0%
Mobility	0%	0%	1%	0%	0%	0%	6%	0%	1%	0%	1%	1%	2%	0%	0%	0%	0%
Industry	0%	0%	0%	0%	0%	5%	4%	3%	2%	0%	0%	11%	2%	0%	0%	0%	0%
Agriculture	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%

Source: Own calculations

Similarly to SDG 2, SDG 6 only has one policy package contributing to its elevated performance. For the latter SDG, it is the Industry policy package and its water efficiency measures which allows a reduction in total water withdrawal through its industrial component. This further improves Germany's resilience when it comes to access to sustainable water sources. Concerning SDG 7, multiple policy packages contribute to the radical change in achievement. However, the interventions don't work in complete synergy as the sum of contributions taken separately are higher than the contribution of them combined. This is explained by the fact that, once SDG 7 performances reached a high attainment level, efforts become proportionately more significant. Note that, as explained in the synergy analysis of the Energy System scenario, combining electricity generation improvements (in particular, decommissioning and renewable investment) with changes towards higher electricity consumption (like in the Housing, Mobility and Industry scenarios) does give way for strong synergies as it further increases the proportion of renewables sources in final energy consumption.

For SDG 8, the major contribution to the modest change in attainment is attributed to the Industry scenario given the increased economic productivity that is envisioned through the Circular Economy framework. Concerning SDG 9, the contribution to the notable change in attainment is shared across the policy packages. Even though led by the Energy System policy package, all policy packages enable higher achievement through their contribution to GHG emissions reduction (and to industrial production for the Industry scenario). Note that the analysis doesn't show any particular synergies in the contributions made. As mentioned previously, the accelerator for material consumption's performance and therefore SDG 12 is defined by the material efficiency measures of the Industry scenario. Finally, similarly to SDG 9, SDG 13's contribution to significant change in attainment are shared across policies with the largest contribution coming from the Energy System policy package.

To carry out a comprehensive analysis encompassing both operational and strategic dimensions, a series of experimental tests were designed to address the following pertinent questions within the context of environmental sustainability:

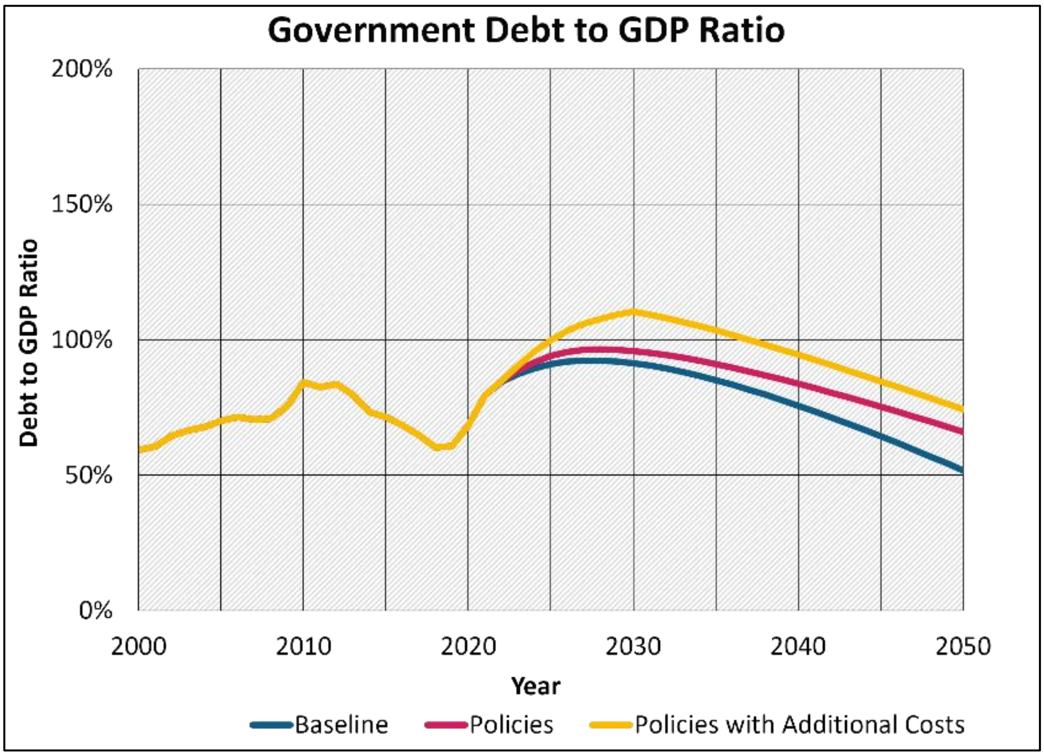
- **Consequences of Delayed Implementation of Electric Vehicles:** Tests were conducted to assess the repercussions of postponing the integration of electric vehicles (EVs) within the transport sector. The primary objective was to determine the potential outcomes of a 10-year delay in transitioning to electric vehicles, compared to a scenario in which the transition proceeded on schedule. The findings not only shed light on the possible outcomes but also carry significant implications for environmental goals. The results indicate that, there would be a substantial 70 % reduction until 2050 in transport energy consumption, as opposed to the anticipated 90 % decrease that result from the Mobility scenario. These findings emphasize the need for immediate action and timely EV adoption to meet sustainability objectives in the transportation sector.
- **Impact of Delayed Energy Efficiency Initiatives:** Another series of tests were conducted to investigate the consequences of delaying energy efficiency measures for households and industries. This analysis assumed that the commencement of these measures would be postponed from 2022 to 2030. The goal was to determine the extent of increased investment required to achieve similar outcomes related to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). The results of this study provide insights into the tangible effects of delaying energy efficiency measures. It was found that, to achieve comparable results in line with SDG 7 and SDG 13, there would be a need to increase investments in wind and solar capacity, effectively doubling the required resources. This finding emphasizes the financial implications of delaying energy efficiency initiatives and underscores the compelling

rationale for the expeditious implementation of such measures. The implications arising from this analysis offer further incentives to accelerate the deployment of energy efficiency initiatives to ensure that sustainability objectives are achieved without incurring excessive additional costs.

In addition to these two fundamental inquiries, it is important to acknowledge that a multitude of other questions related to the timing of environmental policies could be explored. However, due to the complexity and numerous permutations of such investigations, the current study intentionally focuses on the two aforementioned questions.

4.5 A closing sensitivity analysis regarding the implied transformation costs

Figure 55: Projections of govenment debt under altered cost assumptions



Source: Own calculations

As had already been outlined in section 3.2.2, government expenditures represent iSDG's standard impact channel for the consideration of transformation costs. This is justified by the fact that (even though individual investment activities will actually have to be implemented by private actors) public funding programmes are regarded as a general prerequisite for the initialization of respective transformative changes. For all scenarios documented in this report, it was assumed that these transition costs (parametrized as increases in overall government expenditures) were financed by additional public deficits. Thus, the projected development of public debt provides a clear indicator for assessing all the cost assumptions made in the simulations.

Figure 55 shows the development of government debt (measured in relation to GDP) in the baseline scenario (blue line) and the combined policy scenario (red line) together with projections for this indicator that were simulated under altered cost assumptions for the policy scenario (yellow line). The first observation that can be taken from this figure is that the model projects a long-run stabilization of government debt in all scenarios. Although the initial debt to GDP ratio tends to increase in the short run, this trend reverses in the long run in all modelled scenarios.

However, even in the baseline simulation, just towards the end of the simulation period the debt to GDP ratio is projected to fall below the threshold value of 60 % (targeted by the European "Stability and Growth Pact" for this ratio).[52] From a fiscal viewpoint, it therefore seems that the debt projections from the combined policy simulation discourage a real world implementation

[52] See, for example Schuknecht (2005) or Schuknecht et al. (2011) for further references to the Stability and Growth Pact.

of the assumed transformations: In the combined policy simulation, the debt to GDP ratio does still exceed the 60 % threshold value in 2050.

Regarding this finding, it should be noted that the iSDG-model was not developed for long-term fiscal policy forecasts. It does therefore not represent government deficits and debt development in accordance with the detailed specifications of the "Stability and Growth Pact". Nevertheless, the iSDG-projections allow for a classification of the order of magnitude of the transformation costs considered here: In the simulation year 2050, the ratio of government debt to GDP (66.1 %) exceeds in the policy scenario the corresponding reference value of the baseline simulation (51.8 %) by (slightly more than) 14 %. As a comparison, reference can be made to the economic stabilisation fund of the Federal Government, which was set up in March 2020 to mitigate the economic consequences of the measures taken at that time to curb the coronavirus pandemic.[53] As an independent fund for credit approval, this fund was authorised to grant a maximum total of 600 billion euros state aid to applicants. In relation to the value of previous year's gross domestic product (approx. 3474 billion €),[54] these financial resources corresponded to (just over) 17 %. To put it more simply: For our policy simulation, the increase in government debt in relation to Gross Domestic Product remains below what had been regarded as politically necessary in 2020 by the federal government of Germany to mitigate economic consequences of their commitments against the coronavirus.

Whether an increase in public debt in this order of magnitude will also be justifiable to mitigate the climate crisis and curb Germany's hunger for raw materials will undoubtedly also have to be decided politically. Our study provides key arguments for corresponding investments: In our policy simulation, the goals of the Paris Agreement are being met with simultaneous reductions of primary raw material extractions (-40 % by 2050 compared to the baseline) and accelerated economic growth (on average +0.19 % p. a. in the 2020s, +0.48 % p.a. in the 2030s and +0.23 % p.a. in the 2040s, see Figure 56).

However, by their very nature, all model projections will always be subject to uncertainties that should not be disregarded. Like other simulation models, iSDG is not capable of mapping these explicitly by, for example, showing confidence intervals. But we can nevertheless categorise respective uncertainties by additional sensitivity analyses. Figure 55 as well as Figure 56 therefore also illustrate the resulting findings when, compared to the original policy simulation, an additional government spending of 2 % per year is assumed over the entire simulation period. The results of this sensitivity analysis are illustrated by a yellow line in the respective figures.

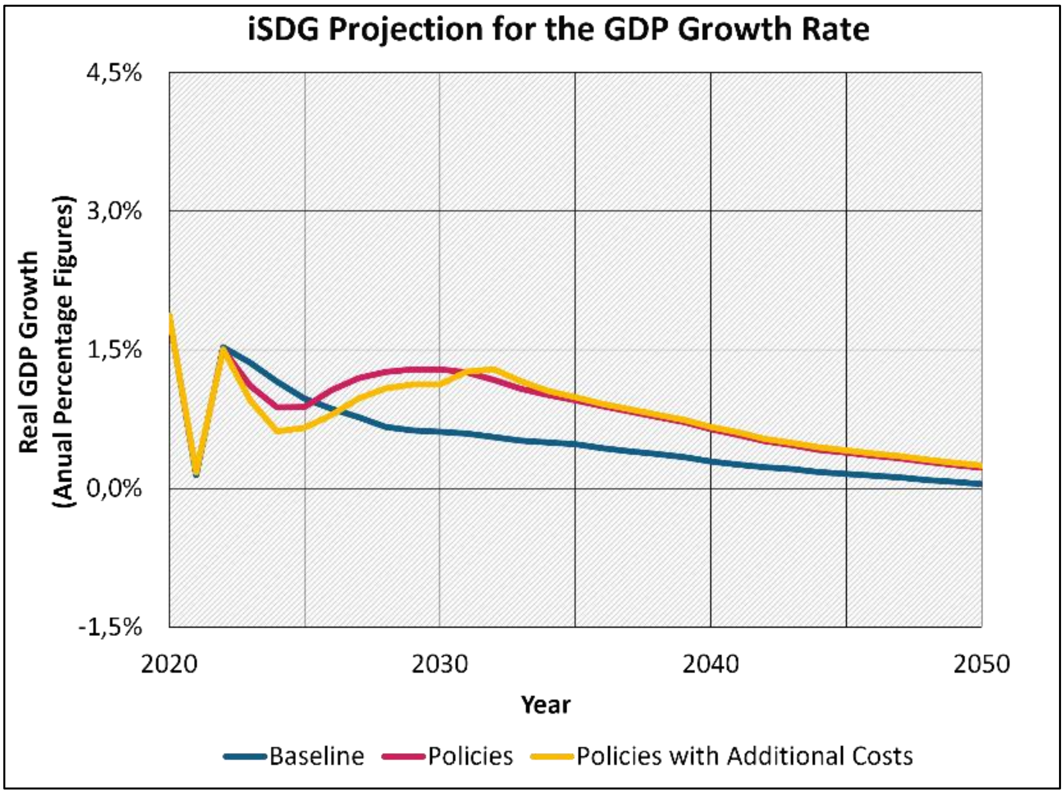
The decision to change this cost assumption reflects the fact that a separate research project would probably have to be carried for estimating individual investment costs in as much detail as possible. A detailed comparison of these simulation results with previously discussed reference values may therefore be omitted here. Overall, however, we note the following: Also this simulation features a long-term convergence behaviour of government debt in relation to GDP. The value simulated for the year 2050 clearly exceeds the reference value of the baseline. However, at 74.3 %, it does still remain well below contemporary average figures for all Euro Member States (88.6 % at the end of 2023).[55]

[53] https://www.bundesfinanzministerium.de/Monatsberichte/2022/08/Inhalte/Kapitel-3-Analysen/3-2-wirtschaftsstabilisierungsfonds-pdf.pdf?__blob=publicationFile&v=1 (retrieved on July 24, 2024)

[54] https://ec.europa.eu/eurostat/databrowser/view/nama_10_gdp/default/table?lang=en&category=na10.nama10.nama_10_ma (retrieved on July 24, 2024)

[55] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Government_finance_statistics (retrieved on July 24, 2024)

Figure 56: Projections of GDP growth rates under altered cost assumptions



Source: Own calculations

5 Conclusions

5.1 Conclusions from the Meta-Analysis

A comprehensive meta-study was carried out in WP1 to identify the current state of research on methods and findings from applications in the numerical assessment of SDG interactions and their evolution in future development pathways. The methods identified in this meta-study can basically be divided into two categories.

Expert judgements and statistical ex post assessments facilitate the numerical assessment of SDG interactions. The applied methods range from the numerical scaling of expert judgements in Cross-Impact matrices (Le Blanc 2015) to the application of complex statistical-econometric methods. Due to the noteworthy availability of extensive indicator datasets, very detailed national as well as international analyses of historical SDG developments and observable SDG interactions can be carried out using statistical econometric methods. With relevant prior knowledge in statistical programming, these methods can be directly applied by sustainability researchers to analyse SDG interactions in Germany. Moreover, by combining the corresponding methods and data sets in stand-alone software applications, a user-friendly access to the visualisation and interpretation of sustainability trends can be provided to a broader general audience (IGES "SDG Interlinkages Analysis & Visualisation Tool", Zhou and Moinuddin 2017).

The most important general finding from these analyses is that for a reliable assessment of SDG developments and interactions, specific assessments are necessary. This applies to partial SDG assessments as well as to integrated sustainability assessments. See, for example, the findings of van Zanten and van Tulder (2021), which illustrate that SDG interactions vary significantly between individual economic sectors, as well as the following quote from Miola et al. (2019) in this context: "In our opinion, any method which proposes a sort of panacea to deal with the inter-linkages misleads the 2030 Agenda process based on inclusiveness and context dependence. In fact, the nature of any inter-linkage often depends on the context of the respective country, the level of development, geographical scale and other characteristics and specific policies which might determine if a given inter-linkage constitutes a trade-off or a synergy" (Miola et al. 2019, p. 19).

To analyse SDG-interactions in transformation pathways, the entire system under consideration should be modelled in a **dynamic macro simulation framework**. **Integrated assessment models (IAM), macroeconomic models and system dynamics models already proved their applicability for respective modelling studies of the climate and resource protection nexus**. Our identified IAM applications are characterised by a very detailed representation of biophysical cause-effect relationships. While these models have traditionally been used to analyse climate policy issues, the explicit mapping and assessment of SDG interactions in IAM analyses has recently been advanced (van Vuuren et al. 2022; van Soest et al. 2019). Nevertheless, for comprehensive mappings of SDG interactions, there is a need for extended consideration of social science modelling skills in future IAM applications.

Macroeconomic models are characterised by a very detailed depiction of socio-economic cause-effect relationships. The high degree of detail mapped for individual economic sectors is of particular significance here. Thanks to this feature, macroeconomic models are inter alia excellently suited for applications of macroeconomic material flow accounting routines (Europäische Kommission 2018) in pathway projections. Corresponding models are therefore frequently applied for resource policy assessments of transformation pathways and their implied economic as well as social impacts (Aguilar-Hernandez et al. 2021).

Within the literature on SDG interaction analyses, however, this class of models has not yet been received with attention. Instead, **national applications of the system dynamic iSDG model prove to be very popular** in this literature (Allen et al. 2016; Allen et al. 2021, 2019b; Pedercini et al. 2020). Hence, the application of the iSDG model to Germany was identified as a cost-effective way to assess SDG interactions of transformation pathways by the application of an internationally comparable framework. In the further course of the project, the iSDG model was therefore calibrated to German data structures and significantly expanded to capture key impact channels across action areas of the RESCUE study. Thanks to this development work, **a model version for Germany is now available that has been significantly expanded in comparison to previous applications of the iSDG-model. This enlarged model version for Germany was handed over to German Environment Agency (UBA) at the end of the project. It can therefore be applied by UBA researchers in own follow-up analyses.**[56] A public presentation of the model and the results generated over the course of this project on the internet is also possible. The model simulator can be accessed via https://exchange.iseesystems.com/public/millenniuminstitute/isdg-germany/.

5.2 General insights from the iSDG-application in the German context

5.2.1 Overall SDG-Indicator performance in the model simulations

The development of numerous SDG indicators has been quantitatively assessed, and ex ante simulated by applications of the adapted iSDG-model. In all initial model applications documented in this report, annual time series up to the year 2050 were simulated. With an averaged overall SDG attainment score of 78 %, Germany already features rather high SDG attainment today. Notably, SDGs 3 (Good Health and Wellbeing), 4 (Quality Education), 6 (Clean Water and Sanitation), and 17 (Partnership for the Goals) are already close to full attainment.

However, for a high-income country like Germany, current attainment scores for SDGs 2 (Zero Hunger), 5 (Gender Equality) and 10 (Reduce inequality within and among countries) do nevertheless appear considerably low. These observations should be considered with references to the applied evaluation criteria: Like any other model, the iSDG maps a simplified representation of reality. This also applies for the selection of SDG indicators mapped by the iSDG. Due to the model originating from the T21 model, it was initially designed for assessments of low-income countries' development prospects (Collste et al. 2017; Pedercini et al. 2019; Allen et al. 2020). Consequently, the selection of mapped SDG indicators was primarily targeted to those indicators deemed to be of relevance for low-income country groups.

Regarding SDG 2, for example, indicators like (inter alia) prevalence of undernourishment, agricultural output per worker, or the proportion of harvested area sustainably managed are mapped and evaluated by the iSDG. However, other available indicators such as the average income of small-scale food producers, total official flows to the agriculture sector, agricultural export subsidies or food price volatilities are not considered by these assessments. (For a complete overview of all respective indicators available from the official UN global indicator framework in this regard together with the subset of indicators represented in the model see Table 21 in the appendix.)

Regarding SDG 5, the two indicators assessed by the iSDG are given by the proportion of women in managerial positions and the proportion of women aged 15–49 years who make their own

[56] The model is available on request for non-commercial purposes and after signing a non-disclosure agreement. Please contact the UBA directly, which will then get in touch with the project partners.

informed decisions regarding sexual relations, contraceptive use and reproductive health care. This limited amount of reported SDG 5 indicators can be understood as an indication of general statistical challenges involved in applied measurement approaches for gender equality. Moreover, Table 27 in the appendix reveals that many of the indicators officially reported by the UN global indicator framework are actually not suitable for individual country assessments. It would therefore be interesting to consider also an inclusion of additional indicators from other sustainability reporting systems in respective assessments. The DNS, for example, also reports on gender pay gap as well as the proportion of fathers receiving parental allowance under SDG 5 (Table 28 in the appendix).

Our own experiences from the model applications for Germany thus confirm findings that were already recognised in the initial meta-study (section 2.1): International experience from SDG monitoring approaches indicate that it is difficult, if not even impossible, to establish universally accepted evaluation methods. "Depending on the chosen indicators and methods applied, countries can receive substantially different relative evaluations" (Miola and Schiltz 2019, p. 1). This suggests that a harmonised agreement on nationally applicable indicators must first be established. For further developments of already existing monitoring approaches, future projects therefore should explore respective methodological development options from a German policy evaluation perspective.

5.2.2 Recommended future developments of the existing SDG-indicator set

This conclusion is all the more important as the internationally established indicators reported by the UN global indicator framework were (at least in some cases) also very strongly adapted to reflect the situation in underdeveloped regions of the world. Goal 7 ("affordable and clean energy") provides a notable example in this regard. Under this Goal, the following key indicators are currently reported by the UN global indicator framework: Proportion of population with access to electricity, proportion of population with primary reliance on clean fuels and technology, renewable energy share in the total final energy consumption, energy intensity measured in terms of primary energy and GDP, international financial flows to developing countries in support of clean energy research and development and renewable energy production (including in hybrid systems), installed renewable energy-generating capacity in developing countries (in watts per capita). Taken individually, all of these indicators have their own justification. Nevertheless, it can certainly not be claimed that this set of indicators provides unambiguous conclusions about the state of "affordable and clean energy" supply in Germany. In view of current national political debates, it is at least somewhat astonishing that, for example, private households' cost and distribution effects have not yet been recognised under Goal 7.

Any follow-up activities in this regard would ideally be based on a multidisciplinary approach: key environmental and socio-political factors for sustainable development in Germany could be identified from an analysis of political debates. Building on this, indicators capable of mapping the identified key factors could then be designed from an applied statistics perspective. Conceptually, respective research activities should ideally also discuss adequate measures for an appropriate evaluation of selected indicators in depth. Finally, similar to the iSDG-applications demonstrated in this study, these indicators would then be evaluated by applying suitable ex ante simulation approaches.

We were not able to draw on any expertise from political science in this project, nor were we commissioned to design and apply own indicators for sustainability assessments in Germany. Instead, this project implemented *necessary methodological adjustments* to the underlying iSDG approach to facilitate an initial ex ante assessment of SDG-implications of an integrated transformation pathway. As such, this project successfully achieved its primary objectives. However, referring to the additional research and development options which remain for future research activities, the first applications of the iSDG for Germany presented here should not be used to derive any (presumably still somewhat premature) political statements. With this in mind, we summarise the following conclusions to describe the model properties as they emerge from our simulation runs:

5.2.3 Key findings from the integrated policy simulation

In line with the conceptual setup of the RESCUE study, our policy simulations analyzed integrated climate and resource policy transformations in the following action areas: Energy system, industry (incl. circular economy), construction and housing, mobility, food and agriculture. No apparent conflicts in terms of SDG target achievement emerged from these model applications. Starting from already high SDG target achievement levels, the assumed transformations overall tend to increase SDG target achievement levels in the simulations. Compared to the baseline, the climate and resource policy scenario is characterized by the fact that in 2050, no significant negative effects on individual SDG target achievement levels are simulated. However, particularly with regard to SDG 2 (zero hunger), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 12 (sustainable consumption and production) and SDG 13 (climate action), significant improvements in SDG target achievement in Germany are simulated. Further, albeit less pronounced, improvements in target achievements are also evident for SDG 6 (clean water and sanitation), and SDG 8 (decent work and economic growth). (Virtually) no changes are found for SDGs 1 (no poverty), 3 (good health and wellbeing), 4 (quality education), 5 (gender equality), 10 (reduced inequalities), 11 (sustainable cities and comunities), 14 (life below water), 15 (life on land), 16 (peace and justice and strong institutions) und 17 (partnership for the goals).

Furthermore, the policy simulation is characterized by its green growth character: While simulated climate policy effects tend to dampen economic growth (via model-endogenous crowding-out effects of additional government investments), these dampening economic effects are overcompensated in the integrated climate and resource policy transformation by significant expansionary economic effects of the assumed circular economy transformations. These expansionary effects are triggered by massive increases in productivity. Despite these positive expansionary effects, the circular economy transformations that are assumed for this scenario (e.g. economy-wide increases in material efficiency) result in a 40 % decrease in domestic material consumption (DMC) by 2050 compared to the baseline. For us, it is interesting to note that these qualitative findings (absolute decoupling irrespective of considerable rebound effects) reveal that the iSDG model for Germany represents key impact interrelationships between the resource policy – economy domains in a manner that is broadly comparable with related findings of Meyer et al. (2012). Here it is noteworthy that Meyer et al. (2012) used a national macroeconomic model to simulate (among other things) scenarios for the development of the resource indicator Total Material Requirement (TMR) (which was not considered in our study).

The climate policy assumptions of the policy scenario imply an 84 % reduction in German greenhouse gas emissions by 2050 compared to 1990 baseline levels. These reductions, which are compatible with original German policy targets to enable global compliance with the 2°C target, are simulated without modeling carbon capture and storage technologies. In the RESCUE study, a 97 % reduction in German greenhouse gas emissions compared to 1990 was achieved in the "Green Supreme" scenario.

The weaker greenhouse gas reductions simulated in our model applications illustrate on the one hand that not all detailed assumptions of the RESCUE study could be mapped even with the extended iSDG assessment approach developed for this project. However, it should also be noted that no dynamic modelling was carried out for the RESCUE study. This means that the expansive economic effects of the assumed circular economy transformations that were clearly observable in our simulations were not captured by the RESCUE study's valuation approach. Instead, the "GreenSupreme" scenario of the RESCUE study assumes zero growth in economic output in Germany from 2030 onwards. One important finding of the present project is therefore that the projection paths of dynamic simulations can deviate significantly from the findings of thematically comparable static modelling (as the latter cannot account for relevant feedback loops in central scenario details).

5.2.4 Recommended future refinements of the overall assessment approach

Considering future refinement options for the applied assessment approach, we think that any follow-up activities should scrutinize the virtually unaltered projections of socio-economic indicators which were, for example, observed for SDG 1 (no poverty) and SDG 10 (reduced inequalities) across all simulation runs. In line with our conclusions concerning poor availabilities of indicators covering specific sustainability aspects of rich countries (as already stated in section 5.2.2), this finding certainly also emphasises the need for additional indicators to be included in the reporting on these SDGs.

However, whereas “SDGs cannot be viewed in isolation of the economic structures in which they are to be achieved” (van Zanten and van Tulder 2021, p. 219), the system properties mapped by iSDG are more akin to a traditional Integrated Assessment Model than a Macroeconomic Model. Whereas we already accounted for this by refinements of the usual iSDG- modelling approach for industrial production activities, several further development options certainly could still be implemented to establish a more comprehensive mapping of socio-economic feedback channels.[57] An overview of respective remaining model development options is presented in the closing subsection 5.3.

Whether and to what extent corresponding model improvements would result in simulations indicating more distinct interactions across the ecological, social, and economic SDG dimensions cannot be finally judged at this stage. Whether and to what extent such remaining development options can be implemented in follow-up projects will always be a matter of project-specific targets and corresponding budget constraints. Consideration should then also be given to soft linked-modelling approaches. As a matter of fact, this was the methodological approach originally chosen for the RESCUE study. Given that the original RESCUE approach does not allow for any dynamic simulation studies, it seems rather unreasonable to link the dynamic iSDG model to this assessment approach. At least it seems much more target-oriented to link the dynamic iSDG model to a dynamic macroeconomic model which is based on a detailed mapping of economic Input-Output structures. This would provide an assessment framework that can map the development dynamics of production technologies, sector-specific intermediate and final demand structures and resulting production and income levels with outstanding degrees of detail. This project initially demonstrated that the iSDG assessment procedures can be successfully applied for integrated assessments of German development trajectories. Hence, it would be a logical development step to evaluate corresponding coupling options with a dynamic

[57] It should be noted that this is not to be interpreted as an individual weakness of the iSDG model, as respective findings have already been generally recognised for Integrated Assessment Models: „IAMs will need to cooperate more closely with social sciences, as understanding biophysical processes is no longer sufficient while studying SDGs (e.g. demography, governance, and poverty research)“ van Soest et al. 2019, p. 218.

macroeconomic model which was also already successfully applied for dynamic assessments of German development trajectories.

With reference to previous applications of the dynamic global macroeconomic simulation model GINFORS$_3$, (Distelkamp and Meyer 2019; Meyer et al. 2018), we note that all expertise required for such an endeavour is already covered by our consortium. Whereas respective multi-national ex ante simulations studies have so far been extremely poorly recognised by the SDG-literature, our Meta-Analysis revealed that multi-national ex ante simulation models are already well established (particularly in the resource policy domain) as they facilitate, inter alia, a sound mapping of multi-national SDG indicators like the material footprint. Apart from the deeper coverage of national social and economic impact relationships, such an approach would then also facilitate an analysis of multi-national spillovers. However, the application of such a sophisticated modelling approach was not considered necessary for this initial assessment of transformation pathways considering SDG synergies and trade-offs.

5.3 Methodological insights from the iSDG-application

The model adaptations documented in Chapter 3 and resulting new parameterization options developed within this project were primarily aimed at a better coverage of key impact relationships relevant for resource policy assessments, including a more detailed mapping of economic feedback loops. Due to this development work, the simulation capabilities of the model were already significantly expanded so that the project could provide insights into spillovers of ambitious climate and resource pathways for Germany. However, the authors nevertheless recognize remaining room for further developments. For budgetary reasons, these could not be addressed in this project. But as additional model structures to capture more spillovers could still be added to the iSDG, other model users should check whether they might want to implement further model features accordingly before subsequent applications of the model. Finalizing our conclusions, we therefore enclose here an overview of corresponding methodological iSDG-expansion options.

5.3.1 Energy System policies

Concerning the Electricity Generation policy package, the following issues could be modelled with more level of detail:

- **Ambiguities related to financial agents for generation capacity changes:** in reality, both public and private actors contribute to electricity generation capacity investment projects and each of them represents a certain share depending on the project. The model structure doesn't make this process explicit, yet it affirms providing realistic assumptions about the share the investment needs to represent in the general government expenses to reach the sought outcome. Government expenditure (and therefore the debt) only considers the additional investment in renewables (compared to the baseline which already account for an increase). If we are to analyse the spillover effect of an increase in expenditure, then the model structure needs to account for this dynamic. Overall, improving this part can enhance estimation of the financial costs for both the government and the private sector. In turn, this misjudgement has a cascading effect that starts with the impact on government's deficit on one hand, and private investment on the other hand.
- **Uncaptured dynamics related to biomass electricity generation:** even though electricity generated through biomass increases, we don't see any impact on material flows or forestry production. The reason behind this is because the link from energy to biomass

extraction/production is defined based on energy consumption which is currently not impacted by the change in electricity generation.

- **Land use and biodiversity related dynamics of renewables not considered:** Limitations and competition regarding land for renewable electricity generation capacity expansion are an important aspect to understand the feasibility of the ramp up of renewables. Additionally, negative affects of renewable electricity generation capacities on nature and in particular biodiversity often mean that climate change mitigation comes at the cost of biodiversity.

Concerning the Energy Consumption policy package, the following issues were identified as remaining major limitations:

- **Missing Energy-Economy feedback loop:** we assume exogenous change in the energy consumption mix of each sector by simply reducing the share of fossil fuel as time goes. However, in reality, changing the source of energy consumption translates into decommissioning the capital previously used and investing into a new genre of capital which both come under a certain cost. For example, in the service sector, companies that want to transition out of fossil fuel heating system to an electric system first needs to get rid of the current system and then implement the new one. This represents financial flows that cannot directly go towards increasing production. It's partially this change in financial flows that currently stops the private sector to transition their energy consumption, however the model does not capture this. For the moment, the model structure is very linear – economic production changes lead to energy consumption changes, yet it should also go the other way around.

- **Efficiency levers for all sectors:** the sectors concerned by the intervention package (agriculture, services, and others) don't have the possibility to benefit from efficiency improvements like the household and industry sector does. In other words, we assume that the only way to reduce the energy consumption of these sectors is by reducing the economic production. This assumption is particularly limiting when dealing with high income countries.

Concerning the Carbon Tax policy package, key development options can be summarized as:

- **Ambiguity of variables representation:** the variables which are concerned by this "tax" are named as "tax" though they do basically mimic surging raw material prices. This dampens the demand for fossil raw materials in the respective policy simulations. However, neither individual sectors are addressed, nor are further flows of the resulting funds modelled. For a full representation of relevant taxation effects, the following improvements can therefore be made:

  - explicit parameterisation of tax rates for individual demand categories of addressed actors (households, industries, etc), and,

  - full integration of this tax revenue into the modelling of the national budget.

5.3.2 Building and Housing

Concerning the Building and Housing policy package, remaining limitations can be summarized as follows:

- **Detailed data availability:** More detailed data would be needed to analyse the energy consumption of residential buildings in more detail. Using the Energy Performance

Certificate (EPC) classification, the analysis would highly benefit from time series of how the building stock has evolved according to this classification. Indeed, knowing how each EPC building stock has evolved over time would enable a more precise calibration. Moreover, data related to renovation could also be used to (1) estimate the distribution of renovation according to EPC classification, and (2) the rate of renovation. In other words, answering questions like which EPC categories are most targeted when renovating or at what rate is each category renovated. In addition, if the analysis seeks to track the impact on material consumption, then one would need to have data related to how the building stock (classified by material used) is evolving.

- **Unaccounted or poor assessment of financial flows:** the current model structure (1) doesn't account for the financial resources required to increase the renovation rate, (2) poorly estimates the cost of households efficiency improvements as it uses global averages even though there is high data discrepancy from one region to the other, and (3) designates the government as the main actor of change when it comes to household efficiency even though the financial burden is mostly taken by households and government only helps through grants.
- **Double representation of household efficiency:** the definition of household efficiency improvements in the Energy Consumption sector seems to be similar to the process of building renovation. Therefore, having both in the model may be a form of double counting.

5.3.3 Mobility

Concerning the Mobility policy package, the following issues could be tackled by follow-up model development acticities:

- **Dominance of cars transport in model structure:** for a high-income country like Germany, the concern around mobility involves other means of transport than cars. Not including these concerns in the model limits the analysis of the policy interventions that are thought to be implemented. For example, the outcome of public transport or cycling lanes investment are measures that can't explicitly be tested given the model structure.
- **Inexistant impact of vehicle cost on purchase:** the integrated cost of purchasing and operating a vehicle isn't considered when defining the growth of the vehicle stock. These costs could include the price of fuel or electricity, the tax on purchase, the insurance costs, etc. If some of these elements would be integrated it would get a better quantification of the efforts needed to change the proportion of vehicles that are electric.

5.3.4 Industry

Concerning the Industry policy package, the following issues could be tackled by follow-up model development acticities:

- **Missing Energy-Economy feedback loop:** the assumption in the model is currently that there is exogenous change in the energy consumption mix of each sector by simply reducing the share of fossil fuel as time goes. However, in reality, changing the source of energy consumption translates into decommissioning the capital previously used and investing into a new genre of capital which both come under a certain cost. For example, in the industry sector, companies that want to transition out of fossil fuel consumption (for production of manufactured goods) to an electric system first needs to get rid of the current system and then implement the new one. This represents financial flows that can't directly go towards increasing production. It's partially this change in financial flows that currently stops the private sector to transition their energy consumption, however the model doesn't capture this. For the moment, the model structure is very linear – economic production changes lead to energy consumption changes, yet it should also go the other way around.

- **Missing Material-Economy feedback loop:** the feedback loop mentioned for energy can also be applied to material efficiency measures. If the industry is to make improvements in material consumption that means they are to change their financial flows. In other words, it entails finding a trade-off between the logic of investment for economic production and investment for environmental responsibilities. This reasoning is also not accounted for in the model.
- **Poor assessment of financial flows:** the current model structure (1) poorly estimates the cost of industrial efficiency improvements as it uses global averages even though there is high data discrepancy from one region to the other, and (2) designates the government as the main actor of change when it comes to industrial efficiency even though the financial burden is mostly taken by industries and government only helps through grants.

5.3.5 Food and Agriculture

Concerning the Food and Agriculture policy package, the major limitations are the following:

- **Absence of consumption patterns:** the model assumes that changing domestic production patterns will entail changes in consumption patterns. This assumption may be valid if the consumption patterns isn't dependent of imports, however, for most high-income countries the domestic consumption acts based on the global market dynamics. Therefore, the changes made in domestic production may have impacts on the domestic material consumption and greenhouse gas emissions, but the results may worsen or remain the same if looking at the footprint of both these indicators. These dynamics are not considered in the model.
- **Inconsequential effect of sustainable practices on fertilizer use:** the increase or decrease in the proportion of harvested land sustainably manged doesn't impact the fertilizer consumption.

5.3.6 General limitations

In addition to the suggested changes made above, the following sectors could/should be revised: education, health, infrastructure, vehicles, biodiversity, government, material flow, investment/economic production, poverty.

- **Education:** in high income countries the dropout rate is affected by other factors than access to electricity and under five mortality rates. Exploring other causes would give the model more relevance. Moreover, issues concerning data availability, led to miscalibration of the key indicators. Therefore, new indicators and data sets should be used to perform a more detailed and rigorous analysis.
- **Health:** new indicators which are more relevant than the ones currently used should be added. For example, one could look into integrating: proportion of population over obesity threshold, healthy life years, proportion of processed food in diet. Moreover, the sector could benefit from explicitly having the dynamics of health care personnel and infrastructure. This would have to be implemented based on data availability but could address critical questions related to the dynamics of an aging population.

- **Infrastructure:** given the context of the energy transition, the electricity transmission infrastructure could be added. Moreover, as mobility remains a major challenge for a high-income country like Germany, infrastructure related to public transport lines (bus, metro, tram) and cycle paths could be added.
- **Vehicle:** could benefit from the addition of a stock for the public transport fleet which could have an impact on the desired number of cars.
- **Biodiversity:** new indicators could be defined in the model such as bird index, butterfly index, or mean surface acidity to have a better coverage of SDG 14 and 15.
- **Government:** the expenditure line could be disaggregated following the European "Classification Of the Functions Of Government" (COFOG) to make sure model outcomes are relatable to the end user. Similarly, on the other side of the balance sheet, one could integrate the concepts that define government revenue (taxes on production and imports, current taxes on income and wealth, capital taxes, social contributions, etc.)
- **Material flow:** concepts that better represent recycling flows could be included given their importance in a high-income country like Germany. Moreover, the estimations regarding footprint are limited by the Balance of Payment's model structure. Indeed, the definition of imports and exports are mostly influenced by the evolution of GDP.
- **Investment/Economic Production:** given the availability of data concerning gross capital formation, gross capital consumption, total assets, compensation of employees, and operating surplus (disaggregated through economic sectors), an improved estimation of the capital-investment nexus could be performed along with the wealth redistribution towards employees and capital holders through an improved estimation of labour share, total capital remuneration and total salaries and wages.

List of references

Aguilar-Hernandez, G. A., Dias Rodrigues, J. F. & Tukker, A. (2021): Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. Journal of Cleaner Production 278, 1-11. DOI: 10.1016/j.jclepro.2020.123421.

Akimoto, K., Sano, F., Homma, T., Oda, J., Nagashima, M. & Kii, M. (2010): Estimates of GHG emission reduction potential by country, sector, and cost. Energy Policy 38 (7), pp. 3384–3393. DOI: 10.1016/j.enpol.2010.02.012.

Allen, C., Metternicht, G. & Wiedmann, T. (2016): National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. Environmental Science & Policy 66 ©, pp. 199–207. DOI: 10.1016/j.envsci.2016.09.

Allen, C., Metternicht, G. & Wiedmann, T. O. (2018): Initial progress in implementing the Sustainable Development Goals (SDGs) – a review of evidence from countries. Sustainability Science 13 (5), pp. 1453–1467.

Allen, C., Metternicht, G. & Wiedmann, T. O. (2019a): Prioritising SDG targets – assessing baselines, gaps and interlinkages. Sustainability Science 14 (2), pp. 421–438. DOI: 10.1007/s11625-018-0596-8.

Allen, C., Metternicht, G., Wiedmann, T. O. & Pedercini, M. (2019b): Greater gains for Australia by tackling all SDGs together but the last steps will be the most challenging. Nature Sustainability 2 (11), pp. 1041–1050. DOI: 10.1038/s41893-019-0409-9.

Allen, C., Metternicht, G., Wiedmann, T. O. & Pedercini, M. (2021): Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing states. Global Sustainability 4, 1-13. DOI: 10.1017/sus.2021.13.

Allen, C., Nejdawi, R., El-Baba, J., Hamati, K., Metternicht, G. & Wiedmann, T. O. (2017): Indicator-based assessments of progress towards the sustainable development goals (SDGs): a case study from the Arab region. Sustainability Science 12 (6), pp. 975–989. DOI: 10.1007/s11625-017-0437-1.

Allen, C., Reid, M., Thwaites, J., Glover, R. & Kestin, T. (2020): Assessing national progress and priorities for the Sustainable Development Goals (SDGs) – experience from Australia. Sustainability Science 15 (2), pp. 521–538. DOI: 10.1007/s11625-019-00711-x.

Andersen, D. F., Vennix, J. A. M., Richardson, G. P. & Rouwette, E A J A (2007): Group Model Building – Problem Structuring, Policy Simulation and Decision Support. Journal of the Operational Research Society 58 (5), pp. 691–694. DOI: 10.1057/palgrave.jors.2602339.

Arezki, R. & Blanchard, O. (2014): Seven Questions About The Recent Oil Price Slump – Oil prices have plunged regecently, affecting everyone: producers, exporters, governments, and consumers. International Monetary Fund, IMFdirect – The IMF Blog. https://blogs.imf.org/2014/12/22/seven-questions-about-the-recent-oil-price-slump/, last access 08.06.2022.

Avelino, A. F. T. & Dall'erba, S. (2019): Comparing the Economic Impact of Natural Disasters Generated by Different Input-Output Models – an Application to the 2007 Chehalis River Flood (WA). Risk Analysis 39 (1), pp. 85–104. DOI: 10.1111/risa.13006.

Bali Swain, R. & Karimu, A. (2020): Renewable electricity and sustainable development goals in the EU. World Development 125, p. 104693. DOI: 10.1016/j.worlddev.2019.104693.

Bali Swain, R. & Ranganathan, S. (2021): Modeling interlinkages between sustainable development goals using network analysis. World Development 138, p. 105136.

Bali Swain, R. & Yang-Wallentin, F. (2020): Achieving sustainable development goals – predicaments and strategies. International Journal of Sustainable Development & World Ecology 27 (2), pp. 96–106. DOI: 10.1080/13504509.2019.1692316.

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A. & Sapio, A. (2017): Complexity and the Economics of Climate Change – a Survey and a Look Forward. Ecological Economics 138, pp. 252–265. DOI: 10.1016/j.ecolecon.2017.03.032.

Barbero Vignola, G., Acs, S., Borchardt, S., Sala, S., Giuntoli, J., Smits, P. & Marelli, L. (2020): Modelling for Sustainable Development Goals (SDGs) – Overview of JRC models. Europäische Kommission. JRC science for policy report EUR 30451 EN, Luxembourg. DOI: 10.2760/697440.

Barro, R. J. (2001): Human Capital and Growth. The American Economic Review 91 (2), pp. 12–17. DOI: 10.1257/aer.91.2.12.

Bennich, T., Weitz, N. & Carlsen, H. (2020): Deciphering the scientific literature on SDG interactions – a review and reading guide. Science of The Total Environment 728, p. 138405. DOI: 10.1016/j.scitotenv.2020.138405.

Bergöö, M., Ebneter, L., Bader, C. & Ott, C. (2019): Über Silos hinweg kohärente Politik gestalten – Die Bedeutung von Wechselwirkungen zwischen den SDGs für eine weitsichtige Nachhaltigkeitspolitik der Schweiz. Sustainable Development Solutions Network Switzerland (Ed.). Sustainable Development Solutions Network Switzerland; CDE Universität, Zürich. (PDF) Über Silos hinweg kohärente Politik gestalten. Die Bedeutung von Wechselwirkungen zwischen den SDGs für eine weitsichtige Nachhaltigkeitspolitik der Schweiz , last access 28.10.2024.

Bertram, C., Luderer, G., Popp, A., Minx, J. C., Lamb, W. F., Stevanović, M., Humpenöder, F., Giannousakis, A. & Kriegler, E. (2018): Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. Environmental Research Letters 13 (6), p. 64038. DOI: 10.1088/1748-9326/aac3ec.

Best, A., Duin, L., Chelminska, M., Woltjer, G. & Rizos, V. (2018): Macroeconomic and Societal Impacts of Mainstreaming the Circular Economy. Ecologic Institute (Ed.), Berlin.

Bizikova, L., Metternicht, G. & Yarde, T. (2018): Environmental mainstreaming and policy coherence – essential policy tools to link international agreements with national development. a case study of the Caribbean region. Environment, Development and Sustainability 20 (3), pp. 975–995. DOI: 10.1007/s10668-017-9924-x.

Bleischwitz, R., Spataru, C., VanDeveer, S. D., Obersteiner, M., van der Voet, E., Johnson, C., Andrews-Speed, P., Boersma, T., Hoff, H. & van Vuuren, D. P. (2018): Resource nexus perspectives towards the United Nations Sustainable Development Goals. Nature Sustainability 1 (12), pp. 737–743. DOI: 10.1038/s41893-018-0173-2.

Bloom, D., Canning, D. & Sevilla, J. (2001): The Effect of Health on Economic Growth – Theory and Evidence. National Bureau of Economic Research. NBER Working Paper Series 8587, Cambridge, MA. https://www.nber.org/system/files/working_papers/w8587/w8587.pdf, last access 08.06.2022. DOI: 10.3386/w8587.

Bosello, F., Antosiewicz, M., Bukowski, M., Eboli, F., Gąska, J., Śniegocki, A., Witajewski Baltvilks, J. & Zotti, J. (2016): Report on Economic Quantitative Ex-Ante Assessment of Proposed Policy Mixes in the EU – DYNAMIX Deliverable D6.2. Ecologic Institute. DYNAMIX, Milan.

Bruno, M. & Easterly, W. (1998): Inflation Crises and Long-Run Growth. Journal of Monetary Economics 41 (1), pp. 3–26. DOI: 10.1016/S0304-3932(97)00063-9.

Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) (2024): Millenniumsentwicklungsziele (MDGs). https://www.bmz.de/de/service/lexikon/mdg-millenniumsentwicklungsziele-mdgs-14674, last access 12.06.2024.

Burke, M., Hsiang, S. M. & Miguel, E. (2015): Global Non-Linear Effect of Temperature on Economic Production. Nature 527 (7577), pp. 235–239. DOI: 10.1038/nature15725.

Calderón, C. & Servén, L. (2004): The Effects of Infrastructure Development on Growth and Income Distribution. World Bank Group. Policy research working papers. DOI: 10.1596/1813-9450-3400.

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., McJeon, H., Patel, P., Smith, S., Waldhoff, S. & Wise, M. (2017): The SSP4 – A world of deepening inequality. Global Environmental Change 42, pp. 284–296. DOI: 10.1016/j.gloenvcha.2016.06.010.

Cambridge Econometrics (2019): E3ME Technical Manual – Version 6.1. Cambridge Econometrics, Cambridge, UK. https://www.e3me.com/wp-content/uploads/sites/3/2019/09/E3ME-Technical-Manual-v6.1-onlineSML.pdf, last access 28.10.2024.

Campagnolo, L. & Davide, M. (2019): Can the Paris deal boost SDGs achievement? – An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. World Development 122, pp. 96–109. DOI: 10.1016/j.worlddev.2019.05.015.

Canning, D. (1999): Infrastructure's contribution to aggregate output. The World Bank. Policy Research Working Paper Series 2246. https://EconPapers.repec.org/RePEc:wbk:wbrwps:2246.

Capellán-Pérez, I., Blas, I. de, Nieto, J., Castro, C. de, Miguel, L. J., Carpintero, Ó., Mediavilla, M., Lobejón, L. F., Ferreras-Alonso, N., Rodrigo, P., Frechoso, F. & Álvarez-Antelo, D. (2020): MEDEAS – a new modeling framework integrating global biophysical and socioeconomic constraints. Energy & Environmental Science 13 (3), pp. 986–1017. DOI: 10.1039/C9EE02627D.

Capros, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., Busch, S., Resch, G., Blesl, M. & Bollen, J. (2014): Description of models and scenarios used to assess European decarbonisation pathways. Energy Strategy Reviews 2 (3), pp. 220–230. DOI: 10.1016/j.esr.2013.12.008.

Château, J., Dellink, R. & Lanzi, E. (2014): An Overview of the OECD ENV-Linkages Model – Version 3. OECD. OECD Environment Working Papers 65, Paris. https://www.oecd-ilibrary.org/content/paper/5jz2qck2b2vd-en. DOI: 10.1787/5jz2qck2b2vd-en.

Chen, W., Yin, X. & Zhang, H. (2016): Towards low carbon development in China – a comparison of national and global models. Climatic Change 136 (1), pp. 95–108. DOI: 10.1007/s10584-013-0937-7.

Ciarli, T. & Savona, M. (2019): Modelling the Evolution of Economic Structure and Climate Change – A Review. Ecological Economics 158, pp. 51–64. DOI: 10.1016/j.ecolecon.2018.12.008.

Climate Interactive (2020): The En-ROADS Climate Solutions Simulator. https://www.climateinteractive.org/en-roads/, last access 19.04.2022.

Cobb, C. W. & Douglas, P. H. (1928): A Theory of Production. The American Economic Review 18 (1), pp. 139–165. http://www.jstor.org/stable/1811556, last access 06.04.2022.

Collste, D., Pedercini, M. & Cornell, S. E. (2017): Policy coherence to achieve the SDGs – using integrated simulation models to assess effective policies. Sustainability Science 12 (6), pp. 921–931. DOI: 10.1007/s11625-017-0457-x.

Cuberes, D. & Teignier, M. (2012): Gender Gaps in the Labor Market and Aggregate Productivity. Article. University of Sheffield, Sheffield. Department of Economics. https://www.researchgate.net/publication/254450693_Gender_Gaps_in_the_Labor_Market_and_Aggregate_Productivity, last access 08.06.2022.

Dawes, J. H. P. (2020): Are the Sustainable Development Goals self-consistent and mutually achievable? Sustainable Development 28 (1), pp. 101–117. DOI: 10.1002/sd.1975.

Dawes, J. H. P. (2022): SDG interlinkage networks – Analysis, robustness, sensitivities, and hierarchies. World Development 149, p. 105693. DOI: 10.1016/j.worlddev.2021.105693.

Dickey, D. A. & Fuller, W. A. (1979): Distribution of the Estimators for Autoregressive Time Series with a Unit Root. Journal of the American Statistical Association 74 (366a), pp. 427–431. DOI: 10.1080/01621459.1979.10482531.

Die Bundesregierung (2021): Deutsche Nachhaltigkeitsstrategie – Weiterentwicklung 2021. Die Bundesregierung (Ed.).

Die Bundesregierung (2024): Ein Plan fürs Klima – Klimaschutzgesetz und Klimaschutzprogramm. Presse- und Informationsamt der Bundesregierung (Ed.). https://www.bundesregierung.de/breg-de/themen/tipps-fuer-verbraucher/klimaschutzgesetz-2197410, last access 15.04.2024.

Distelkamp, M., Meyer, B. & Meyer, M. (2010): Quantitative and qualitative effects of a forced resource efficiency strategy – summary report of task 5 within the framework of the” Material efficiency and resource conservation”(MaRess) project. Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal.

Distelkamp, M. & Meyer, M. (2018): Langfristszenarien und Potenziale zur Ressourceneffizienz in Deutschland im globalen Kontext – Quantitative Abschätzungen mit dem Modell GINFORS. Modelle, Potentiale und Langfristszenarien für Ressourceneffizienz (SimRess). Bericht 2. Umweltbundesamt (Ed.). 50, Dessau-Roßlau.

Distelkamp, M. & Meyer, M. (2019): Pathways to a Resource-Efficient and Low-Carbon Europe. Ecological Economics 155, pp. 88–104. DOI: 10.1016/j.ecolecon.2017.07.014.

Dittrich, M., Dünnebeil, F., Köppen, S., von Oehsen, A., Vogt, R., Biermann, K., Fehrenbach, H., Ewers, B., Limberger, S., Gerhardt, N., Becker, S., Böttger, D., Frischmuth, F. & Schoer, K. (2020a): Transformationsprozess zum treibhausgasneutralen und ressourcenschonenden Deutschland – GreenEe. Abschlussbericht. Umweltbundesamt (Ed.). Climate Change 01, Dessau-Roßlau.

Dittrich, M., Gerhardt, N., Schoer, K., Dünnebeil, F., Becker, S., von Oehsen, A., Vogt, R., Köppen, S., Biemann, K., Böttger, D., Ewers, B., Frischmuth, F. & Fehrenbach, H. (2020b): Transformationsprozess zum treibhausgasneutralen und ressourcenschonenden Deutschland - GreenSupreme. Umweltbundesamt (Ed.). Climate Change 05/2020, Dessau-Roßlau.

Dörgő, G., Sebestyén, V. & Abonyi, J. (2018): Evaluating the Interconnectedness of the Sustainable Development Goals Based on the Causality Analysis of Sustainability Indicators. Sustainability 10 (10), pp. 1–26. https://ideas.repec.org/a/gam/jsusta/v10y2018i10p3766-d176658.html.

Edwards, S. (1998): Openness, Productivity and Growth – What Do We Really Know? The Economic Journal 108 (447), pp. 383–398. DOI: 10.1111/1468-0297.00293.

Ekins, P., Gupta, J. & Boileau, P. (Hg.) (2019): Global environment outlook – GEO-6 : healthy planet, healthy people. UNEP. 1. ed. Cambridge University Press, Cambridge, New York, Port Melbourne, New Delhi, Singepore. https://wedocs.unep.org/bitstream/handle/20.500.11822/27539/GEO6_2019.pdf?sequence=1&isAllowed=y.

Ellen MacArthur Foundation (2015a): Delivering the circular economy – A toolkit for policymakers.

Ellen MacArthur Foundation (2015b): Growth Within – a circular economy vision for a competitive Europe. Ellen MacArthur Foundation, SUN und McKinsey Center for Business and Environment (Eds.).

Emmerling, J., Drouet, L., Reis, L. A., Bevione, M., Berger, L., Bosetti, V., Carrara, S., Cian, E. de, D’Aertrycke, G. D. M. & Longden, T. (2016): The WITCH 2016 model-documentation and implementation of the shared socioeconomic pathways. JSTOR. 42, Milan.

Europäische Kommission (2018): Economy-wide material flow accounts – Handbook. 2018 edition. Manuals and guidelines. Publications Office of the European Union, Luxembourg. https://ec.europa.eu/eurostat/documents/3859598/9117556/KS-GQ-18-006-EN-N.pdf/b621b8ce-2792-47ff-9d10-067d2b8aac4b.

European Commission (2014): Study on modelling of the economic and environmental impacts of raw material consumption – final report. With the collaboration of Cambridge Econometrics und BIO Intelligence Service. European Union (Ed.), Luxembourg.

European Commission, Directorate-General for Environment, ICF, Trinomics & Cambridge Econometrics (2018): Impacts of circular economy policies on the labour market – final report and annexes. Publications Office of the European Union (Ed.).

Faehn, T., Bachner, G., Beach, R., Chateau, J., Fujimori, S., Ghosh, M., Hamdi-Cherif, M., Lanzi, E., Paltsev, S., Vandyck, T., Cunha, B., Garaffa, R. & Steininger, K. (2020): Capturing key energy and emission trends in CGE models – Assessment of Status and Remaining Challenges. Journal of Global Economic Analysis 5 (1), pp. 196–272. DOI: 10.21642/JGEA.050106AF.

Farmer, J. D., Hepburn, C., Mealy, P. & Teytelboym, A. (2015): A Third Wave in the Economics of Climate Change. Environmental and Resource Economics 62 (2), pp. 329–357. DOI: 10.1007/s10640-015-9965-2.

Ferri, G. & Sedehi, H. (2018): The System view of the Sustainable Development Goals. CERBE Center for Relationship Banking and Economics. CERBE Working Papers wpC28. https://ideas.repec.org/p/lsa/wpaper/wpc28.html.

Fischer, S. (1993): The Role of Macroeconomic Factors in Growth. Journal of Monetary Economics 32 (3), pp. 485–512. DOI: 10.1016/0304-3932(93)90027-D.

Folke, C., Biggs, R., Norström, A. V., Reyers, B. & Rockström, J. (2016): Social-ecological resilience and biosphere-based sustainability science. Ecology and Society 21 (3), p. 41. DOI: 10.5751/ES-08748-210341.

Fonseca, L. M., Domingues, J. P. & Dima, A. M. (2020): Mapping the Sustainable Development Goals Relationships. Sustainability 12 (8), pp. 1–15. https://ideas.repec.org/a/gam/jsusta/v12y2020i8p3359-d348181.html.

Forrester, J. W. (1958): Industrial Dynamics – a Major Breakthrough for Decision Makers. Harvard Business Review 36 (4), pp. 37–66. DOI: 10.1225/58404.

Fraunhofer IEE (2015): SCOPE – Sektorenübergreifende Einsatz- und Ausbauoptimierung für Analysen des zukünftigen Energieversorgungssystems, Kassel.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D. L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W. & Riahi, K. (2017): The marker quantification of the Shared Socioeconomic Pathway 2 – A middle-of-the-road scenario for the 21st century. Global Environmental Change 42, pp. 251–267. DOI: 10.1016/j.gloenvcha.2016.06.004.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Silva Herran, D., Dai, H., Hijioka, Y. & Kainuma, M. (2017): SSP3 – AIM implementation of Shared Socioeconomic Pathways. Global Environmental Change 42, pp. 268–283. DOI: 10.1016/j.gloenvcha.2016.06.009.

Greenspan, A. & Cohen, D. (1999): Motor Vehicle Stocks, Scrappage, and Sales. The Review of Economics and Statistics 81 (3), pp. 369–383. https://ideas.repec.org/a/tpr/restat/v81y1999i3p369-383.html.

Groothuis, F. (2016): New Era. New Plan. Europe – A Fiscal Strategy for an Inclusive, Circular Economy. The Ex'tax Project, Utrecht.

Grubb, M., Wieners, C. & Yang, P. (2021): Modeling myths – On DICE and dynamic realism in integrated assessment models of climate change mitigation. WIREs Climate Change 12 (3), e698. DOI: 10.1002/wcc.698.

Günther, J., Lehmann, H., Nuss, P. & Purr, K. (2019): Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE. Summary Report. Umweltbundesamt, Dessau-Roßlau. DOI: 10.1787/888933026145.

Haddaway, N. R., Macura, B., Whaley, P. & Pullin, A. S. (2018): ROSES RepOrting standards for Systematic Evidence Syntheses – pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environmental Evidence 7 (7). DOI: 10.1186/s13750-018-0121-7.

Haddaway, N. R., Woodcock, P., Macura, B. & Collins, A. (2015): Making literature reviews more reliable through application of lessons from systematic reviews. Conservation biology 29 (6), pp. 1596–1605. DOI: 10.1111/cobi.12541.

Hafner, S., Anger-Kraavi, A., Monasterolo, I. & Jones, A. (2020): Emergence of New Economics Energy Transition Models – A Review. Ecological Economics 177, p. 106779. DOI: 10.1016/j.ecolecon.2020.106779.

Hardt, L. & O'Neill, D. W. (2017): Ecological Macroeconomic Models – Assessing Current Developments. Ecological Economics 134, pp. 198–211. DOI: 10.1016/j.ecolecon.2016.12.027.

Hatfield-Dodds, S., Schandl, H., Newth, D., Obersteiner, M., Cai, Y., Baynes, T., West, J. & Havlík, P. (2017): Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. Journal of Cleaner Production 144, pp. 403–414. DOI: 10.1016/j.jclepro.2016.12.170.

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Bodirsky, B. L., Pradhan, P., Barrett, C. B., Benton, T. G., Hall, A. & Pikaar, I. (2021): Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health 5 (1), e50-e62.

Hirschnitz-Garbers, M., Koca, D., Sverdrup, H., Meyer, M. & Distelkamp, M. (2018): System analysis for environmental policy – System thinking through system dynamic modelling and policy mixing as used in the SimRess project. Umweltbundesamt (Ed.). 49, Dessau-Roßlau.

Hoffmann, Martin; Spittler, Nathalie; Aigner, Ernest; Körner, Daniel; Hinterberger, Friedrich (2024): Earth4All: Austria. Five turnarounds towards wellbeing for all within planetary boundaries. Hg. v. Earth4All. Club of Rome, Millennium Institute, Universität für Bodenkultur.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D. & Turkenburg, W. (2003): Exploration of the Ranges of the Global Potential of Biomass for Energy. Biomass and Bioenergy 25 (2), pp. 119–133. DOI: 10.1016/S0961-9534(02)00191-5.

Howitt, P. (2005): Health, human capital and economic growth – a Schumpeterian perspective. In: López-Casasnovas, G., Rivera, B. & Currais, L. (Hg.): Health and Economic Growth. Findings and Policy Implications. The MIT Press, Cambridge, pp. 19–40.

Hu, J., Moghayer, S. & Reynes, F. (2015): D3.7b Report about Integrated Scenario Interpretation EXIOMOD/LPJmL results – WP 3 - Scenarios and modeling of policy implementation for resource efficiency. TNO (Ed.). Policy Options for a Resource-Efficient Economy.

Humpenöder, F., Popp, A., Bodirsky, B. L., Weindl, I., Biewald, A., Lotze-Campen, H., Dietrich, J.-P., Klein, D., Kreidenweis, U. & Müller, C. (2018): Large-scale bioenergy production – how to resolve sustainability trade-offs? Environmental Research Letters 13 (2), p. 24011.

Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Calvin, K., Humpenoeder, F., Popp, A., Rose, S. K., Weyant, J., Bauer, N., Bertram, C., Bosetti, V., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fujimori, S., Gernaat, D., Grubler, A., Guivarch, C., Haigh, M., Holz, C., Iyer, G., Kato, E., Keramidas, K., Kitous, A., Leblanc, F., Liu, J.-Y., Löffler, K., Luderer, G., Marcucci, A., McCollum, D., Mima, S., Sands, R. D., Sano, F., Strefler, J., Tsutsui, J., van Vuuren, D., Vrontisi, Z., Wise, M. & Zhang, R. (2019): IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. DOI: 10.5281/zenodo.3363345.

International Council for Science (ICSU) (2017): A guide to SDG interactions – from science to implementation, Paris. DOI: 10.24948/2017.01.

International Council for Science (ICSU) & International Social Science Council (ISSC) (2015): Review of targets for the Sustainable Development Goals – The science perspective. With the collaboration of Anne-Sophie Stevance. International Council for Science (ICSU) (Ed.). International Social Science Council; International

Council of Scientific Unions, Paris. https://council.science/publications/review-of-targets-for-the-sustainable-development-goals-the-science-perspective-2015/, last access 28.10.2024.

IPCC (2018): Global warming of 1.5°C – An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Jackson, T. & Victor, P. A. (2020): The Transition to a Sustainable Prosperity – A Stock-Flow-Consistent Ecological Macroeconomic Model for Canada. Ecological Economics 177, p. 106787. DOI: 10.1016/j.ecolecon.2020.106787.

Jiang, K.-J., Zhuang, X., He, C.-M., Liu, J., Xu, X.-Y. & Chen, S. (2016): China's low-carbon investment pathway under the 2 °C scenario. Advances in Climate Change Research 7 (4), pp. 229–234. DOI: 10.1016/j.accre.2016.12.004.

Jiménez-Rodríguez, R. & Sánchez, M. (2005): Oil Price Shocks and Real GDP Growth – Empirical Evidence for Some OECD Countries. Applied Economics 37 (2), pp. 201–228. DOI: 10.1080/0003684042000281561.

Kaufmann, D., Kraay, A. & Zoido-Lobaton, P. (2002): Governance matters II – updated indicators for 2000-01. The World Bank. Policy Research Working Paper Series 2772. https://ideas.repec.org/p/wbk/wbrwps/2772.html.

Kemmler, A., Kirchner, A., auf der Maur, A., Ess, F., Kreidelmeyer, S., Piégsa, A., Spillmann, T., Straßburg, S., Wünsch, M. & Ziegenhagen, I. (2020): Energiewirtschaftliche Projektionen und Folgeabschätzungen 2030/2050 – Dokumentation von Referenzszenario und Szenario mit Klimaschutzprogramm 2030. Prognos AG (Ed.), Basel.

Kenny, C. (2012): infrastructure governance and corruption – where next? World Bank. Policy research working papers 4331. https://books.google.de/books?id=wU9mqFz68WsC.

Kleemann, M., Dianat, K. & Pedercini, M. (2022): Elasticity formulations: theory and practice in System Dynamics. System Dynamics Society (Ed.). Millennium Institute.

Klimont, Z., Cofala, J., Bertok, I., Amann, M., Heyes, C. & Gyarfas, F. (2002): Modeling Particulate Emissions in Europe – A Framework to Estimate Reduction Potential and Control Costs. IIASA Interim Report. IIASA, Laxenburg. http://pure.iiasa.ac.at/id/eprint/6712/.

Kluza, K., Zioło, M., Bąk, I. & Spoz, A. (2021): Achieving Environmental Policy Objectives through the Implementation of Sustainable Development Goals – The Case for European Union Countries. Energies 14 (8), pp. 1–22. https://ideas.repec.org/a/gam/jeners/v14y2021i8p2129-d533994.html.

Knörr, W., Heidt, C., Gores, S. & Bergk, F. (2016): Aktualisierung „Daten- und Rechenmodell: Energieverbrauch und Schadstoffemissionen des motorisierten Verkehrs in Deutschland 1960-2035" (TREMOD) für die Emissionsberichterstattung 2016 – (Berichtsperiode 1990-2014). Ifeu-Institut für Energie- und Umweltforschung Heidelberg GmbH (Ed.).

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S. & Edenhofer, O. (2017): Fossil-fueled development (SSP5) – An energy and resource intensive scenario for the 21st century. Global Environmental Change 42, pp. 297–315. DOI: 10.1016/j.gloenvcha.2016.05.015.

Kriegler, E., Petermann, N., Krey, V., Schwanitz, V. J., Luderer, G., Ashina, S., Bosetti, V., Eom, J., Kitous, A., Méjean, A., Paroussos, L., Sano, F., Turton, H., Wilson, C. & van Vuuren, D. P. (2015): Diagnostic indicators for integrated assessment models of climate policy. Technological Forecasting and Social Change 90, pp. 45–61. DOI: 10.1016/j.techfore.2013.09.020.

Kroll, C., Warchold, A. & Pradhan, P. (2019): Sustainable Development Goals (SDGs) – Are we successful in turning trade-offs into synergies? Palgrave Communications 5 (1), pp. 1–11. DOI: 10.1057/s41599-019-0335-5.

Lambert, M. & Huh, K. (2004): Fixing It First – Targeting Infrastructure Investments to Improve State Economies and Invigorate Existing Communities. Issue Brief. With the collaboration of John Ratliff, John Thomasian und Tracey Westfield. NGA Center for Best Practices, Washington, DC.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A. & Sapio, A. (2018): Faraway, So Close – Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. Ecological Economics 150, pp. 315–339. DOI: 10.1016/j.ecolecon.2018.03.023.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A. & Sapio, A. (2020): Climate change and green transitions in an agent-based integrated assessment model. Technological Forecasting and Social Change 153, p. 119806. DOI: 10.1016/j.techfore.2019.119806.

Lane, D. C. (2008): The Emergence and Use of Diagramming in System Dynamics – a Critical Account. Systems Research and Behavioral Science 25 (1), pp. 3–23. DOI: 10.1002/sres.826.

Le Blanc, D. (2015): Towards integration at last? – The sustainable development goals as a network of targets. Sustainable Development 23 (3), pp. 176–187.

Lee, D.-H. (2019): Building evaluation model of biohydrogen industry with circular economy in Asian countries. International Journal of Hydrogen Energy 44 (6), pp. 3278–3289.

Lehr, U. & Lutz, C. (2020): Macro-econometric and structural models. In: Soytaş, U. & Sarı, R. (Hg.): Routledge handbook of energy economics. Routledge International Handbooks. Routledge, London, New York, pp. 473–481.

Lim, M. M. L., Søgaard Jørgensen, P. & Wyborn, C. A. (2018): Reframing the sustainable development goals to achieve sustainable development in the anthropocene – A systems approach. Ecology and Society 23 (3), p. 22.

Litman, T. (2015): A New Traffic Safety Agenda – Incorporating Transportation Demand Management Safety Strategies. Victoria Transport Policy Institute.

Loko, B. & Diouf, M. A.: Revisiting the Determinants of Productivity Growth – What's new? IMF Working Papers 2009. DOI: 10.5089/9781451873726.001.

López-Casasnovas, G., Rivera, B. & Currais, L. (2005): The role of health on economic growth – An introduction. In: López-Casasnovas, G., Rivera, B. & Currais, L. (Hg.): Health and Economic Growth. Findings and Policy Implications. The MIT Press, Cambridge, pp. 1–25.

Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., Boer, H. S. de, Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R., Popp, A., van den Berg, M., van Vuuren, D. P. & Hertwich, E. G. (2019): Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. Nature communications 10 (5229). DOI: 10.1038/s41467-019-13067-8.

Lütkepohl, H. (Hg.) (2005): New Introduction to Multiple Time Series Analysis. Springer-Verlag GmbH, Berlin, Heidelberg. https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=145686.

Mabhaudhi, T., Nhamo, L., Chibarabada, T. P., Mabaya, G., Mpandeli, S., Liphadzi, S., Senzanje, A., Naidoo, D., Modi, A. T. & Chivenge, P. P. (2021): Assessing Progress towards Sustainable Development Goals through Nexus Planning. Water 13 (9), p. 1321.

Mathias, J.-D., Debeljak, M., Deffuant, G., Diemer, A., Dierickx, F., Donges, J. F., Gladkykh, G., Heitzig, J., Holtz, G., Obergassel, W., Pellaud, F., Sánchez, Angel, Trajanov, A. & Videira, N. (2020): Grounding Social Foundations for Integrated Assessment Models of Climate Change. Earth's future 8 (7), e2020EF001573. DOI: 10.1029/2020ef001573.

McCarthy, A., Dellink, R. & Bibas, R. (2018): The Macroeconomics of the Circular Economy Transition – A Critical Review of Modelling Approaches. OECD Publishing (Ed.). OECD Environment Working Papers 130, Paris. DOI: 10.1787/af983f9a-en.

McCollum, D., Echeverri, L. G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., Krey, V., Minx, J. C., Nilsson, M. & Stevance, A.-S. (2018): Connecting the sustainable development goals by their energy inter-linkages. Environmental Research Letters 13 (3), p. 33006.

Meadows, D. H., Meadows, D. L., Randers, J. & Behrens, W. (1972): The Limits to growth – a report for the Club of Rome's project on the predicament of mankind. Universe Books, New York.

Mellwig, P., Jochum, P., Lempik, J., Kulka, M., Blachut, T., Wolff, J., Wallstab, T., Oehsen, A., Pehnt, M., Fehr, J. & Fortunaik, A. (2015): Dämmbarkeit des deutschen Gebäudebestands. Beuth Hochschule für Technik Berlin; ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH.

Mendelsohn, R. (2020): Integrated Assessment and Climate Change. Climate Change Economics 11 (04), pp. 1–13. DOI: 10.1142/s2010007820400047.

Meyer, B., Distelkamp, M. & Beringer, T. (2015): D3.7a Report about Integrated Scenario Interpretation GINFORS/LPJmL results – WP 3 – Scenarios and modelling of policy implementation for resource efficiency. Policy Options for a Resource-Efficient Economy.

Meyer, B., Distelkamp, M. & Meyer, M. (2012): Modeling green growth and resource efficiency: new results. Mineral Economics 24 (2), pp. 145–154.

Meyer, M. (2019): Quantitative Bewertung von Umweltindikatoren – Sachverständigengutachten im Auftrag des Umweltbundesamtes. Umweltbundesamt (Ed.). UBA Texte 37, Dessau-Roßlau. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-03-29_texte_37-2019_svg_quantitativebewertungumweltindikatoren.pdf.

Meyer, M., Hirschnitz-Garbers, M. & Distelkamp, M. (2018): Contemporary Resource Policy and Decoupling Trends – Lessons Learnt from Integrated Model-Based Assessments. Sustainability 10 (6), p. 1858. DOI: 10.3390/su10061858.

Meyer, M., Löschel, A. & Lutz, C. (2021): Carbon price dynamics in ambitious climate mitigation scenarios: an analysis based on the IAMC 1.5 °C scenario explorer. Environmental Research Communications 3 (8), p. 81007. DOI: 10.1088/2515-7620/ac02ad.

Miguel Ramos, C. de & Laurenti, R. (2020): Synergies and Trade-offs among Sustainable Development Goals – The Case of Spain. Sustainability 12 (24), pp. 1–14. https://ideas.repec.org/a/gam/jsusta/v12y2020i24p10506-d462677.html.

Millennium Institute (2021): iSDG Sectors. https://isdgdoc.millennium-institute.org/en/docs/0104-isdg-sectors.html, last access 08.06.2022.

Miola, A., Borchardt, S., Neher, F. & Buscaglia, D. (2019): Interlinkages and policy coherence for the Sustainable Development Goals implementation – An operational method to identify trade-offs and co-benefits in a systemic way. Publications Office of the European Union. JRC technical reports, Luxembourg. DOI: 10.2760/780152.

Miola, A. & Schiltz, F. (2019): Measuring sustainable development goals performance – How to monitor policy action in the 2030 Agenda implementation? Ecological Economics 164, p. 106373. DOI: 10.1016/j.ecolecon.2019.106373.

Moallemi, E. A., Haan, F. J. de, Hadjikakou, M., Khatami, S., Malekpour, S., Smajgl, A., Smith, M. S., Voinov, A., Bandari, R., Lamichhane, P., Miller, K. K., Nicholson, E., Novalia, W., Ritchie, E. G., Rojas, A. M., Shaikh, M. A., Szetey, K. & Bryan, B. A. (2021): Evaluating Participatory Modeling Methods for Co-creating Pathways to Sustainability. Earth's future 9 (3), e2020EF001843. DOI: 10.1029/2020EF001843.

Naidoo, D., Nhamo, L., Lottering, S., Mpandeli, S., Liphadzi, S., Modi, A. T., Trois, C. & Mabhaudhi, T. (2021a): Transitional Pathways towards Achieving a Circular Economy in the Water, Energy, and Food Sectors. Sustainability 13 (17), pp. 1–15. https://ideas.repec.org/a/gam/jsusta/v13y2021i17p9978-d630024.html.

Naidoo, D., Nhamo, L., Mpandeli, S., Sobratee, N., Senzanje, A., Liphadzi, S., Slotow, R., Jacobson, M., Modi, A. T. & Mabhaudhi, T. (2021b): Operationalising the water-energy-food nexus through the theory of change. Renewable and Sustainable Energy Reviews 149 ©, p. 111416. DOI: 10.1016/j.rser.2021.11141.

Nelson, R. R. & Phelps, E. S. (1966): Investment in Humans, Technological Diffusion, and Economic Growth. The American Economic Review 56 (1/2), pp. 69–75. http://www.jstor.org/stable/1821269, last access 06.04.2022.

Newman, M. E. J. (2018): Networks. Second edition. Oxford University Press, Oxford.

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S. & Modi, A. T. (2020a): An integrative analytical model for the water-energy-food nexus – South Africa case study. Environmental Science & Policy 109, 15-24. DOI: 10.1016/j.envsci.2020.04.

Nhamo, L., Ndlela, B., Mpandeli, S. & Mabhaudhi, T. (2020b): The Water-Energy-Food Nexus as an Adaptation Strategy for Achieving Sustainable Livelihoods at a Local Level. Sustainability 12 (20), pp. 1–16. https://ideas.repec.org/a/gam/jsusta/v12y2020i20p8582-d429245.html.

Nilsson, M., Chisholm, E., Griggs, D., Howden-Chapman, P., McCollum, D., Messerli, P., NEUMANN, B., Stevance, A.-S., Visbeck, M. & Stafford-Smith, M. (2018): Mapping interactions between the sustainable development goals: lessons learned and ways forward. Sustainability Science 13 (6), pp. 1489–1503.

Nilsson, M., Griggs, D. & Visbeck, M. (2016): Policy: Map the interactions between Sustainable Development Goals. Nature 534 (7607), pp. 320–322. DOI: 10.1038/534320a.

Nogueira, L. P. P., Frossard Pereira de Lucena, A., Rathmann, R., Rua Rodriguez Rochedo, P., Szklo, A. & Schaeffer, R. (2014): Will thermal power plants with CCS play a role in Brazil's future electric power generation? International Journal of Greenhouse Gas Control 24, pp. 115–123. DOI: 10.1016/j.ijggc.2014.03.002.

Nordhaus, W. (2014): Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. Journal of the Association of Environmental and Resource Economists 1 (1/2), pp. 273–312. DOI: 10.1086/676035.

Oberpriller, Q., Peter, M., Füssler, J., Zimmer, A., Aboumahboub, T., Schleypen, J., Gidden, M., Schaeffer, M., Schleussner, C.-F. & Schwarze, R. (2021): Climate cost modelling – analysis of damage and mitigation frameworks and guidance for political use. With the collaboration of German Environment Agency. Umweltbundesamt (Ed.). Climate Change 68, Dessau-Roßlau.

Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S. & van Vuuren, D. P. (2016): Assessing the land resource – food price nexus of the Sustainable Development Goals. Science advances 2 (9), e1501499.

OECD.Stat: Annual National Accounts – 7A. Labour input by activity, ISIC rev4. Data. https://stats.oecd.org/Index.aspx?DataSetCode=SNA_TABLE7A, last access 25.04.2024.

Pedercini, M. (2011): Development Policy Analysis in Mali – Sustainable Growth Prospects. In: Barthe, G., Pardo, A. & Schneider, G. (Hg.): Software Engineering and Formal Methods. Springer, Berlin, Heidelberg, pp. 447–463.

Pedercini, M., Arquitt, S. & Chan, D. (2020): Integrated simulation for the 2030 agenda. System Dynamics Review 36 (3), pp. 333–357. DOI: 10.1002/sdr.1665.

Pedercini, M., Arquitt, S., Collste, D. & Herren, H. (2018a): Harvesting synergy from Sustainable Development Goal interactions. SocArXiv. Center for Open Science. jt6r7. https://ideas.repec.org/p/osf/socarx/jt6r7.html. DOI: 10.31219/osf.io/jt6r7.

Pedercini, M., Arquitt, S., Collste, D. & Herren, H. (2019): Harvesting synergy from sustainable development goal interactions. Proceedings of the National Academy of Sciences 116 (46), pp. 23021–23028.

Pedercini, M., Zuellich, G., Dianati, K. & Arquitt, S. (2018b): Toward achieving sustainable development goals in Ivory Coast – Simulating pathways to sustainable development. Sustainable Development 26 (6), pp. 588–595.

Peersman, G. & van Robays, I. (2012): Cross-country Differences in the Effects of Oil Shocks. Energy Economics 34 (5), pp. 1532–1547. DOI: 10.1016/j.eneco.2011.11.010.

Pham-Truffert, M., Metz, F., Fischer, M., Rueff, H. & Messerli, P. (2020): Interactions among Sustainable Development Goals – Knowledge for identifying multipliers and virtuous cycles. Sustainable Development 28 (5), pp. 1236–1250.

Philippidis, G., Shutes, L., M'Barek, R., Ronzon, T., Tabeau, A. & van Meijl, H. (2020): Snakes and ladders – World development pathways' synergies and trade-offs through the lens of the Sustainable Development Goals. Journal of Cleaner Production 267, p. 122147.

Pindyck, R. S. (2013): Climate Change Policy – What Do the Models Tell Us? Journal of Economic Literature 51 (3), pp. 860–872. DOI: 10.1257/jel.51.3.860.

Pollitt, H., Barker, A., Barton, J., Pirgmaier, E., Polzin, C., Lutter, S., Hinterberger, F. & Stocker, A. (2010): A Scoping Study on the Macroeconomic View of Sustainability – Final report for the European Commission, DG Environment. Cambridge Econometrics, Cambridge.

Pötzsch, O. & Rößger, F. (2015): Germany´s Population by 2060 – Results of the 13th coordinated population projection. With the collaboration of Staff at the "Demographic Analyses, Methods and Projections, Births and Deaths" Section. Federal Statistical Office of Germany (Ed.), Wiesbaden.

Pradhan, P., Costa, L., Rybski, D., Lucht, W. & Kropp, J. P. (2017): A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earth's future 5 (11), pp. 1169–1179. DOI: 10.1002/2017EF000632.

Rademaekers, K., Svatikova, K., Vermeulen, J., Smit, T. & Baroni, L. (2017): Environmental potential of the collaborative economy – Final Report and Annexes. With the collaboration of Pierre Hausemer, Marius Dragulin, Unnada Chewpreecha, Hector Pollitt, Katrien Boonen, An Vercalsteren, Jeroen Gillabe. European Commission.

Randers, J., Rockström, J., Stoknes, P.-E., Goluke, U., Collste, D., Cornell, S. E. & Donges, J. (2019): Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. Global Sustainability 2 (e24), pp. 1–11. DOI: 10.1017/sus.2019.22.

Ranganathan, S., Nicolis, S. C., Bali Swain, R. & Sumpter, D. J. T. (2017): Setting development goals using stochastic dynamical system models. Plos one 12 (2), e0171560. DOI: 10.1371/journal.pone.0171560.

Reilly, J., Paltsev, S., Strzepek, K., Selin, N. E., Cai, Y., Nam, K.-M., Monier, E., Dutkiewicz, S., Scott, J., Webster, M. & Sokolov, A. (2012): Valuing climate impacts in integrated assessment models – The MIT IGSM. MIT Joint Program on the Science and Policy of Global Change (Ed.). MIT. 219, Cambridge. DOI: 10.1007/s10584-012-0635-x.

Revesz, R. L., Howard, P. H., Arrow, K., Goulder, L. H., Kopp, R. E., Livermore, M. A., Oppenheimer, M. & Sterner, T. (2014): Global warming – Improve economic models of climate change. Nature 508, pp. 173–175. DOI: 10.1038/508173a.

Rioja, F. K. (2003): Filling potholes – macroeconomic effects of maintenance versus new investments in public infrastructure. Journal of Public Economics 87 (9), pp. 2281–2304. DOI: 10.1016/S0047-2727(01)00200-6.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., Wit, C. A. de, Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J. (2009): Planetary boundaries – Exploring the safe operating space for humanity. Ecology and Society 14 (2), p. 32.

Romer, P. M. (1990): Endogenous Technological Change. Journal of Political Economy 98 (5, Part 2), 71-102. DOI: 10.1086/261725.

Rose, A. (2004): Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation. In: Okuyama, Y. & Chang, S. E. (Hg.): Modeling Spatial and Economic Impacts of Disasters. Springer, Berlin, Heidelberg, pp. 13–36.

Rutherford, T. F. & Böhringer, C. (2015): The circular economy – an economic impact assessment. report to SUN-IZA.

Sachs, J. D., Lafortune, G., Fuller, G. & Drumm, E. (2023): Sustainable Development Report 2023 – Implementing the SDG Stimulus. Includes the SDG Index and Dashboards. Dublin University Press (Ed.). SDSN, Paris, Dublin. DOI: 10.25546/102924.

Schandl, H., Hatfield-Dodds, S., Wiedmann, T. O., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M. & Owen, A. (2016): Decoupling global environmental pressure and economic growth – scenarios for energy use, materials use and carbon emissions. Journal of Cleaner Production 132, pp. 45–56. DOI: 10.1016/j.jclepro.2015.06.100.

Scherer, L., Behrens, P., Koning, A. de, Heijungs, R., Sprecher, B. & Tukker, A. (2018): Trade-offs between social and environmental Sustainable Development Goals. Environmental Science & Policy 90, pp. 65–72.

Schuknecht, L. (2005): Stability and Growth Pact: issues and lessons from political economy. IEEP 2 (1), pp. 65–89. DOI: 10.1007/s10368-005-0028-3-y.

Schuknecht, L., Moutot, P., Rother, P. & Stark, J. (2011): The Stability and Growth Pact: Crisis and Reform.

Sebestyén, V. & Abonyi, J. (2021): Data-driven comparative analysis of national adaptation pathways for Sustainable Development Goals. Journal of Cleaner Production 319, p. 128657.

Sebestyén, V., Bulla, M., Rédey, Á. & Abonyi, J. (2019): Network model-based analysis of the goals, targets and indicators of sustainable development for strategic environmental assessment. Journal of Environmental Management 238, pp. 126–135. DOI: 10.1016/j.jenvman.2019.02.096.

Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., Hofmann, M., Bauer, N., Bertram, C., Bodirsky, B. L., Leimbach, M., Leininger, J., Levesque, A., Luderer, G., Pehl, M., Wingens, C., Baumstark, L., Beier, F., Dietrich, J.-P., Humpenöder, F., Jeetze, P. von, Klein, D., Koch, J., Pietzcker, R., Strefler, J., Lotze-Campen, H. & Popp, A. (2021): A sustainable development pathway for climate action within the UN 2030 Agenda. Nature Climate Change 11 (8), pp. 656–664. DOI: 10.1038/s41558-021-01098-3.

Spaiser, V., Ranganathan, S., Bali Swain, R. & 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), pp. 457–470. DOI: 10.1080/13504509.2016.1235624.

Spittler, N., Gladkykh, G., Diemer, A. & Davidsdottir, B. (2019): Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development. Energies 12 (8), p. 1584.

Spittler, N. & Kirchner, M. (2022): Ein SDG Modell für Österreich – Erfassung der Wechselwirkungen zw. SDG13 & anderen SDGs zur Simulation von Entwicklungspfaden & Kosten. Endbericht von StartClim2021.A in StartClim2021: Handeln und Aktivieren. BMK, BMWFW, Klima- und Energiefonds und Land Oberösterreich (Eds.), Wien.

Stechow, C. von, McCollum, D., Riahi, K., Minx, J. C., Kriegler, E., van Vuuren, D. P., Jewell, J., Robledo-Abad, C., Hertwich, E. G., Tavoni, M., Mirasgedis, S., Lah, O., Roy, J., Mulugetta, Y., Dubash, N. K., Bollen, J., Uerge-Vorsatz, D. & Edenhofer, O. (2015): Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives – A Synthesis. Annual Review of Environment and Resources 40, 363-394. DOI: 10.1146/annurev-environ-021113-095626.

Stechow, C. von, Minx, J. C., Riahi, K., Jewell, J., McCollum, D., 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), p. 34022. DOI: 10.1088/1748-9326/11/3/034022.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B. & Sörlin, S. (2015): Sustainability. Planetary boundaries – guiding human development on a changing planet. Science 347 (6223), p. 1259855. DOI: 10.1126/science.1259855.

Sterman, J. (2000): Business Dynamics – System Thinking and Modeling for a Complex World. 19. McGraw-Hill Education, New York City.

Sterman, J. D. (1984): Appropriate summary statistics for evaluating the historical fit of system dynamics models. Dynamica 10 (2), pp. 51–66.

Stern, N. (2013): The Structure of Economic Modeling of the Potential Impacts of Climate Change – Grafting Gross Underestimation of Risk onto Already Narrow Science Models. Journal of Economic Literature 51 (3), pp. 838–859. DOI: 10.1257/jel.51.3.838.

Stern, N. (2016): Economics – Current climate models are grossly misleading. Nature 530, pp. 407–409. DOI: 10.1038/530407a.

Theil, H. (1966): Applied economic forecasting. North-Holland Pub. Co., Rand McNally, Amsterdam, Chicago. https://openlibrary.org/books/OL5977059M/Applied_economic_forecasting.

Tuladhar, S., Yuan, M. & Montgomery, W. D. (2016): An economic analysis of the circular economy. NERA Economic Consulting.

Turner, G. M. (2014): Is global collapse imminent?. MSSI Research paper series no. 4. The University of Melbourne, Melbourne Sustainable Society Institute, Parkville VIC.

TWI2050 - The World in 2050 (2018): Transformations to achieve the Sustainable Development Goals – Report prepared by The World in 2050 initiative. With the collaboration of Elmar Kriegler, Dirk Messner, Nebojsa Nakicenovic, Keywan Riahi, Johan Rockström, Jeffrey Sachs et al. International Institute for Applied Systems Analysis, Laxenburg. http://pure.iiasa.ac.at/id/eprint/15347/.

UNEP (2011): Towards a Green Economy – Pathways to Sustainable Development and Poverty Eradication. A Synthesis for Policy Makers.

UNEP (2017): Resource Efficiency – Potential and Economic Implications. International Resource Panel Report. With the collaboration of Paul Ekins, Nick Hughes, Stefan Bringezu, Charles Arden-Clarke, Marina Fischer-Kowalski, Thomas Graedel et al.

United Nations (2015a): The Millennium Development Goals Report 2015. Working Papers. eSocialSciences. id:7222. https://ideas.repec.org/p/ess/wpaper/id7222.html.

United Nations (2015b): Transforming our World – the 2030 Agenda for Sustainable Development. Working Papers. eSocialSciences. id:7559. https://ideas.repec.org/p/ess/wpaper/id7559.html.

United Nations (2023): Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development.

https://unstats.un.org/sdgs/indicators/Global%20Indicator%20Framework%20after%202023%20refinement_Eng.pdf, last access 25.04.2024.

Valin, H., Hertel, T., Bodirsky, B. L., Hasegawa, T. & Stehfest, E. (2021): Achieving Zero Hunger by 2030 – A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals. A paper from the Scientific Group of the UN Food Systems Summit 26 May 2021. Center for Development Research (ZEF) und Scientific Group for the UN Food System Summit 2021 (Eds.), Bonn. DOI: 10.48565/scgr2021-2337.

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, p. 102191. DOI: 10.1016/j.gloenvcha.2020.102191.

van den Berg, M., Neumann, K., van Vuuren, D. P., Bouwman, A. F., Kram, T. & Bakkes, J. (2016): Exploring resource efficiency for energy, land and phosphorus use – Implications for resource scarcity and the global environment. Global Environmental Change - Human and Policy Dimensions 36, pp. 21–34. DOI: 10.1016/j.gloenvcha.2015.09.016.

van Soest, H. L., van Vuuren, D. P., Hilaire, J., Minx, J. C., Harmsen, M. J. H. M., Krey, V., Popp, A., Riahi, K. & Luderer, G. (2019): Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. Global Transitions 1, pp. 210–225. DOI: 10.1016/j.glt.2019.10.004.

van Vuuren, D. P., Kok, M., Lucas, P. L., Prins, A. G., Alkemade, R., van den Berg, M., Bouwman, L., van der Esch, S., Jeuken, M., Kram, T. & 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, pp. 303–323. DOI: 10.1016/j.techfore.2015.03.005.

van Vuuren, D. P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., KC, S., Kriegler, E. & O'Neill, B. (2017a): The Shared Socio-economic Pathways – Trajectories for human development and global environmental change. Global Environmental Change 42, pp. 148–152. DOI: 10.1016/j.gloenvcha.2016.10.009.

van Vuuren, D. P., Stehfest, E., Gernaat, D. E., Doelman, J. C., van den Berg, M., Harmsen, M., Boer, H. S. de, Bouwman, L. F., Daioglou, V., Edelenbosch, O. Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P. L., van Meijl, H., Müller, C., van Ruijven, B. J., van der Sluis, S. & Tabeau, A. (2017b): Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42, pp. 237–250. DOI: 10.1016/j.gloenvcha.2016.05.008.

van Vuuren, D. P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D., Nakicenovic, N., Rockstrom, J., Riahi, K., Sperling, F., Bosetti, V., Cornell, S., Gaffney, O., Lucas, P. L., Popp, A., Ruhe, C., Schiller, A. von, Schmidt, J. O. & Soergel, B. (2022): Defining a sustainable development target space for 2030 and 2050. One Earth. DOI: 10.1016/j.oneear.2022.01.003.

van Zanten, J. A. & van Tulder, R. (2021): Towards nexus-based governance – defining interactions between economic activities and Sustainable Development Goals (SDGs). International Journal of Sustainable Development & World Ecology 28 (3), pp. 210–226.

Vieille Blanchard, E. (2010): Modelling the Future – an Overview of the 'Limits to Growth' Debate. Centaurus 52 (2), pp. 91–116. DOI: 10.1111/j.1600-0498.2010.00173.x.

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P. D., Bommel, P., Prell, C., Zellner, M., Paolisso, M., Jordan, R., Sterling, E., Olabisi, L. S., Giabbanelli, P. J., Sun, Z., Le Page, C., Elsawah, S., BenDor, T. K., Hubacek, K., Laursen, B. K., Jetter, A., Basco-Carrera, L., Singer, A., Young, L., Brunacini, J. & Smajgl, A. (2018): Tools and methods in participatory modeling – Selecting the right tool for the job. Environmental Modelling & Software 109, pp. 232–255. DOI: 10.1016/j.envsoft.2018.08.028.

Weimer-Jehle, W. (2006): Cross-impact balances – A system-theoretical approach to cross-impact analysis. Technological Forecasting and Social Change 73 (4), pp. 334–361. DOI: 10.1016/j.techfore.2005.06.005.

Weitz, N., Carlsen, H., Nilsson, M. & Skånberg, K. (2018): Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustainability Science 13 (2), pp. 531–548.

Weitzman, M. L. (2013): Tail-Hedge Discounting and the Social Cost of Carbon. Journal of Economic Literature 51 (3), pp. 873–882. DOI: 10.1257/jel.51.3.873.

Weyant, J. (2017): Some Contributions of Integrated Assessment Models of Global Climate Change. Review of Environmental Economics and Policy 11 (1), pp. 115–137. DOI: 10.1093/reep/rew018.

Wiese, F., Thema, J. & Cordroch, L. (2022): Strategies for climate neutrality – Lessons from a meta-analysis of German energy scenarios. Renewable and Sustainable Energy Transition 2, p. 100015. DOI: 10.1016/j.rset.2021.100015.

Winning, M., Calzadilla, A., Bleischwitz, R. & Nechifor, V. (2017): Towards a circular economy – insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. International Economics and Economic Policy 14 (3), pp. 383–407.

Yanikkaya, H. (2003): Trade openness and economic growth – a cross-country empirical investigation. Journal of Development Economics 72 (1), pp. 57–89. DOI: 10.1016/S0304-3878(03)00068-3.

Zelinka, D. & Amadei, B. (2019): A systems approach for modeling interactions among the Sustainable Development Goals Part 2 – System dynamics. International Journal of System Dynamics Applications 8 (1), pp. 41–59.

Zhou, X. & Moinuddin, M. (2017): Sustainable Development Goals Interlinkages and Network Analysis – A practical tool for SDG integration and policy coherence. IGES Research Report. Institute for Global Environmental Strategies (IGES) (Ed.), Kanagawa. https://sdginterlinkages.iges.jp/files/IGES_Research%20Report_SDG%20Interlinkages_Printing%20Version.pdf.

Appendix: Focal Goals and Targets from the 2030 Agenda for Sustainable Development

Tabular overviews

Ideally, indicators assessed in the model applications should also be linked to Germany's SDG indicators at national level to ensure national policy relevance. The national online platform https://sdg-indikatoren.de/en/ provides access to two databases, namely the German set of indicators for the global sustainability goals (Sustainable Development Goals, SDGs) of the United Nations 2030 Agenda and the indicator set of the German Sustainable Development Strategy (Deutsche Nachhaltigkeitsstrategie, DNS). Since the German Sustainable Development Strategy is aimed at implementing the 2030 Agenda at the national level, indicators shared by both strategies are linked to each other on the platform. The following tables provide an overview on global as well as national SDG targets and indicators. Indicators that are generally covered by the iSDG are highlighted in blue.

Table 19: Targets and related indicators from the 2030 Agenda, SDG1

SDG 1: Targets	SDG 1: Indicators
1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day	1.1.1 Proportion of the population living below the international poverty line by sex, age, employment status and geographic location (urban/rural)
1.2 By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions	1.2.1 Proportion of population living below the national poverty line, by sex and age
	1.2.2 Proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions
1.3 Implement nationally appropriate social protection systems and measures for all, including floors, and by 2030 achieve substantial coverage of the poor and the vulnerable	1.3.1 Proportion of population covered by social protection floors/systems, by sex, distinguishing children, unemployed persons, older persons, persons with disabilities, pregnant women, newborns, work-injury victims and the poor and the vulnerable
1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	1.4.1 Proportion of population living in households with access to basic services
	1.4.2 Proportion of total adult population with secure tenure rights to land, (a) with legally recognized documentation, and (b) who perceive their rights to land as secure, by sex and type of tenure
1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related	1.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population

SDG 1: Targets	SDG 1: Indicators
extreme events and other economic, social and environmental shocks and disasters	
	1.5.2 Direct economic loss attributed to disasters in relation to global gross domestic product (GDP)
	1.5.3 Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030
	1.5.4 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies
1.a Ensure significant mobilization of resources from a variety of sources, including through enhanced development cooperation, in order to provide adequate and predictable means for developing countries, in particular least developed countries, to implement programmes and policies to end poverty in all its dimensions	1.a.1 Total official development assistance grants from all donors that focus on poverty reduction as a share of the recipient country's gross national income
	1.a.2 Proportion of total government spending on essential services (education, health and social protection)
1.b Create sound policy frameworks at the national, regional and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions	1.b.1 Pro-poor public social spending

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 20: Indicators of the German Sustainable Development Strategy, Goal 1

Goal 1: Range of indicators and postulates	Goal 1: Indicators
Poverty: Limiting poverty	1.1.a, b Material deprivation and severe material deprivation

Source: https://dns-indikatoren.de/en/1/ (accessed 26.04.2024)

Table 21: Targets and related indicators from the 2030 Agenda, SDG2

SDG 2: Targets	SDG 2: Indicators
2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2.1.1 Prevalence of undernourishment
	2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES)
2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons	2.2.1 Prevalence of stunting (height for age <-2 standard deviation from the median of the World Health Organization (WHO) Child Growth Standards) among children under 5 years of age
	2.2.2 Prevalence of malnutrition (weight for height >+2 or <-2 standard deviation from the median of the WHO Child Growth Standards) among children under 5 years of age, by type (wasting and overweight)
	2.2.3 Prevalence of anaemia in women aged 15 to 49 years, by pregnancy status (percentage)
2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	2.3.1 Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size
	2.3.2 Average income of small-scale food producers, by sex and indigenous status
2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	2.4.1 Proportion of agricultural area under productive and sustainable agriculture
2.5 By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed	2.5.1 Number of (a) plant and (b) animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities
	2.5.2 Proportion of local breeds classified as being at risk of extinction

SDG 2: Targets	SDG 2: Indicators
2.a Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries	2.a.1 The agriculture orientation index for government expenditures
	2.a.2 Total official flows (official development assistance plus other official flows) to the agriculture sector
2.b Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round	2.b.1 Agricultural export subsidies
2.c Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility	2.c.1 Indicator of food price anomalies

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 22: Indicators of the German Sustainable Development Strategy, Goal 2

Goal 2: Range of indicators and postulates	Goal 2: Indicators
Farming: Environmentally sound production in our cultivated landscapes	2.1.a Nitrogen surplus in agriculture
	2.1.b Organic farming
Food security: Realising the right to food worldwide	2.2 Support for good governance in attaining appropriate nutrition worldwide

Source: https://dns-indikatoren.de/en/2/ (accessed 26.04.2024)

Table 23: Targets and related indicators from the 2030 Agenda, SDG3

SDG 3: Targets	SDG 3: Indicators
3.1 By 2030, reduce the global maternal mortality ratio to less than 70 per 100,000 live births	3.1.1 Maternal mortality ratio
	3.1.2 Proportion of births attended by skilled health personnel
3.2 By 2030, end preventable deaths of newborns and children under 5 years of age, with all countries aiming to reduce neonatal mortality to at least as low as 12 per 1,000 live births and under-5 mortality to at least as low as 25 per 1,000 live births	3.2.1 Under-5 mortality rate
	3.2.2 Neonatal mortality rate
3.3 By 2030, end the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases and other communicable diseases	3.3.1 Number of new HIV infections per 1,000 uninfected population, by sex, age and key populations
	3.3.2 Tuberculosis incidence per 100,000 population
	3.3.3 Malaria incidence per 1,000 population
	3.3.4 Hepatitis B incidence per 100,000 population
	3.3.5 Number of people requiring interventions against neglected tropical diseases
3.4 By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being	3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease
	3.4.2 Suicide mortality rate
3.5 Strengthen the prevention and treatment of substance abuse, including narcotic drug abuse and harmful use of alcohol	3.5.1 Coverage of treatment interventions (pharmacological, psychosocial and rehabilitation and aftercare services) for substance use disorders
	3.5.1 Coverage of treatment interventions (pharmacological, psychosocial and rehabilitation and aftercare services) for substance use disorders
3.6 By 2020, halve the number of global deaths and injuries from road traffic accidents	3.6.1 Death rate due to road traffic injuries
3.7 By 2030, ensure universal access to sexual and reproductive health-care services, including for family planning, information and education, and the integration of reproductive health into national strategies and programmes	3.7.1 Proportion of women of reproductive age (aged 15–49 years) who have their need for family planning satisfied with modern methods

SDG 3: Targets	SDG 3: Indicators
	3.7.2 Adolescent birth rate (aged 10–14 years; aged 15–19 years) per 1,000 women in that age group
3.8 Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality and affordable essential medicines and vaccines for all	3.8.1 Coverage of essential health services
	3.8.2 Proportion of population with large household expenditures on health as a share of total household expenditure or income
3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	3.9.1 Mortality rate attributed to household and ambient air pollution
	3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services)
	3.9.3 Mortality rate attributed to unintentional poisoning
3.a Strengthen the implementation of the World Health Organization Framework Convention on Tobacco Control in all countries, as appropriate	3.a.1 Age-standardized prevalence of current tobacco use among persons aged 15 years and older
3.b Support the research and development of vaccines and medicines for the communicable and non-communicable diseases that primarily affect developing countries, provide access to affordable essential medicines and vaccines, in accordance with the Doha Declaration on the TRIPS Agreement and Public Health, which affirms the right of developing countries to use to the full the provisions in the Agreement on Trade-Related Aspects of Intellectual Property Rights regarding flexibilities to protect public health, and, in particular, provide access to medicines for all	3.b.1 Proportion of the target population covered by all vaccines included in their national programme
	3.b.2 Total net official development assistance to medical research and basic health sectors
	3.b.3 Proportion of health facilities that have a core set of relevant essential medicines available and affordable on a sustainable basis
3.c Substantially increase health financing and the recruitment, development, training and retention of the health workforce in developing countries, especially in least developed countries and small island developing States	3.c.1 Health worker density and distribution
3.d Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction and management of national and global health risks	3.d.1 International Health Regulations (IHR) capacity and health emergency preparedness

SDG 3: Targets	SDG 3: Indicators
	3.d.2 Percentage of bloodstream infections due to selected antimicrobial-resistant organisms

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 24: Indicators of the German Sustainable Development Strategy, Goal 3

Goal 3: Range of indicators and postulates	Goal 3: Indicators
Health and nutrition: Living healthy longer	3.1.a, b Premature mortality
	3.1.c, d Smoking rate among young people and adults
	3.1.e Obesity rates among children and adolescents
	3.1.f Obesity rates among adults
Air pollution: Keeping the environment healthy	3.2.a Emissions of air pollutants
	3.2.b Share of the population with excessive exposure to PM
Global health: Strengthening the global health architecture	3.3 Germany’s contribution to global pandemic prevention and response

Source: https://dns-indikatoren.de/en/3/ (accessed 26.04.2024)

Table 25: Targets and related indicators from the 2030 Agenda, SDG4

SDG 4: Targets	SDG 4: Indicators
4.1 By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes	4.1.1 Proportion of children and young people (a) in grades 2/3; (b) at the end of primary; and (c) at the end of lower secondary achieving at least a minimum proficiency level in (i) reading and (ii) mathematics, by sex
	4.1.2 Completion rate (primary education, lower secondary education, upper secondary education)
4.2 By 2030, ensure that all girls and boys have access to quality early childhood development, care and pre-primary education so that they are ready for primary education	4.2.1 Proportion of children aged 24–59 months who are developmentally on track in health, learning and psychosocial well-being, by sex
	4.2.2 Participation rate in organized learning (one year before the official primary entry age), by sex
4.3 By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education, including university	4.3.1 Participation rate of youth and adults in formal and non-formal education and training in the previous 12 months, by sex
4.4 By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship	4.4.1 Proportion of youth and adults with information and communications technology (ICT) skills, by type of skill
4.5 By 2030, eliminate gender disparities in education and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples and children in vulnerable situations	4.5.1 Parity indices (female/male, rural/urban, bottom/top wealth quintile and others such as disability status, indigenous peoples and conflict-affected, as data become available) for all education indicators on this list that can be disaggregated
4.6 By 2030, ensure that all youth and a substantial proportion of adults, both men and women, achieve literacy and numeracy	4.6.1 Proportion of population in a given age group achieving at least a fixed level of proficiency in functional (a) literacy and (b) numeracy skills, by sex
4.7 By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development	4.7.1 Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment
4.a Build and upgrade education facilities that are child, disability and gender sensitive and provide safe, non-violent, inclusive and effective learning environments for all	4.a.1 Proportion of schools offering basic services, by type of service

SDG 4: Targets	SDG 4: Indicators
4.b By 2020, substantially expand globally the number of scholarships available to developing countries, in particular least developed countries, small island developing States and African countries, for enrolment in higher education, including vocational training and information and communications technology, technical, engineering and scientific programmes, in developed countries and other developing countries	4.b.1 Volume of official development assistance flows for scholarships by sector and type of study
4.c By 2030, substantially increase the supply of qualified teachers, including through international cooperation for teacher training in developing countries, especially least developed countries and small island developing States	4.c.1 Proportion of teachers with the minimum required qualifications, by education level

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 26: Indicators of the German Sustainable Development Strategy, Goal 4

Goal 4: Range of indicators and postulates	Goal 4: Indicators
Education: Continuously improving education and vocational training	4.1.a Early school leavers
	4.1.b Persons with an academic or higher vocational qualification (30 to 34-year-olds with a tertiary or post-secondary non-tertiary level of education)
Prospects for families: Improving the compatibility of work and family life	4.2.a, b All-day care provision for children

Source: https://dns-indikatoren.de/en/4/ (accessed 26.04.2024)

Table 27: Targets and related indicators from the 2030 Agenda, SDG5

SDG 5: Targets	SDG 5: Indicators
5.1 End all forms of discrimination against all women and girls everywhere	5.1.1 Whether or not legal frameworks are in place to promote, enforce and monitor equality and non-discrimination on the basis of sex
5.2 Eliminate all forms of violence against all women and girls in the public and private spheres, including trafficking and sexual and other types of exploitation	5.2.1 Proportion of ever-partnered women and girls aged 15 years and older subjected to physical, sexual or psychological violence by a current or former intimate partner in the previous 12 months, by form of violence and by age
	5.2.2 Proportion of women and girls aged 15 years and older subjected to sexual violence by persons other than an intimate partner in the previous 12 months, by age and place of occurrence
5.3 Eliminate all harmful practices, such as child, early and forced marriage and female genital mutilation	5.3.1 Proportion of women aged 20–24 years who were married or in a union before age 15 and before age 18
	5.3.2 Proportion of girls and women aged 15–49 years who have undergone female genital mutilation/cutting, by age
5.4 Recognize and value unpaid care and domestic work through the provision of public services, infrastructure and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate	5.4.1 Proportion of time spent on unpaid domestic and care work, by sex, age and location
5.5 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life	5.5.1 Proportion of seats held by women in (a) national parliaments and (b) local governments
	5.5.2 Proportion of women in managerial positions
5.6 Ensure universal access to sexual and reproductive health and reproductive rights as agreed in accordance with the Programme of Action of the International Conference on Population and Development and the Beijing Platform for Action and the outcome documents of their review conferences	5.6.1 Proportion of women aged 15–49 years who make their own informed decisions regarding sexual relations, contraceptive use and reproductive health care
	5.6.2 Number of countries with laws and regulations that guarantee full and equal access to women and men aged 15 years and older to sexual and reproductive health care, information and education
5.a Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws	5.a.1 (a) Proportion of total agricultural population with ownership or secure rights over agricultural land, by sex; and (b) share of women among owners or rights-bearers of agricultural land, by type of tenure

SDG 5: Targets	SDG 5: Indicators
	5.a.2 Proportion of countries where the legal framework (including customary law) guarantees women's equal rights to land ownership and/or control
5.b Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women	5.b.1 Proportion of individuals who own a mobile telephone, by sex
5.c Adopt and strengthen sound policies and enforceable legislation for the promotion of gender equality and the empowerment of all women and girls at all levels	5.c.1 Proportion of countries with systems to track and make public allocations for gender equality and women's empowerment

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 28: Indicators of the German Sustainable Development Strategy, Goal 5

Goal 5: Range of indicators and postulates	Goal 5: Indicators
Equality: Promoting equality and a partnership-based division of responsibilities	5.1.a Gender pay gap
	5.1.b, c Women in management positions in business and in the federal civil service
	5.1.d Proportion of fathers receiving parental allowance
Equality: Strengthening the economic participation of women globally	5.1.e Vocational qualification of women and girls through German development cooperation

Source: https://dns-indikatoren.de/en/5/ (accessed 26.04.2024)

Table 29: Targets and related indicators from the 2030 Agenda, SDG6

SDG 6: Targets	SDG 6: Indicators
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Proportion of population using safely managed drinking water services
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	6.2.1 Proportion of population using (a) safely managed sanitation services and (b) a hand-washing facility with soap and water
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1 Proportion of domestic and industrial wastewater flows safely treated
	6.3.2 Proportion of bodies of water with good ambient water quality
6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.1 Change in water-use efficiency over time
	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	6.5.1 Degree of integrated water resources management
	6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	6.6.1 Change in the extent of water-related ecosystems over time
6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan
6.b Support and strengthen the participation of local communities in improving water and sanitation management	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 30: Indicators of the German Sustainable Development Strategy, Goal 6

Goal 6: Range of indicators and postulates	Goal 6: Indicators
Water quality: Reduction of substance pollution in water	6.1.a Phosphorus in flowing waters
	6.1.b Nitrate in groundwater
Drinking water and sanitation: Better access to drinking water and sanitation worldwide, higher (safer) quality	6.2.a, b Development cooperation for access to drinking water and sanitation

Source: https://dns-indikatoren.de/en/6/ (accessed 26.04.2024)

Table 31: Targets and related indicators from the 2030 Agenda, SDG7

SDG 7: Targets	SDG 7: Indicators
7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.1 Proportion of population with access to electricity
	7.1.2 Proportion of population with primary reliance on clean fuels and technology
7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption
7.3 By 2030, double the global rate of improvement in energy efficiency	7.3.1 Energy intensity measured in terms of primary energy and GDP
7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology	7.a.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems
7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support	7.b.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 32: Indicators of the German Sustainable Development Strategy, Goal 7

Goal 7: Range of indicators and postulates	Goal 7: Indicators
Resource conservation: Using resources economically and efficiently	7.1.a, b Final energy productivity and primary energy consumption
Renewable energies: Strengthening a sustainable energy supply	7.2.a Share of renewable energies in gross final energy consumption
	7.2.b Share of electricity from renewable sources in gross electricity consumption

Source: https://dns-indikatoren.de/en/7/ (accessed 26.04.2024)

Table 33: Targets and related indicators from the 2030 Agenda, SDG8

SDG 8: Targets	SDG 8: Indicators
8.1 Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries	8.1.1 Annual growth rate of real GDP per capita
8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors	8.2.1 Annual growth rate of real GDP per employed person
8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services	8.3.1 Proportion of informal employment in total employment, by sector and sex
8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead	8.4.1 Material footprint, material footprint per capita, and material footprint per GDP
	8.4.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value	8.5.1 Average hourly earnings of employees, by sex, age, occupation and persons with disabilities
	8.5.2 Unemployment rate, by sex, age and persons with disabilities
8.6 By 2020, substantially reduce the proportion of youth not in employment, education or training	8.6.1 Proportion of youth (aged 15–24 years) not in education, employment or training
8.7 Take immediate and effective measures to eradicate forced labour, end modern slavery and human trafficking and secure the prohibition and elimination of the worst forms of child labour, including recruitment and use of child soldiers, and by 2025 end child labour in all its forms	8.7.1 Proportion and number of children aged 5–17 years engaged in child labour, by sex and age
8.8 Protect labour rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment	8.8.1 Fatal and non-fatal occupational injuries per 100,000 workers, by sex and migrant status
	8.8.2 Level of national compliance with labour rights (freedom of association and collective bargaining) based on International Labour Organization (ILO) textual sources and national legislation, by sex and migrant status

SDG 8: Targets	SDG 8: Indicators
8.9 By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	8.9.1 Tourism direct GDP as a proportion of total GDP and in growth rate
8.10 Strengthen the capacity of domestic financial institutions to encourage and expand access to banking, insurance and financial services for all	8.10.1 (a) Number of commercial bank branches per 100,000 adults and (b) number of automated teller machines (ATMs) per 100,000 adults
	8.10.2 Proportion of adults (15 years and older) with an account at a bank or other financial institution or with a mobile-money-service provider
8.a Increase Aid for Trade support for developing countries, in particular least developed countries, including through the Enhanced Integrated Framework for Trade-related Technical Assistance to Least Developed Countries	8.a.1 Aid for Trade commitments and disbursements
8.b By 2020, develop and operationalize a global strategy for youth employment and implement the Global Jobs Pact of the International Labour Organization	8.b.1 Existence of a developed and operationalized national strategy for youth employment, as a distinct strategy or as part of a national employment strategy

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 34: Indicators of the German Sustainable Development Strategy, Goal 8

Goal 8: Range of indicators and postulates	Goal 8: Indicators
Resource conservation: Using resources economically and efficiently	8.1 Raw material input productivity
Government debt: Consolidating public finances – creating intergenerational equity	8.2.a, b Government deficit, structural deficit
	8.2.c Government debt
Provision for future economic stability: Creating favourable investment conditions – securing long-term prosperity	8.3 Gross fixed capital formation in relation to GDP
Economic performance: Combining greater economic output with environmental and social responsibility	8.4 Gross domestic product per capita
Employment: Boosting employment levels	8.5.a, b Employment rate
Global supply chains: Enabling decent work worldwide	8.6 Members of the Textiles Partnership

Source: https://dns-indikatoren.de/en/8// (accessed 26.04.2024)

Table 35: Targets and related indicators from the 2030 Agenda, SDG9

SDG 9: Targets	SDG 9: Indicators
9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all	9.1.1 Proportion of the rural population who live within 2 km of an all-season road
	9.1.2 Passenger and freight volumes, by mode of transport
9.2 Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries	9.2.1 Manufacturing value added as a proportion of GDP and per capita
	9.2.2 Manufacturing employment as a proportion of total employment
9.3 Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets	9.3.1 Proportion of small-scale industries in total industry value added
	9.3.2 Proportion of small-scale industries with a loan or line of credit
9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	9.4.1 CO_2 emission per unit of value added
9.5 Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending	9.5.1 Research and development expenditure as a proportion of GDP
	9.5.2 Researchers (in full-time equivalent) per million inhabitants
9.a Facilitate sustainable and resilient infrastructure development in developing countries through enhanced financial, technological and technical support to African countries, least developed countries, landlocked developing countries and small island developing States	9.a.1 Total official international support (official development assistance plus other official flows) to infrastructure
9.b Support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities	9.b.1 Proportion of medium and high-tech industry value added in total value added
9.c Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020	9.c.1 Proportion of population covered by a mobile network, by technology

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 36: Indicators of the German Sustainable Development Strategy, Goal 9

Goal 9: Range of indicators and postulates	Goal 9: Indicators
Innovation: Shaping the future sustainably with new solutions	9.1.a Private and public expenditure on research and development
	9.1.b Rollout of broadband

Source: https://dns-indikatoren.de/en/9/ (accessed 26.04.2024)

Table 37: Targets and related indicators from the 2030 Agenda, SDG10

SDG 10: Targets	SDG 10: Indicators
10.1 By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average	10.1.1 Growth rates of household expenditure or income per capita among the bottom 40 per cent of the population and the total population
10.2 By 2030, empower and promote the social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status	10.2.1 Proportion of people living below 50 per cent of median income, by sex, age and persons with disabilities
10.3 Ensure equal opportunity and reduce inequalities of outcome, including by eliminating discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard	10.3.1 Proportion of population reporting having personally felt discriminated against or harassed in the previous 12 months on the basis of a ground of discrimination prohibited under international human rights law
10.4 Adopt policies, especially fiscal, wage and social protection policies, and progressively achieve greater equality	10.4.1 Labour share of GDP
	10.4.2 Redistributive impact of fiscal policy
10.5 Improve the regulation and monitoring of global financial markets and institutions and strengthen the implementation of such regulations	10.5.1 Financial Soundness Indicators
10.6 Ensure enhanced representation and voice for developing countries in decision-making in global international economic and financial institutions in order to deliver more effective, credible, accountable and legitimate institutions	10.6.1 Proportion of members and voting rights of developing countries in international organizations
10.7 Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies	10.7.1 Recruitment cost borne by employee as a proportion of monthly income earned in country of destination
	10.7.2 Number of countries with migration policies that facilitate orderly, safe, regular and responsible migration and mobility of people
	10.7.3 Number of people who died or disappeared in the process of migration towards an international destination
	10.7.4 Proportion of the population who are refugees, by country of origin
10.a Implement the principle of special and differential treatment for developing countries, in particular least developed countries, in accordance with World Trade Organization agreements	10.a.1 Proportion of tariff lines applied to imports from least developed countries and developing countries with zero-tariff

SDG 10: Targets	SDG 10: Indicators
10.b Encourage official development assistance and financial flows, including foreign direct investment, to States where the need is greatest, in particular least developed countries, African countries, small island developing States and landlocked developing countries, in accordance with their national plans and programmes	10.b.1 Total resource flows for development, by recipient and donor countries and type of flow (e.g. official development assistance, foreign direct investment and other flows)
10.c By 2030, reduce to less than 3 per cent the transaction costs of migrant remittances and eliminate remittance corridors with costs higher than 5 per cent	10.c.1 Remittance costs as a proportion of the amount remitted

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 38: Indicators of the German Sustainable Development Strategy, Goal 10

Goal 10: Range of indicators and postulates	Goal 10: Indicators
Equal educational opportunities: Improving educational success of foreigners in German schools	10.1 Foreign school graduates
Distributive justice: Preventing excessive inequality within Germany	10.2 Gini coefficient of income after social transfers

Source: https://dns-indikatoren.de/en/10/ (accessed 26.04.2024)

Table 39: Targets and related indicators from the 2030 Agenda, SDG11

SDG 11: Targets	SDG 11: Indicators
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	11.1.1 Proportion of urban population living in slums, informal settlements or inadequate housing
11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	11.2.1 Proportion of population that has convenient access to public transport, by sex, age and persons with disabilities
11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	11.3.1 Ratio of land consumption rate to population growth rate
	11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically
11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage	11.4.1 Total per capita expenditure on the preservation, protection and conservation of all cultural and natural heritage, by source of funding (public, private), type of heritage (cultural, natural) and level of government (national, regional, and local/municipal)
11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	11.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
	11.5.2 Direct economic loss in relation to global GDP, damage to critical infrastructure and number of disruptions to basic services, attributed to disasters
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.1 Proportion of municipal solid waste collected and managed in controlled facilities out of total municipal waste generated, by cities
	11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)
11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities
	11.7.2 Proportion of persons victim of physical or sexual harassment, by sex, age,

SDG 11: Targets	SDG 11: Indicators
	disability status and place of occurrence, in the previous 12 months
11.a Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning	11.a.1 Number of countries that have national urban policies or regional development plans that (a) respond to population dynamics; (b) ensure balanced territorial development; and (c) increase local fiscal space
11.b By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels	11.b.1 Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030
	11.b.2 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies
11.c Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials	No suitable replacement indicator was proposed. The global statistical community is encouraged to work to develop an indicator that could be proposed for the 2025 comprehensive review. See E/CN.3/2020/2, paragraph 23.

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 40: Indicators of the German Sustainable Development Strategy, Goal 11

Goal 11: Range of indicators and postulates	Goal 11: Indicators
Land use: Using land sustainably	11.1.a Expansion of settlement and transport area
	11.1.b Loss of open space area
	11.1.c Density of settlements
Mobility: Guaranteeing mobility – protecting the environment	11.2.a Final energy consumption in goods transport
	11.2.b Final energy consumption in passenger transport
	11.2.c Accessibility of medium-sized and large cities by public transport
Housing: Affordable housing for all	11.3 Housing cost overload
Cultural heritage: Improving access to cultural heritage	11.4 Number of objects in the German Digital Library

Source: https://dns-indikatoren.de/en/11/ (accessed 26.04.2024)

Table 41: Targets and related indicators from the 2030 Agenda, SDG12

SDG 12: Targets	SDG 12: Indicators
12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries	12.1.1 Number of countries developing, adopting or implementing policy instruments aimed at supporting the shift to sustainable consumption and production
12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP
	12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	12.3.1 (a) Food loss index and (b) food waste index
12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement
	12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment
12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled
12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle	12.6.1 Number of companies publishing sustainability reports
12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities	12.7.1 Degree of sustainable public procurement policies and action plan implementation
12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	12.8.1 Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment
12.a Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production	12.a.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)

SDG 12: Targets	SDG 12: Indicators
12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	12.b.1 Implementation of standard accounting tools to monitor the economic and environmental aspects of tourism sustainability
12.c Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities	12.c.1 Amount of fossil-fuel subsidies (production and consumption) per unit of GDP

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 42: Indicators of the German Sustainable Development Strategy, Goal 12

Goal 12: Range of indicators and postulates	Goal 12: Indicators
Sustainable consumption: Making consumption environmentally and socially compatible	12.1.a Market share of products certified by publicly managed eco-labelling schemes
	12.1.b Global environmental impact by private household consumption
Sustainable production: Steadily increasing the proportion of sustainable production	12.2 EMAS eco-management
Sustainable procurement: Giving shape to the public sector’s exemplary role in sustainable procurement	12.3.a, b Sustainable procurement

Source: https://dns-indikatoren.de/en/12/ (accessed 26.04.2024)

Table 43: Targets and related indicators from the 2030 Agenda, SDG13

SDG 13: Targets	SDG 13: Indicators
13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
	13.1.2 Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030
	13.1.3 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies
13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change
	13.2.2 Total greenhouse gas emissions per year
13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	13.3.1 Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment
13.a Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible	13.a.1 Amounts provided and mobilized in United States dollars per year in relation to the continued existing collective mobilization goal of the $100 billion commitment through to 2025
13.b Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities	13.b.1 Number of least developed countries and small island developing States with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 44: Indicators of the German Sustainable Development Strategy, Goal 13

Goal 13: Range of indicators and postulates	Goal 13: Indicators
Climate protection: Reducing greenhouse gases	13.1.a Greenhouse gas emissions
Climate protection: Contribution to international climate finance	13.1.b International climate finance for the reduction of greenhouse gases and adaptation to climate change

Source: https://dns-indikatoren.de/en/13/ (accessed 26.04.2024)

Table 45: Targets and related indicators from the 2030 Agenda, SDG14

SDG 14: Targets	SDG 14: Indicators
14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	14.1.1 (a) Index of coastal eutrophication; and (b) plastic debris density
14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans	14.2.1 Number of countries using ecosystem-based approaches to managing marine areas
14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels	14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations
14.4 By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics	14.4.1 Proportion of fish stocks within biologically sustainable levels
14.5 By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information	14.5.1 Coverage of protected areas in relation to marine areas
14.6 By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the World Trade Organization fisheries subsidies negotiation	14.6.1 Degree of implementation of international instruments aiming to combat illegal, unreported and unregulated fishing
14.7 By 2030, increase the economic benefits to small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism	14.7.1 Sustainable fisheries as a proportion of GDP in small island developing States, least developed countries and all countries
14.a Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries	14.a.1 Proportion of total research budget allocated to research in the field of marine technology
14.b Provide access for small-scale artisanal fishers to marine resources and markets	14.b.1 Degree of application of a legal/regulatory/ policy/institutional framework which recognizes and protects access rights for small-scale fisheries

SDG 14: Targets	SDG 14: Indicators
14.c Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of "The future we want"	14.c.1 Number of countries making progress in ratifying, accepting and implementing through legal, policy and institutional frameworks, ocean-related instruments that implement international law, as reflected in the United Nations Convention on the Law of the Sea, for the conservation and sustainable use of the oceans and their resources

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 46: Indicators of the German Sustainable Development Strategy, Goal 14

Goal 14: Range of indicators and postulates	Goal 14: Indicators
Protecting the oceans: Protecting and sustainably using oceans and marine resources	14.1.a Nitrogen inputs via the inflows into the North and Baltic Seas
	14.1.b Share of sustainably fished stocks in the North Sea and Baltic Sea

Source: https://dns-indikatoren.de/en/14/ (accessed 26.04.2024)

Table 47: Targets and related indicators from the 2030 Agenda, SDG15

SDG 15: Targets	SDG 15: Indicators
15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	15.1.1 Forest area as a proportion of total land area
	15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type
15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally	15.2.1 Progress towards sustainable forest management
15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	15.3.1 Proportion of land that is degraded over total land area
15.4 By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development	15.4.1 Coverage by protected areas of important sites for mountain biodiversity
	15.4.2 Mountain Green Cover Index
15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	15.5.1 Red List Index
15.6 Promote fair and equitable sharing of the benefits arising from the utilization of genetic resources and promote appropriate access to such resources, as internationally agreed	15.6.1 Number of countries that have adopted legislative, administrative and policy frameworks to ensure fair and equitable sharing of benefits
15.7 Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products	15.7.1 Proportion of traded wildlife that was poached or illicitly trafficked
15.8 By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species	15.8.1 Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species
15.9 By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts	15.9.1 (a) Number of countries that have established national targets in accordance with or similar to Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011–2020 in their national biodiversity strategy and action plans and the progress reported towards these targets; and (b) integration of biodiversity into national

SDG 15: Targets	SDG 15: Indicators
	accounting and reporting systems, defined as implementation of the System of Environmental-Economic Accounting
15.a Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems	15.a.1 (a) Official development assistance on conservation and sustainable use of biodiversity; and (b) revenue generated and finance mobilized from biodiversity-relevant economic instruments
15.b Mobilize significant resources from all sources and at all levels to finance sustainable forest management and provide adequate incentives to developing countries to advance such management, including for conservation and reforestation	15.b.1 (a) Official development assistance on conservation and sustainable use of biodiversity; and (b) revenue generated and finance mobilized from biodiversity-relevant economic instruments
15.c Enhance global support for efforts to combat poaching and trafficking of protected species, including by increasing the capacity of local communities to pursue sustainable livelihood opportunities	15.c.1 Proportion of traded wildlife that was poached or illicitly trafficked

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 48: Indicators of the German Sustainable Development Strategy, Goal 15

Goal 15: Range of indicators and postulates	Goal 15: Indicators
Biodiversity: Conserving species – protecting habitats	15.1 Biodiversity and landscape quality
Ecosystems: Protecting ecosystems, conserving ecosystem services and preserving habitats	15.2 Eutrophication of ecosystems
Ecosystems: Preventing deforestation and protecting soils worldwide	15.3.a, b Preservation or restoration of forests under REDD+ and investment in international soil protection

Source: https://dns-indikatoren.de/en/15/ (accessed 26.04.2024)

Table 49: Targets and related indicators from the 2030 Agenda, SDG16

SDG 16: Targets	SDG 16: Indicators
16.1 Significantly reduce all forms of violence and related death rates everywhere	16.1.1 Number of victims of intentional homicide per 100,000 population, by sex and age
	16.1.2 Conflict-related deaths per 100,000 population, by sex, age and cause
	16.1.3 Proportion of population subjected to (a) physical violence, (b) psychological violence and (c) sexual violence in the previous 12 months
	16.1.4 Proportion of population that feel safe walking alone around the area they live
16.2 End abuse, exploitation, trafficking and all forms of violence against and torture of children	16.2.1 Proportion of children aged 1–17 years who experienced any physical punishment and/or psychological aggression by caregivers in the past month
	16.2.2 Number of victims of human trafficking per 100,000 population, by sex, age and form of exploitation
	16.2.3 Proportion of young women and men aged 18–29 years who experienced sexual violence by age 18
16.3 Promote the rule of law at the national and international levels and ensure equal access to justice for all	16.3.1 Proportion of victims of violence in the previous 12 months who reported their victimization to competent authorities or other officially recognized conflict resolution mechanisms
	16.3.2 Unsentenced detainees as a proportion of overall prison population
	16.3.3 Proportion of the population who have experienced a dispute in the past two years and who accessed a formal or informal dispute resolution mechanism, by type of mechanism
16.4 By 2030, significantly reduce illicit financial and arms flows, strengthen the recovery and return of stolen assets and combat all forms of organized crime	16.4.1 Total value of inward and outward illicit financial flows (in current United States dollars)
	16.4.2 Proportion of seized, found or surrendered arms whose illicit origin or context has been traced or established by a competent authority in line with international instruments
16.5 Substantially reduce corruption and bribery in all their forms	16.5.1 Proportion of persons who had at least one contact with a public official and who paid a bribe to a public official, or were asked for a bribe by those public officials, during the previous 12 months
	16.5.2 Proportion of businesses that had at least one contact with a public official and that paid a bribe to a public official, or were asked for a bribe by those public officials during the previous 12 months

SDG 16: Targets	SDG 16: Indicators
16.6 Develop effective, accountable and transparent institutions at all levels	16.6.1 Primary government expenditures as a proportion of original approved budget, by sector (or by budget codes or similar)
	16.6.2 Proportion of population satisfied with their last experience of public services
16.7 Ensure responsive, inclusive, participatory and representative decision-making at all levels	16.7.1 Proportions of positions in national and local institutions, including (a) the legislatures; (b) the public service; and (c) the judiciary, compared to national distributions, by sex, age, persons with disabilities and population groups
	16.7.2 Proportion of population who believe decision-making is inclusive and responsive, by sex, age, disability and population group
16.8 Broaden and strengthen the participation of developing countries in the institutions of global governance	16.8.1 Proportion of members and voting rights of developing countries in international organizations
16.9 By 2030, provide legal identity for all, including birth registration	16.9.1 Proportion of children under 5 years of age whose births have been registered with a civil authority, by age
16.10 Ensure public access to information and protect fundamental freedoms, in accordance with national legislation and international agreements	16.10.1 Number of verified cases of killing, kidnapping, enforced disappearance, arbitrary detention and torture of journalists, associated media personnel, trade unionists and human rights advocates in the previous 12 months
	16.10.2 Number of countries that adopt and implement constitutional, statutory and/or policy guarantees for public access to information
16.a Strengthen relevant national institutions, including through international cooperation, for building capacity at all levels, in particular in developing countries, to prevent violence and combat terrorism and crime	16.a.1 Existence of independent national human rights institutions in compliance with the Paris Principles
16.b Promote and enforce non-discriminatory laws and policies for sustainable development	16.b.1 Proportion of population reporting having personally felt discriminated against or harassed in the previous 12 months on the basis of a ground of discrimination prohibited under international human rights law

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 50: Indicators of the German Sustainable Development Strategy, Goal 16

Goal 16: Range of indicators and postulates	Goal 16: Indicators
Crime: Further increasing personal security	16.1 Criminal offences
Peace and security: Taking practical action to combat proliferation, especially of small arms	16.2 Number of projects to secure, register and destroy small arms and light weapons carried out by Germany in affected regions of the world
Good governance: Combating corruption	16.3.a, b Corruption Perceptions Index (CPI) in Germany and in partner countries in the German development cooperation

Source: https://dns-indikatoren.de/en/16/ (accessed 26.04.2024)

Table 51: Targets and related indicators from the 2030 Agenda, SDG17

SDG 17: Targets	SDG 17: Indicators
Finance	
17.1 Strengthen domestic resource mobilization, including through international support to developing countries, to improve domestic capacity for tax and other revenue collection	17.1.1 Total government revenue as a proportion of GDP, by source
	17.1.2 Proportion of domestic budget funded by domestic taxes
17.2 Developed countries to implement fully their official development assistance commitments, including the commitment by many developed countries to achieve the target of 0.7 per cent of gross national income for official development assistance (ODA/GNI) to developing countries and 0.15 to 0.20 per cent of ODA/GNI to least developed countries; ODA providers are encouraged to consider setting a target to provide at least 0.20 per cent of ODA/GNI to least developed countries	17.2.1 Net official development assistance, total and to least developed countries, as a proportion of the Organization for Economic Cooperation and Development (OECD) Development Assistance Committee donors' gross national income (GNI)
17.3 Mobilize additional financial resources for developing countries from multiple sources	17.3.1 Foreign direct investment, official development assistance and South-South cooperation as a proportion of gross national income
	17.3.2 Volume of remittances (in United States dollars) as a proportion of total GDP
17.4 Assist developing countries in attaining long-term debt sustainability through coordinated policies aimed at fostering debt financing, debt relief and debt restructuring, as appropriate, and address the external debt of highly indebted poor countries to reduce debt distress	17.4.1 Debt service as a proportion of exports of goods and services
17.5 Adopt and implement investment promotion regimes for least developed countries	17.5.1 Number of countries that adopt and implement investment promotion regimes for developing countries, including the least developed countries
Technology	
17.6 Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge-sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism	17.6.1 Fixed Internet broadband subscriptions per 100 inhabitants, by speed5
17.7 Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed	17.7.1 Total amount of funding for developing countries to promote the development, transfer, dissemination and diffusion of environmentally sound technologies

SDG 17: Targets	SDG 17: Indicators
17.8 Fully operationalize the technology bank and science, technology and innovation capacity-building mechanism for least developed countries by 2017 and enhance the use of enabling technology, in particular information and communications technology	17.8.1 Proportion of individuals using the Internet
Capacity-building	
17.9 Enhance international support for implementing effective and targeted capacity-building in developing countries to support national plans to implement all the Sustainable Development Goals, including through North-South, South-South and triangular cooperation	17.9.1 Dollar value of financial and technical assistance (including through North-South, South-South and triangular cooperation) committed to developing countries
Trade	
17.10 Promote a universal, rules-based, open, non-discriminatory and equitable multilateral trading system under the World Trade Organization, including through the conclusion of negotiations under its Doha Development Agenda	17.10.1 Worldwide weighted tariff-average
17.11 Significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports by 2020	17.11.1 Developing countries' and least developed countries' share of global exports
17.12 Realize timely implementation of duty-free and quota-free market access on a lasting basis for all least developed countries, consistent with World Trade Organization decisions, including by ensuring that preferential rules of origin applicable to imports from least developed countries are transparent and simple, and contribute to facilitating market access	17.12.1 Weighted average tariffs faced by developing countries, least developed countries and small island developing States
Systemic issues	
Policy and institutional coherence	
17.13 Enhance global macroeconomic stability, including through policy coordination and policy coherence	17.13.1 Macroeconomic Dashboard
17.14 Enhance policy coherence for sustainable development	17.14.1 Number of countries with mechanisms in place to enhance policy coherence of sustainable development
17.15 Respect each country's policy space and leadership to establish and implement policies for poverty eradication and sustainable development	17.15.1 Extent of use of country-owned results frameworks and planning tools by providers of development cooperation
Multi-stakeholder partnerships	
17.16 Enhance the Global Partnership for Sustainable Development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support	17.16.1 Number of countries reporting progress in multi-stakeholder development effectiveness monitoring frameworks that support the achievement of the sustainable development goals

SDG 17: Targets	SDG 17: Indicators
the achievement of the Sustainable Development Goals in all countries, in particular developing countries	
17.17 Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships	17.17.1 Amount in United States dollars committed to public-private partnerships for infrastructure
Data, monitoring and accountability	
17.18 By 2020, enhance capacity-building support to developing countries, including for least developed countries and small island developing States, to increase significantly the availability of high-quality, timely and reliable data disaggregated by income, gender, age, race, ethnicity, migratory status, disability, geographic location and other characteristics relevant in national contexts	17.18.1 Statistical capacity indicator for Sustainable Development Goal monitoring
	17.18.2 Number of countries that have national statistical legislation that complies with the Fundamental Principles of Official Statistics
	17.18.3 Number of countries with a national statistical plan that is fully funded and under implementation, by source of funding
17.19 By 2030, build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity-building in developing countries	17.19.1 Dollar value of all resources made available to strengthen statistical capacity in developing countries
	17.19.2 Proportion of countries that (a) have conducted at least one population and housing census in the last 10 years; and (b) have achieved 100 per cent birth registration and 80 per cent death registration

Source: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed 17.04.2024)

Table 52: Indicators of the German Sustainable Development Strategy, Goal 17

Goal 17: Range of indicators and postulates	Goal 17: Indicators
Development cooperation: Supporting sustainable development	17.1 Official development assistance as a proportion of gross national income
Knowledge transfer, especially in technical areas: Sharing knowledge internationally	17.2 Number of students and researchers from developing countries and LDC per year
Opening markets: Improving trade opportunities for developing countries	17.3 Imports from least developed countries

Source: https://dns-indikatoren.de/en/17/ (accessed 26.04.2024)

Appendix: Detailed findings from the literature review

Tabular overviews

Table 53: Identified authors from the SDGs Trade-Offs and Synergies literature

Sequential number	Author name	Number of contributions identified
1	van Vuuren, Detlef P.	8
2	Luderer, Gunnar	6
3	Metternicht, Graciela	6
4	Allen, Cameron	5
5	Bodirsky, Benjamin L.	5
6	Mabhaudhi, Tafadzwanashe	5
7	Minx, Jan C.	5
8	Pedercini, Matteo	5
9	Popp, Alexander	5
10	Wiedmann, Thomas	5
11	Havlík, Petr	4
12	Humpenöder, Florian	4
13	Kriegler, Elmar	4
14	McCollum, David	4
15	Mpandeli, Sylvester	4
16	Nhamo, Luxon	4
17	Nilsson, Måns	4
18	Pradhan, Prajal	4
19	Riahi, Keywan	4
20	Weitz, Nina	4
21	Balvanera, Patricia	3
22	Bertram, Christoph	3
23	Carlsen, Henrik	3
24	Distelkamp, Martin	3
25	Dong, Liang	3

Sequential number	Author name	Number of contributions identified
26	Geng, Yong	3
27	Hertwich, Edgar G.	3
28	Krey, Volker	3
29	Liphadzi, Stanley	3
30	Mason-D'Croz, Daniel	3
31	Messerli, Peter	3
32	Meyer, Mark	3
33	Modi, Albert T.	3
34	Naidoo, Dhesigen	3
35	Obersteiner, Michael	3
36	OECD	3
37	Valin, Hugo	3
38	Afionis, Stavros	2
39	Amadei, Bernard	2
40	Arvesen, Anders	2
41	Bali Swain, Ranjula	2
42	Banerjee, Onil	2
43	Bennich, Therese	2
44	Borchardt, Steve	2
45	Bryan, Brett A.	2
46	Busch, Sebastian	2
47	Campagnolo, Lorenza	2
48	Cavender-Bares, Jeannine	2
49	Chaturvedi, Sachin	2
50	Chaturvedi, Vaibhav	2
51	Cicowiez, Martin	2
52	Dai, Hancheng	2
53	Dawes, Jonathan H. P.	2
54	Dietrich, Jan-Philipp	2

Sequential number	Author name	Number of contributions identified
55	Farzaneh, Hooman	2
56	Hasegawa, Tomoko	2
57	Hejazi, Mohamad	2
58	Herrero, Mario	2
59	Hoff, Holger	2
60	Horan, David	2
61	Horridge, Mark	2
62	Hutton, Craig W.	2
63	Jewell, Jessica	2
64	Kanter, David R.	2
65	Keijzer, Niels	2
66	King, Elizabeth	2
67	Klein, David	2
68	Klimont, Zbigniew	2
69	Kram, Tom	2
70	Kropp, Jürgen P.	2
71	Laurenti, Rafael	2
72	Liu, Jianguo	2
73	Lotze-Campen, Hermann	2
74	Lu, Yonglong	2
75	Lucht, Wolfgang	2
76	Masui, Toshihiko	2
77	Miola, Apollonia	2
78	Morrison-Saunders, Angus	2
79	Nicholls, Robert J.	2
80	Palazzo, Amanda	2
81	Pauliuk, Stefan	2
82	Pehl, Michaja	2
83	Pietzcker, Robert	2

Sequential number	Author name	Number of contributions identified
84	Polasky, Stephen	2
85	Ranganathan, Shyam	2
86	Ringler, Claudia	2
87	Scholes, Robert J.	2
88	Senzanje, Aidan	2
89	Srigiri, Srinivasa R.	2
90	Stafford-Smith, Mark	2
91	von Stechow, Christoph	2
92	Stehfest, Elke	2
93	Stevance, Anne-Sophie	2
94	van den Berg, Maurits	2
95	van Tulder, Rob	2
96	van Zanten, Jan A.	2
97	Vargas, Renato	2
98	Warchold, Anne	2
99	Weindl, Isabelle	2
100	Winkler, Harald	2
101	Wood, Sylvia L. R.	2
102	Xie, Yang	2
103	Zeigermann, Ulrike	2
104	Zelinka, David	2

Source: Own analysis. This table lists only those authors who contributed to more than one publication covered by our database.