DISS. ETH NO. 24246

LONG-TERM TECHNOLOGY-BASED MULTI-CRITERIA SUSTAINABILITY ANALYSIS OF ENERGY SYSTEMS

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by

KATHRIN ANDREA VOLKART

MSc ETH in Energy Science and Technology, ETH Zurich, Switzerland
born on 25.09.1985
citizen of Zurich (ZH), Switzerland

accepted on the recommendation of

Prof. Dr. A. Wokaun, examiner
Dr. S. Hirschberg, co-examiner
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Acknowledgements

First and foremost I would like to thank Prof. Dr. Alexander Wokaun for giving me the opportunity to do this PhD. His guidance and valuable inputs throughout my master and doctoral studies were highly appreciated.

I would like to thank Dr. Martin Densing for agreeing to supervise my work. I appreciated his open door in case of questions, his helpful methodological inputs, the valuable feedback to my work, and the efficient collaboration in the INSIGHT_E project. I would like to express my gratitude to Dr. Stefan Hirschberg for posing critical questions, for taking time whenever needed, for his supportive attitude and for agreeing to be co-examiner of this thesis. I am also indebted to Prof. Dr. Konrad Hungerbühler, who kindly agreed to act as a co-examiner of this thesis.

I acknowledge the great support of Dr. Christopher Mutel and Dr. Evangelos Panos and the time they dedicated to me and my project. I would like to thank Dr. Hal Turton, Dr. Martin Densing, Dr. Evangelos Panos and Dr. Tom Kober for their work on the two most recent versions of the GMM model. I would also like to thank Christian Bauer and Brian Cox for their support related to mobility technologies. I would like to thank two students, Michael Hegglin and Moritz Köhme, for their contributions to my work. I am grateful for the continuous and prompt support of Dr. Tom Kober in the final phase of this work, and Dr. Warren Schenler for proofreading the manuscript.

I would like to thank all my colleagues from LEA, particularly Rajesh, Adriana, Matteo, Christian and Karin, for the joyful moments inside and outside PSI. I am grateful to the PSI football team for many hours of fun.

I would like to thank my friends, who have accompanied me in my life up to now and who have been neglected over the last weeks and months, for being there. Last but not least I would like to thank my parents Hans Ruedi and Regula, my brother Andreas, and significant other Florian. Their continuous support in smaller and larger issues of life, the common chats, meals and journeys, and exchange of thoughts are invaluable. Thank you.

Summary

Today's global energy system is not sustainable according to the definition of the Sustainable Development Goal (SDG) in the field of energy, which has the goal of affordable, reliable and sustainable energy for all. Apart from the lack of access to energy for a substantial share of the world's population, the global energy system is dominated by fossil fuels and their associated impacts such as climate change, air pollution and accidents in extraction, transport and conversion. However, the use of non-fossil energy resources instead can for example be associated with intermittency in energy supply, long-lasting radioactive waste, ecosystem damages or high cost of energy supply. In general, all energy technologies and their supply chains have benefits and drawbacks with regard to the provision of affordable, reliable and sustainable energy for all. To achieve the SDG in the field of energy, the current energy systems must be transformed. The decisions made today have long-term effects not only on climate change and resource depletion but also on the development of the energy infrastructure, which is characterised by long-term capital investments and long lifetimes. In the current transformation phase, it is therefore important to consider the long-term consequences of decisions on all sustainability dimensions.

In this thesis, four combined methods for long-term multi-criteria sustainability analysis of energy systems are described, analysed and applied. In particular, they combine Partial Equilibrium energy system models, which have a long-term energy system perspective, and Multi-criteria Decision Analysis (MCDA), which comprehensively addresses the sustainability dimensions. The combined methods represent progressive integration steps: the sustainability indicators are first quantified on end-use technology level, then on the supply and end-use technology levels, then they are monetised and eventually they are endogenised in the energy system model. The practicality of the combined methods is demonstrated by implementing them in full-scale models of the whole energy system with full MCDA (if applicable). The goal of each type of analysis is to inform decision-makers and policy-makers in companies in the energy sector and in governments about the long-term sustainability impacts of their transformation strategies. This thesis can serve as a basis for future long-term multi-criteria sustainability analysis of energy systems and assist with the selection of the appropriate combined method and the quantification of energy chain and life-cycle assessment-based indicators for respective case studies.

The first combination of methods is a bottom-up ex-post multi-criteria analysis of energy systems on end-use technology level. The analysis of three Swiss energy system scenarios for 2035 is based on twelve sustainability indicators, which are all defined from an energy chain or life-cycle perspective. The implementation of a Greenhouse Gas (GHG) emission reduction target is found to lead to co-benefits such as the reduction in fossil fuel use (-34%), better overall public acceptance of energy system technologies, enhanced resource autonomy and less fatalities from severe accidents in the energy sector (-13%). The availability of Carbon Capture and Storage technology allows the reduction of the GHG emissions at lower cost (-7% investment cost), but the technology is expected to face societal opposition due to the storage of the Carbon Dioxide (CO_2) in the ground. The results of the analysis can give the Swiss government indications of possible fields for complementary policies or research (e.g. strategies for handling higher variability of the energy supply), while they point out business opportunities for companies.

The second combination of methods is a bottom-up ex-post multi-criteria analysis of energy systems on the supply and end-use technology levels. Due to the disaggregation of the indicator values to the supply and end-use technology levels and the global scope of the energy system model, the quantification of the energy chain impacts is facilitated. The analysis of the three World Energy Scenarios of the World Energy Council for 2010 to 2060 is based on a set of 22 bottom-up and top-down sustainability indicators and shows that CHINAREG (China, Macau and Mongolia) remains an important region with regard to the global energy consumption by 2060. At the same time, its sustainability is found to improve with respect to environmental and human health damages and socio-economic indicators. The EU31 (European Union plus Liechtenstein, Norway and Switzerland) as a developed region reduces its share in the global energy consumption by 2060 and improves with respect to most of the sustainability indicators. The developing region SSAFRICA (Sub-Saharan Africa) is instead found to undergo large changes in its energy system and most of the human health, environmental and risk indicators worsen, although development of the economic indicators is positive.

The third combination of methods is an ex-post external cost analysis of energy systems. Considering the external costs of emissions instead of physical quantities allows one to benchmark the sustainability impacts with the energy system cost and the Gross Domestic Product (GDP), and can facilitate communication to the public. The case study analyses external costs from human health damages due to Local Air Pollutant (LAP) emissions and from damages related to the emission of GHG in the World Energy Scenarios. The external costs due to LAP are estimated to be between 0.3 and 0.7% of the GDP in the three scenarios in 2060. The GHG emissions are estimated to be between additional 0.2 and 0.7% of the GDP in the three scenarios in 2060. Among the emissions considered, CO_2, Nitrogen Oxides, Particulate Matter with a diameter of <2.5µm and Sulphur Dioxide are found to contribute most to the total external cost. Developing regions are often characterised by increasing GDP, urbanisation and GHG and LAP emissions, so that they are expected to bear 61 to 73% of the external cost burdens of LAP emissions in the three scenarios in 2060. CHINAREG can break the trend of increasing external costs by reducing the coal use and associated impacts and by reducing Total Primary Energy Supply. The results of the case studies with the second and third combination of methods allow governments for example to justify engagement in climate change mitigation, to estimate the progress regarding the SDG in the field of energy and to identify "hotspots" for possible political interventions.

The fourth combination of methods endogenises multiple objectives in the PE energy system model. The optimisation of the different objectives leads to pathways which represent consequences of specific policies and which frame the space of possible developments. The illustrative case study quantifies global energy scenarios for three policy objectives, namely minimal total discounted system cost, minimal CO_2 emissions and minimal energy carrier imports. From the optimisation of these three objectives, extreme possible pathways and the corresponding lowest possible cumulative objective values can be derived, which amount to $191 trillion for cost, 706 Gt for CO_2 emissions and 3.85 ZJ for energy carrier imports for the period 2010-2110. Overall, the CO_2 minimal pathway is characterised by efficient energy use, more renewable and less fossil resource use than in the cost minimal pathway, and by decreasing (by 2070) and even negative (from 2080) CO_2 emissions of the energy system. The energy carrier import minimal pathway is characterised by more domestic coal and less imported oil use than in the cost minimal pathway, slowly decreasing CO_2 emissions and very low energy imports from 2070. The single focus on security of supply leads to higher costs (+7% compared to the cost minimal pathway) and CO_2 emissions (+31% compared to the CO_2 minimal pathway) for the period 2010 to 2060. The CO_2 minimal pathway indicates that even with high economic growth and according energy demands, the 2°C pathway can be reached, but only at higher cost (+16% cumulative costs from 2010 to 2060 compared to the cost minimal pathway).

All of the described combined methods for long-term technology-based multi-criteria sustainability analysis of energy systems require interdisciplinary work in energy system modelling and technology assessment with inputs from different disciplines such as life-cycle assessment, risk assessment and external cost assessment. The multidisciplinarity as well as the regional and temporal aspects of the analysis are implied by the definition of the sustainable development and the SDG in the field of energy. The development of the world regions is not homogenous and regional solutions are required. Long-term multi-criteria sustainability analysis of energy systems can contribute to finding such solutions and defining sound strategies and energy policies, which lead to sustainable development.

Kurzfassung

Das heutige globale Energiesystem ist nicht nachhaltig, wenn man die Definition des Sustainable Development Goals (SDG) im Bereich Energie als Massstab nimmt, welche eine bezahlbare, zuverlässige und nachhaltige Energieversorgung für alle fordert. Neben dem fehlenden Zugang zu modernen Energieformen für einen beträchtlichen Teil der Weltbevölkerung, basiert das globale Energiesystem stark auf der Nutzung fossiler Energieträger, die zu negativen Auswirkungen wie Klimawandel, Luftverschmutzung und schweren Unfällen in der Energieversorgung führen. Die Verwendung nichtfossiler Energieressourcen kann hingegen beispielsweise fluktuierende Energieerzeugung, langlebige radioaktive Abfälle, Ökosystemschäden oder hohe Kosten der Energieerzeugung zur Folge haben. Allgemein gilt, dass alle Energietechnologien und –versorgungsketten im Hinblick auf eine bezahlbare, zuverlässige und nachhaltige Energieversorgung Vor- und Nachteile aufweisen. Für die Erreichung des SDG im Bereich Energie müssen die heutigen Energiesysteme umgebaut werden. Entscheidungen, die heute getroffen werden, haben langfristige Auswirkungen nicht nur im Hinblick auf den Klimawandel oder die Erschöpfung nichterneuerbarer Ressourcen, sondern auch im Hinblick auf die Entwicklung der Energiesysteminfrastruktur, die durch langfristige Investitionen und lange Lebensdauern gekennzeichnet ist. In der jetzigen Transformationsphase ist es deshalb besonders wichtig, die langfristigsten Auswirkungen von Entscheidungen hinsichtlich aller Nachhaltigkeitsaspekte zu berücksichtigen.

In dieser Doktorarbeit werden vier Methodenkombinationen für die langfristige multikriterielle Nachhaltigkeitsanalyse von Energiesystemszenarien beschrieben, analysiert und angewandt. Konkret handelt es sich um Kombinationen von partiellen Gleichgewichtsmodellen, die eine langfristige Systemperspektive einbringen, und Multi-kriteriellen Entscheidungsanalysen (MCDA), die die Nachhaltigkeitsaspekte umfassend betrachten. Die Methodenkombinationen bauen aufeinander auf, indem sie die Nachhaltigkeitsindikatoren immer stärker ins Energiesystemmodell integrieren: Zuerst werden die Nachhaltigkeitsindikatoren auf Endenergieebene berechnet, dann auf Energieversorgungs- und Endenergiestufe, dann werden sie monetarisiert und schliesslich im Energiesystemmodell endogenisiert. Die Anwendbarkeit der Methodenkombinationen wird durch deren Anwendung auf grosse Energiesystemmodelle mit vollständiger MCDA (falls anwendbar) demonstriert. Das Ziel jeder Kombination ist die Information von Entscheidungsträgern aus Wirtschaft und Verwaltung hinsichtlich der langfristigen Auswirkungen ihrer Strategien auf die drei Dimensionen der Nachhaltigkeit. Diese Doktorarbeit

kann als Basis für künftige langfristige multi-kriterielle Nachhaltigkeitsanalysen dienen und bei der Auswahl der geeigneten Methodenkombination und Quantifizierung von auf Ökobilanzen und Energieketten basierenden Indikatoren unterstützen.

Die erste Methodenkombination ist eine bottom-up, ex-post Multikriterienanalyse von Energiesystemen auf Endenergieebene. Die Analyse von drei Schweizer Energiesystemszenarien für das Jahr 2035 basiert auf zwölf Indikatoren, die alle aus der Energieketten- oder Lebenszyklusperspektive definiert werden. Die Einführung eines Reduktionsziels für Treibhausgasemissionen führt zu Zusatznutzen wie der Reduktion der Nutzung fossiler Ressourcen (-34%), der gesamthaft besseren gesellschaftlichen Akzeptanz der Energietechnologien, der verbesserten Ressourcenautonomie und der Reduktion der Anzahl Todesfälle aufgrund schwerer Unfälle in der Energieversorgung (-13%). Wenn die Technologien zur CO_2-Abscheidung und –Speicherung zur Verfügung stehen, kann die angestrebte Treibhausgasreduktion zu tieferen Kosten (-7%) erreicht werden. Aufgrund der Speicherung des Kohlendioxids (CO_2) im Boden müssen jedoch gesellschaftliche Akzeptanzprobleme erwartet werden. Die Resultate dieser Studie können der Schweizer Regierung Hinweise auf mögliche Themenbereiche für zusätzliche Politikmassnahmen oder Forschung geben (z.B. Strategien zum Umgang mit den Schwankungen in der Energieerzeugung), während sie die Wirtschaft auf mögliche Geschäftsfelder hinweisen.

Die zweite Methodenkombination ist eine bottom-up ex-post Multikriterienanalyse von Energiesystemen auf Energieversorgungs- und Endenergiestufe. Aufgrund der Dissaggregierung der Indikatorwerte auf die Ebene von Energieversorgungs- und Endenergietechnologien und der Verwendung eines globalen Energiesystemmodells vereinfacht sich die Quantifizierung der Auswirkungen der Energieketten auf die Nachhaltigkeit. Die Analyse der drei Weltenergieszenarien des Weltenergierats für die Jahre 2010 bis 2060, die auf 22 bottom-up und top-down Indikatoren basiert, zeigt, dass CHINAREG (China, Macau, Mongolei) in Bezug auf den Energiekonsum bis zum Jahr 2060 eine wichtige Region bleibt. Gleichzeitig verbessert sich die Nachhaltigkeit der Region besonders im Hinblick auf Schäden an der Umwelt und der menschlichen Gesundheit und hinsichtlich sozioökonomischer Indikatoren. Die EU31-Länder (EU28 mit Liechtenstein, Norwegen und Schweiz) als Beispiel einer entwickelten Weltregion verringern bis 2060 ihren Anteil am globalen Energieverbrauch und verbessern sich gleichzeitig hinsichtlich der meisten Nachhaltigkeitsindikatoren. Im Gegensatz dazu wird das Energiesystem SSAFRICAs (Sub-Sahara Afrika), einer Weltregion, die sich stark entwickelt, grossen Veränderungen unterworfen sein, wobei sich die meisten Indikatoren im Bereich Umwelt, menschliche Gesundheit und Unfallrisiken verschlechtern. Gleichzeitig verbessern sich jedoch die Indikatoren für ökonomische Entwicklung.

Die dritte Methodenkombination ist eine ex-post Analyse der externen Kosten von Energiesystemen. Die Betrachtung von Kosten von Emissionen anstelle physikalischer Flüsse erlaubt den Vergleich der Nachhaltigkeitsauswirkungen mit Schlüsselgrössen wie den Gesamtenergiesystemkosten und dem Bruttoinlandprodukt (BIP) und kann die Kommunikation mit der Gesellschaft erleichtern. Die Fallstudie untersucht die externen Kosten, die aufgrund menschlicher Gesundheitsschäden wegen der Emission von 15 Luftschadstoffen und aufgrund von Schäden wegen der Emission von drei Treibhausgasen in den drei Weltenergieszenarien entstehen. Die externen Kosten für die Emissionen der untersuchten Luftschadstoffe und Treibhausgase in den drei Szenarien liegen bei 0.3% bis 0.7% beziehungsweise 0.2 bis 0.7% des BIP im Jahr 2060. Von den betrachteten Emissionen tragen CO_2, Stickoxide, Partikel mit einem Durchmesser von <2.5μm und Schwefeldioxid am meisten zu den gesamten externen Kosten bei. Entwicklungsländer haben häufig ein steigendes BIP, steigende Urbanisierung und ansteigende Emissionen von Luftschadstoffen und Treibhausgasen, sodass diese in den drei Szenarien im Jahr 2060 61% bis 73% der globalen externen Kosten von Luftschadstoffen vergegenwärtigen müssen. CHINAREG kann diesen Trend der steigenden externen Kosten durchbrechen, indem es die Nutzung von Kohle und damit die verbundenen negativen Auswirkungen reduziert und den Gesamtenergieverbrauch nach Erreichen eines Höchstwerts bis 2060 senkt. Die Resultate der Studien mit der zweiten und dritten Methodenkombination ermöglichen es der Regierung Argumente für ein Engagement in den Klimaverhandlungen zu untermauern, den Fortschritt hinsichtlich der SDG abzuschätzen und „Hotspots" für mögliche Politikmassnahmen zu identifizieren.

Die vierte Methodenkombination endogenisiert verschiedene Nachhaltigkeitsziele in einem partiellen Gleichgewichtsmodell. Die Optimierung der unterschiedlichen Ziele führt zu Energiesystempfaden, die die Konsequenzen der Verfolgung unterschiedlicher Politikziele aufzeigen und die den Raum für mögliche Entwicklungen abstecken. Die Fallstudie illustriert dies anhand globaler Energiesystempfade für die drei Nachhaltigkeitsziele minimale diskontierte Gesamtsystemkosten, minimale CO_2-Emissionen und minimale Energieträgerimporte. Mittels der Optimierung der drei Ziele können bestmöglichen Pfade und die entsprechenden minimalen kumulierten Zielwerte ermittelt werden, die sich auf 191 Billionen $ für die Kosten, 206 Gt für die CO_2-Emissionen und 3.85 ZJ für die Energieträgerimporte im Zeitraum 2010-2110 belaufen. Insgesamt ist ein CO_2 minimaler Pfad im Vergleich zum kostenminimalen Fall durch effiziente

Energienutzung, mehr erneuerbare und weniger fossile Energieträger und sinkende (bis 2070) beziehungsweise sogar negative (ab 2080) CO_2 Emissionen des Energiesystems gekennzeichnet. Ein Pfad, der auf minimalen Energieträgerimporten basiert, weist weniger Verbrauch importierten Öls und mehr Verbrauch heimischer Kohle als im kostenminimalen Fall, nur langsam sinkende CO_2-Emissionen und ab 2070 sehr tiefe Energieimporte auf. Der alleinige Fokus auf Versorgungssicherheit führt zu höheren Kosten (+7% gegenüber dem kostenminimalen Pfad) und höheren CO_2 Emissionen (+31% gegenüber dem CO_2 minimalen Pfad) für die Zeit von 2010 bis 2060. Der CO_2 minimale Pfad zeigt, dass sogar mit hohem Wirtschaftswachstum und entsprechender Energienachfrage der 2°C-Pfad erreicht werden kann, aber nur zu höheren Kosten (+16% kumulierte Kosten von 2010 bis 2060 gegenüber dem kostenminimalen Pfad).

Alle beschriebenen Methodenkombinationen zur technologiebasierten langfristigen multi-kriteriellen Nachhaltigkeitsanalyse von Energiesystemen erfordern interdisziplinäre Arbeit in den Bereichen Energiesystemmodellierung und Technologiebewertung mit ihren unterschiedlichen Disziplinen wie Ökobilanzierung, Risikoanalysen und Kostenschätzungen. Die Multidisziplinarität sowie die regionalen und zeitlichen Aspekte der Analyse werden bereits durch die Definition von nachhaltiger Entwicklung und des SDG im Bereich Energie impliziert. Die Entwicklungen in den verschiedenen Weltregionen sind nicht einheitlich, sodass es regional unterschiedliche Lösungsansätze braucht. Die langfristige multi-kriterielle Nachhaltigkeitsanalyse von Energiesystemen kann zu solchen Lösungsansätzen und zu fundierten Strategien und Energiepolitiken, die in Richtung einer nachhaltigen Entwicklung zielen, beitragen.

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Abbreviations

ACC	Access to clean energy
AFOLU	Agriculture, Forestry and Other Land Use
ALO	Agricultural Land Occupation
ASIAPAC	Pacific Asia
AUSNZL	Australia and New Zealand
CANMEX	Canada and Mexico
CAP	Capacity
CAPINV	Capacity Investment
CARS	Car ownership
CC	Combined Cycle
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CENASIA	Central Asia
CETP	China Energy Technology Program
CH_4	Methane
CHINAREG	China and Mongolia
CHP	Combined Heat and Power
Clim	Climate protection scenario variant without CCS
Clim+CCS	Climate protection scenario variant with CCS
CO_2	Carbon Dioxide
CONSQ	Maximum credible consequences of severe accidents
D	Demand
DALY	Disability Adjusted Life Years
EEA	European Environment Agency
EEUR	Eastern Europe
EGS	Enhanced Geothermal System
ENSAD	Energy-Related Severe Accident Database
EU27	European Union as of June 2013
EU31	European Union as of today, including Liechtenstein, Norway and Switzerland
ExpJ	Expert Judgement
Fe	Iron
FE	Freshwater Eutrophication
FOSSIL	Fossil energy use
FR	France
GDP	Gross Domestic Product
GEA	Global Energy Assessment
Gen	Generation
GHG	Greenhouse Gases
GLO	Global
GMM	Global Multi-Regional MARKAL
GRID	Grid investments
GWP	Global Warming Potential
HT	Human Toxicity
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis

IMP	Energy carrier imports
INT	Energy intensity of the economy
INV	Investment
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardisation Organisation
JPKRTW	Japan, Korea and Taiwan
LAC	Latin America and the Caribbean
LAP	Local Air Pollutant
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LNG	Liquefied Natural Gas
LP	Linear Programming
MC	Marginal Cost
MCDA	Multi-criteria Decision Analysis
MEC	Marginal External Cost
MENA	Middle East and North Africa
MER	Market Exchange Rate
MORT	Expected mortality in severe accidents
MSC	Marginal Social Cost
N_2O	Nitrogen Oxide
NGO	Non-Governmental Organisation
NH_3	Ammonia
NMC	New Member Countries
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NUCL	Nuclear energy use
O&M	Operation & Maintenance
OcCC	Organe consultatif sur les changements climatiques
OECD	Organisation for Economic Co-operation and Development
OIL	Oil imports
PE	Partial Equilibrium
PM10	Particulate Matter with diameter <10 μm
PM2.5	Particulate Matter with diameter <2.5 μm
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Foramtion
PPP	Purchase Power Parity
PSA	Probabilistic Safety Assessment
PSI	Paul Scherrer Institute
PV	Photovoltaics
RA	Risk Assessment
Ref	Reference scenario variant
Ref./Proc.	Refining / Processing
RENEW	Variable renewable generation
RER	Europe
RoW	Rest of the World
S	Supply
SBB	Schweizerische Bundesbahnen
SDG	Sustainable Development Goals

SEDAC	Socioeconomic Data and Application Center
SMM	Swiss MARKAL Model
SO_2	Sulphur Dioxide
SSAFRICA	Sub-Saharan Africa
T&D	Transport & Distribution
TA	Terrestrial Acidification
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
UCTE	Union for the Co-ordination of Transmission of Electricity
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
USA	United States of America
US EPA	United States Environmental Protection Agency
WD	Water Depletion
WEC	World Energy Council
WHVC	World Harmonized Vehicle Cycle
WSA	Weighted Sum Approach
WTP	Willingness-To-Pay

1. Introduction

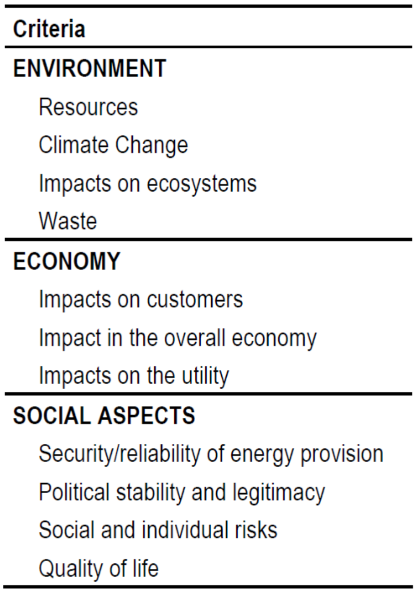
1.1. Motivation

The World Commission on Environment and Development has stated that sustainable development:

> *"[…] meets the needs of the present without compromising the ability of future generations to meet their own needs. […] sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs."* [1]

Sustainable development is related to the energy sector because finite natural resources are exploited for the provision of energy services, large investments are made in energy infrastructure which is operated over generations, and energy technologies are developed today with the purpose of satisfying future energy demands. The importance of the energy sector for sustainable development has recently been emphasised by the United Nations' (UN) formulation of the Sustainable Development Goals (SDG) which envisages a world "*where there is universal access to affordable, reliable and sustainable energy*" [2]. Universal access to affordable, reliable and sustainable energy contributes to the overarching goals of ending poverty, protecting the planet, and ensuring prosperity for all.

The above-mentioned vision for the energy sector refers to the three dimensions, economy, society and environment, which have been used to operationalise the definition of sustainability by the World Commission on Environment and Development, for example in the course of the initiative of the International Atomic Energy Agency (IAEA) for developing a set of energy indicators for sustainable development in collaboration with the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), Eurostat and the European Environment Agency (EEA) [3]. These three dimensions of sustainability can be further differentiated into a set of criteria, which represents relevant areas of concern. Such a criteria set for the energy sector was for example provided by Hirschberg et al. [4] and is presented in Figure 1. The performance of energy technologies and systems regarding the sustainability criteria can be measured with specific qualitative and quantitative indicators for the current status as well as for future progress in the direction of sustainable development.



Criteria
ENVIRONMENT
Resources
Climate Change
Impacts on ecosystems
Waste
ECONOMY
Impacts on customers
Impact in the overall economy
Impacts on the utility
SOCIAL ASPECTS
Security/reliability of energy provision
Political stability and legitimacy
Social and individual risks
Quality of life

Figure 1: Main environmental, economic and social criteria for sustainability assessment [4]

Today's energy systems do not reach the SDG in the field of energy. 1.3 billion people have no access to electricity [5], and the reliance on non-commercial forms of energy (e.g. fuel wood and charcoal) and the lack of clean cooking fuels leads to human health damages and degradation of (local) ecosystems. Currently, 81% of the global primary energy supply is provided by fossil fuels [6]. Their combustion not only contributes to the climate change, but also to the depletion of finite natural resources and to human health and ecosystem damages due to air pollution and wastes. Every step in the relevant energy chains, from the extraction of the energy resource to transport, storage and end-use of the energy carrier, requires materials and fuels, produces emissions and wastes, and contains accident risks. Renewable energies can be associated with high energy supply costs, they can lead to intermittency in energy supply, and their decentralised installations can lead to societal conflicts. Nuclear energy use creates long-living radioactive waste and bears the risk of proliferation of radioactive materials for nuclear weapons.

As all energy technologies and energy systems have different strengths and weaknesses regarding sustainability criteria such as the ones listed in Figure 1, there is no single energy technology or system which is completely "*affordable, reliable and sustainable"*. The world's energy systems are diverse not only regarding the type and technical status of the applied conversion technologies, but also regarding the type of energy resources used and the sectoral and technology mixes on the demand side. Therefore, developments are expected to be regionally diverse and there is no "one-size-fits-all" solution for sustainable development in the energy sector.

1.2. Research questions

Sustainable development of energy systems in the direction of the SDG in the field of energy requires the investigation of multiple criteria on the one hand and long-term strategic planning due to the large investments and the long lifetimes of the energy infrastructure on the other hand. This applies on the level of companies in the energy sector but particularly on the level of governments where policy-makers set the boundary conditions for the transformation to more sustainable energy systems. Decision-making in the context of energy system transformation can be supported with modelling approaches, which consider the long-term energy system perspective and multiple sustainability criteria. This leads to the research questions of this thesis:

- How can long-term developments of the energy technologies and the energy systems they are embedded in be analysed?

- How can the sustainability of the energy systems be investigated taking into account multiple criteria?
- Which combined methods can be applied for long-term multi-criteria sustainability analysis of energy systems?
- Which approaches to data processing and changes to the existing approaches are required for the implementation of the combined methods?
- How does the future Swiss energy system perform with respect to a set of sustainability criteria under different technological and political boundary conditions?
- What are the global and regional sustainability trends in different long-term transformation pathways of the global energy system?

1.3. Structure of the thesis

Chapter 2 gives an overview of methods and combined methods for the analysis of the long-term development of energy systems and their sustainability. The four combined methods described in Chapter 2 are then applied in separate case studies, which are presented in Chapters 3 to 6. In Chapter 3, three energy system pathways for Switzerland are analysed with a focus on the sustainability impacts of the Swiss climate policy and the availability of the Carbon Capture and Storage (CCS) technologies. In Chapter 4, the long-term sustainability of the World Energy Scenarios of the World Energy Council (WEC) is addressed from a global as well as from selected regional perspectives. In Chapter 5, the external costs from human health damages due to air pollution are quantified for the World Energy Scenarios and benchmarked with the external costs of greenhouse gas (GHG) emissions, the energy system costs and the Gross Domestic Product (GDP). In Chapter 6, three different sustainability indicators are endogenised in the energy system modelling framework. Based on the optimisation of these three policy objectives, corresponding global energy system pathways are quantified. The thesis concludes with a summary of the insights regarding the research questions and an outlook for further research.

2. Methods for Long-term Multi-criteria Sustainability Analysis of Energy Systems

Energy systems can be analysed by different types of models: energy system optimisation or simulation models, power system and electricity market models, and qualitative or mixed-methods scenarios [7]. Among these types, bottom-up partial equilibrium (PE) energy system optimisation models are widely applied for long-term analysis of large-scale energy systems such as national and global systems while being able to capture energy technology details [7]. Hence, they are suitable for long-term sustainability analysis and described in more detail in the following as a basis for combination with multi-criteria decision analysis, which is subsequently described.

2.1. Partial equilibrium energy system models

In contrast, to macro-economic models, PE energy system models are used for analysis of the energy sector and for identifying of this sectors' equilibrium, i.e. only a part of the whole economy is analysed. Due to the sectoral approach, interactions with other economic sectors are generally not considered[1]. Instead, bottom-up PE energy system models are characterised by their technology richness. They allow for detailed consideration of energy technologies and their techno-economic characteristics as well as the sectoral interdependencies in the energy sector based on the reference system approach (Figure 2). The energy service demands are exogenous to the model and estimated based on key drivers such as population and GDP. The equilibria of supply and demand on the energy markets are calculated based on minimisation of cost as single decision variable. The optimisation algorithm identifies the least-cost combinations of resource, conversion and end-use technologies required to satisfy the energy service demands over the time horizon considered based on perfect foresight. The perfect foresight assumption however is only an approximation of how decisions are made in reality [8] as most real decision-makers decide with a shorter-term view (myopically) and more mixed criteria. The resulting so-called energy system scenarios describe the expected development of the energy system under the specified boundary conditions (constraints).

PE energy system models are applied to support decision-making in the context transforming energy systems by deriving policy recommendations from long-term energy system scenarios. On the one hand, the models can be used to explore the impact of policy decisions on the development of the energy system with so-called *explorative* scenarios, and – on the other hand – to quantify the efforts required to reach specific targets such as full access to energy or carbon dioxide (CO_2) emission caps in so-called *normative* scenarios.

PE energy system models can be established based on dedicated modelling frameworks such as MARKAL [9] and TIMES [10]. Among other features, these frameworks allow the integration of environmental flows such as CO_2 emissions. These flows are specified on the technology level, and can be quantified per activity (they occur whenever the energy system technology is operated), per investment (they occur when the technology infrastructure is built) or per capacity (they occur over the infrastructure's whole life time).

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[1] Nevertheless, the MARKAL framework for example offers a macroeconomic model, i.e. a General Equilibrium model, which merges MARKAL with a set of macroeconomic equations.

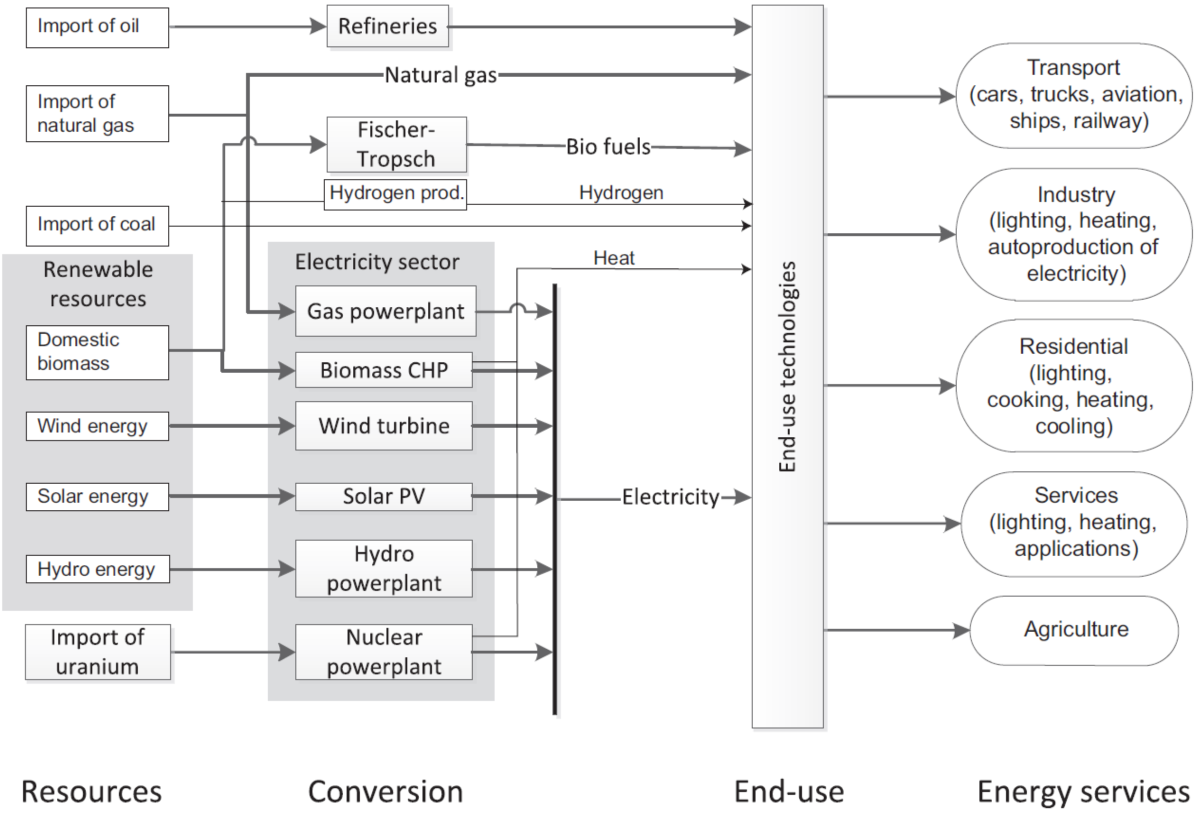


Figure 2: Simplified representation of the reference energy system of a partial equilibrium modelling framework representing complete energy chains from resource extraction, via conversion and end-use to the energy services [11]

Two bottom-up PE energy system models are used in this thesis. An overview of the two models is given in the subsequent sections.

2.1.1. Swiss MARKAL model

The Swiss MARKAL model (SMM) covers a time horizon of 50 years from 2000 to 2050 and is calibrated to the year 2010 [12]. This technology-rich PE energy system model explicitly models primary energy supply, conversion to secondary energy commodities (e.g. electricity, fuels and district heat) and end-use technologies. It provides a detailed representation of energy service demands from the industrial, transport, residential, services and agricultural sectors. Technological characteristics such as investment costs, operation and maintenance (O&M) costs, efficiencies, and lifetimes are further model inputs. Model outputs include the consumption of primary and final energy consumption as well as electricity generation, CO_2 emissions, and energy system costs. The most recent version of the SMM is described in Weidmann [11].

2.1.2. Global Multi-regional MARKAL model

The Global Multi-regional MARKAL (GMM) model is a technology-rich, bottom-up PE energy system model. It explicitly models the linked energy systems of 15 world regions (Figure 3) and it covers the years 2010 to 2110 in 10 year time steps. The GMM model has been developed at the Paul Scherrer Institute (PSI) over the last 15 years [5, 13-19]. The energy systems of the 15 regions are modelled from the energy resources to the conversion sector and the end-use sector. The most recent version of the GMM model [19] was adapted for this thesis by introducing the CO_2 storage costs and potentials of Ecofys [20] as presented in Appendix, Table 41.

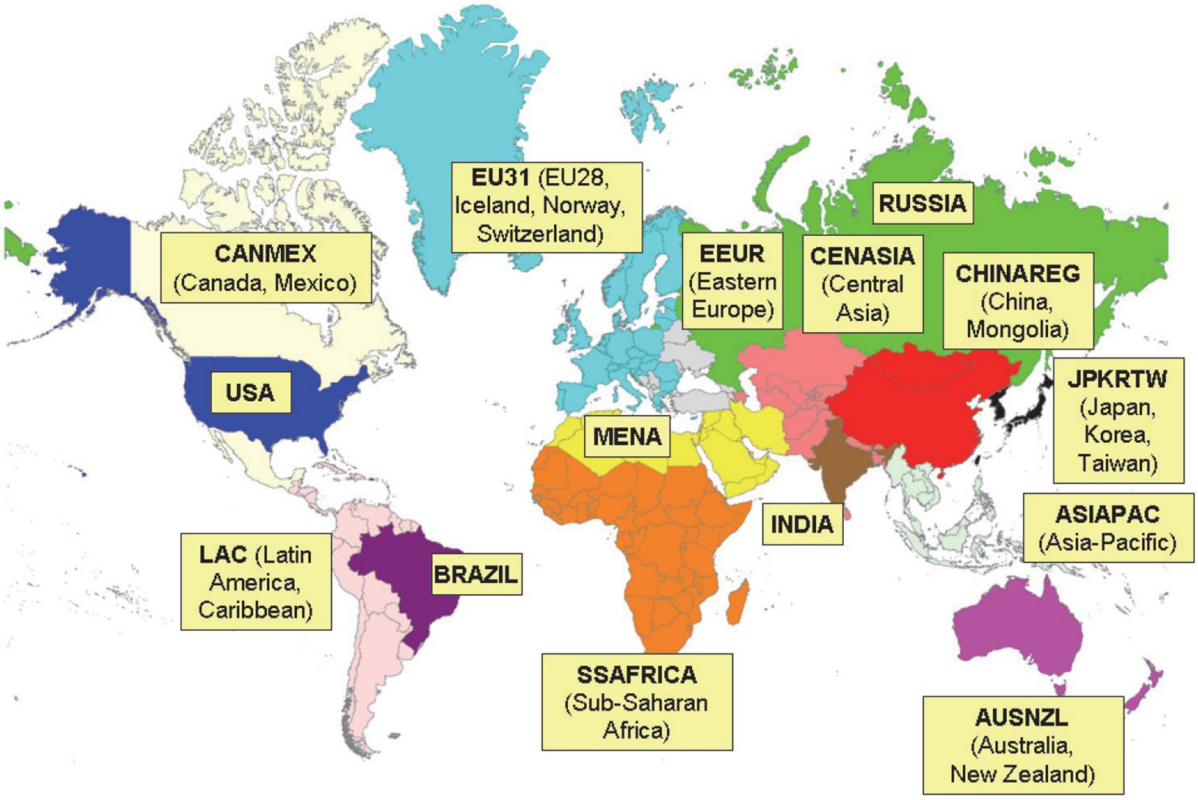


Figure 3: 15 world regions in the Global Multi-regional MARKAL (GMM) model [21]

While relevant economic indicators such as energy system investments and energy carrier and CO_2 costs are comprehensively covered in both the SMM and the GMM model, environmental aspects are only reflected by CO_2 emissions, and social aspects such as health damages due to emissions from the energy sector are not explicitly reflected. Overall, the three sustainability dimensions are not equally covered.

Comparative sustainability analysis of energy system technologies or scenarios based on a comprehensive set of criteria which cover all dimensions of sustainability is the goal of the multi-criteria decision analysis (MCDA) method, which is described in the next section.

2.2. Multi-criteria decision analysis

MCDA supports structured, transparent and comprehensive decision-making in complex situations, i.e. in situations with many alternatives, and many decision criteria [22]. It also incorporates the subjective preferences of the decision-maker for specific criteria. The decision-maker can explore the influence of his/her subjective preferences on the ranking of the alternatives, explore the trade-offs of each decision and make a well-informed decision.

MCDA is used in the energy field for the comparative sustainability analysis of electricity generation technologies (e.g. Schenler et al. [23], Roth et al. [24], Volkart et al. [25] and Hirschberg et al. [26]) and passenger car technologies (e.g. Hofer [27]). Compared to PE energy system models, MCDA takes into account more than one decision variable, i.e. it considers a comprehensive set of criteria which covers the three sustainability dimensions, and it does not minimise costs but maximises utility.

The process to perform a full MCDA with the weighted sum approach (WSA) as described in Triantaphyllou [28] is structured as follows and as illustrated in Figure 4 (solid arrows):

1) All alternatives, which are supposed to be compared, are selected and characterised.
2) All criteria and indicators, which are relevant for the assessment, are selected and specified.
3) For each alternative and criterion the corresponding specific indicator values are quantified. Qualitative criteria are subjectively valued.
4) The indicator values are normalised.
5) The criteria are weighted according to the decision-maker’s subjective preferences.
6) The normalised indicator values are aggregated.

7) The alternative options are ranked. At this point, it is possible to iterate altering the initial criterion weights.
8) As the last step, the results are interpreted.

Alternatively – if weighting is not possible or desired – the indicator values of the alternatives can be directly compared, and the trade-offs can be subjectively evaluated in a multi-criteria analysis (Figure 4, dashed arrows).

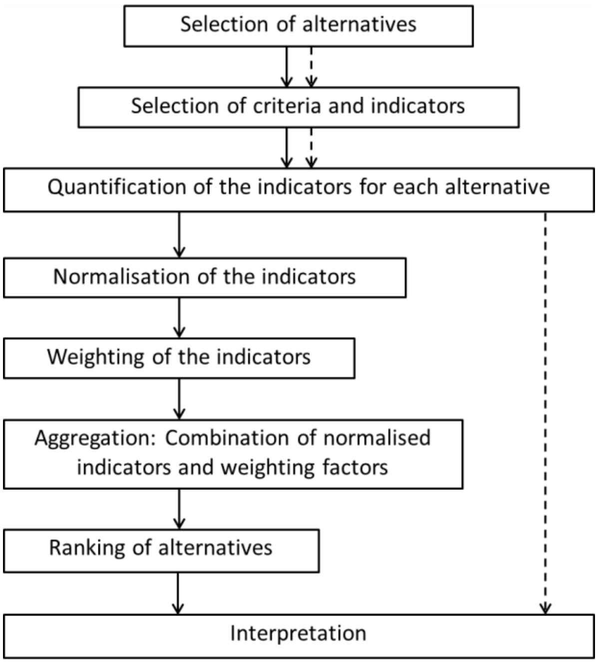


Figure 4: Schematic representation of the multi-criteria decision analysis (MCDA; solid arrows) and multi-criteria analysis (dashed arrows)

Common pitfalls when designing MCDA studies include the lack of completeness in the set of alternatives, lack of consensus on technological data or characteristics, incomplete criteria sets and overlapping of criteria. Hirschberg et al. provide an overview of the criteria categories that are important in the context of energy technologies (Figure 1), and comprehensively describe the requirements for indicator definition [4].

MCDA is usually applied for technology comparisons with limited system perspective and with a focus on specific time horizons. In contrast, the PE energy system models described in Section 2.1 focus on the systemic interaction of energy system technologies and the development of the energy system over time. The complementary characteristics of the two methods indicate that it may be advantageous to combine them. In this way, the individual strengths of the PE energy system model and MCDA can be combined with the aim of performing long-term multi-criteria sustainability analyses of energy systems. As the PE energy system models are and MCDA can be technology-based, they can be combined for technology-based assessments.

Four combined methods combining PE energy system models and multi-criteria sustainability analysis are described and analysed in Sections 2.3 to 2.6.

2.3. Bottom-up ex-post multi-criteria analysis of energy systems on end-use technology level

PE energy system models quantify energy system scenarios, which are – among other features – characterised by detailed end-use technology mixes, i.e. combinations of end-use technologies such as oil heating systems, coal industrial furnaces and diesel passenger cars. A set of sustainability indicators can be quantified for each of the end-use technologies in the mix as illustrated in Figure 5, and these are aggregated to total indicator values for each scenario. These total indicator values can be compared with or without MCDA, thus allowing for long-term multi-criteria sustainability assessment of energy systems.

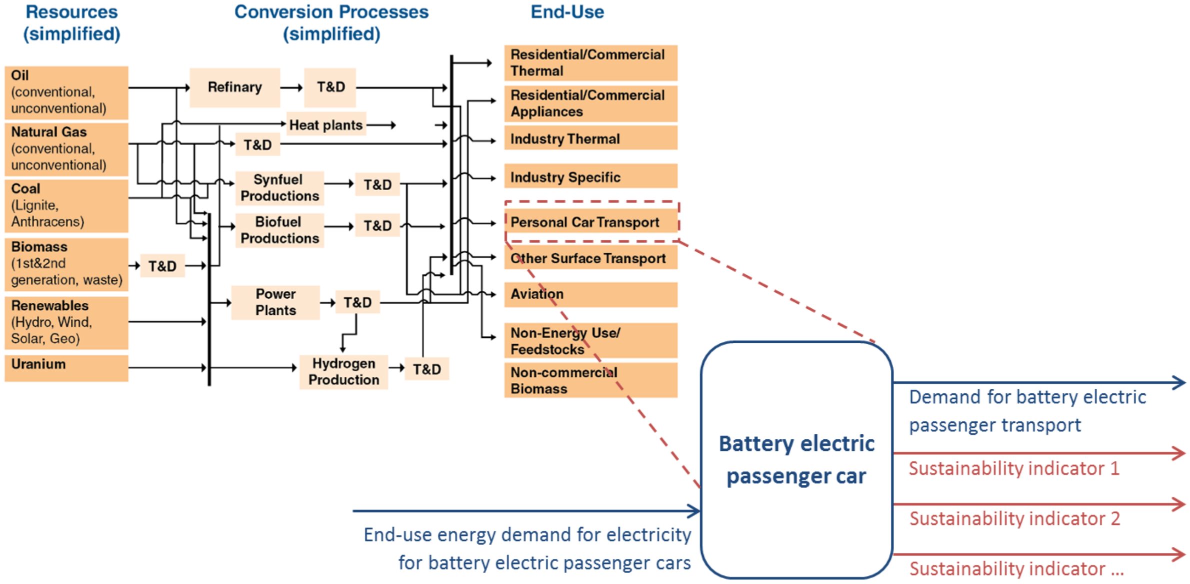


Figure 5: Illustration of the bottom-up quantification of sustainability indicators on end-use technology level based on the simplified reference energy system from [18]

2.3.1. Formalisation of the combined method

The bottom-up ex-post multi-criteria analysis of energy systems on the end-use technology level introduced above can be sub-divided into the following steps:

1) Scenario description
2) Quantification of scenarios based on cost minimisation
3) Technology characterisation, criteria definition and specific indicator quantification for each end-use technology
4) Total indicator value quantification per scenario, possible calculation of MCDA results, and interpretation of the results

Figure 6 depicts the data flows throughout the four steps.

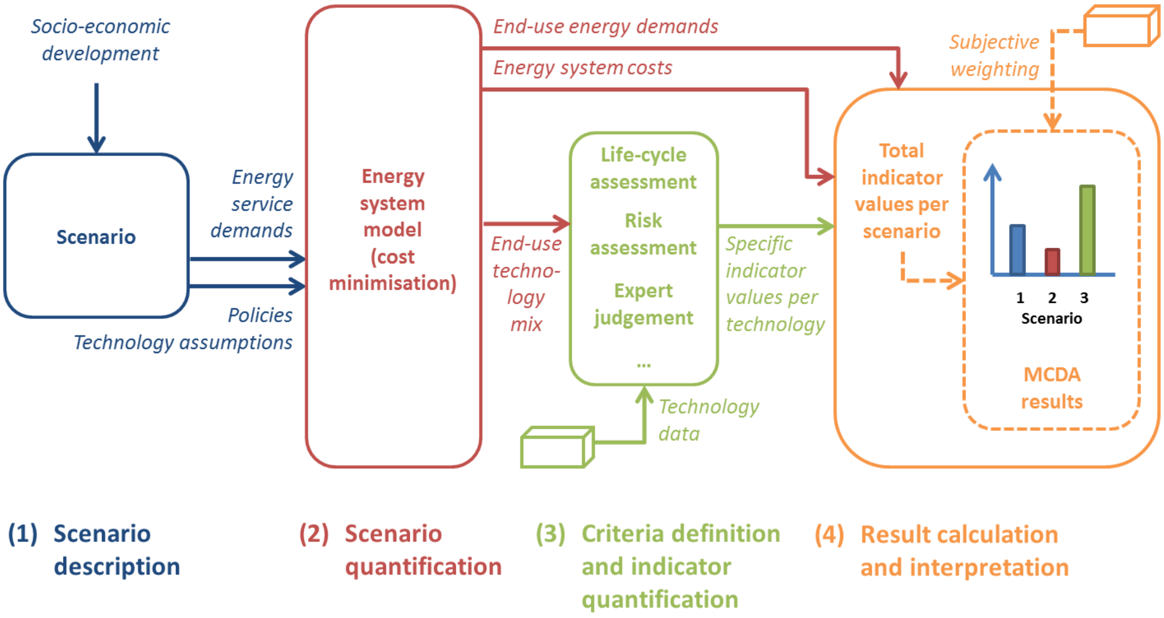


Figure 6: Illustration of the methodological steps of the bottom-up ex-post multi-criteria sustainability analysis of energy systems on the end-use technology level. The calculation of MCDA results is indicated by dashed lines.

As a first step, the energy system scenarios are developed as described in Section 2.1. In the second step, the energy service demands and policy and technology assumption of the scenarios as defined in the first step are implemented in the PE energy system model. The model quantifies – among other quantities – the end-use technology mixes for each scenario and the corresponding end-use energy demands (e.g. electricity demand for battery electric passenger cars and oil demand for residential oil boilers) based on cost minimisation. In the third step, a set of criteria is defined which covers all aspects that are considered to be relevant for the scenario comparison. Specific indicator values (e.g. CO_2 emissions of a diesel passenger car and risk for severe accidents related to the operation of an industrial coal furnace) are quantified for each technology in the end-use technology mix using data from environmental, risk and cost assessments, surveys, and expert judgement.

The fourth step of calculating results can be based on the trade-offs for the total indicator values or on a full MCDA, which includes subjective weighting of the criteria (Figure 6). The total indicator values for each scenario are derived from the end-use energy demands from the second step and the specific indicator values from the third step. It is also possible to extract total indicator values from the PE energy system model outputs (e.g. annualised investments costs). For a full MCDA, the total indicator values are normalised, weighted and aggregated to one single value. This allows for a comparative, subjective ranking of the scenarios under consideration.

2.3.2. Discussion of the combined method

2.3.2.1. Definition of indicators on the end-use technology level

Applying the combined method described above, the indicator values are quantified for each end-use technology in the energy system model. If the indicators are defined in this way, the impacts of the whole energy chains, i.e. from extraction to transport, storage and conversion of the energy carriers used by the end-use technologies, are *not* considered. This contradicts the aim of the combined method which is to consider the impacts of the whole energy system.

There are two possibilities to overcome this issue: First, define the indicators from a Life-Cycle Assessment (LCA) perspective. By doing so, not only the impacts of the energy chain but also the impacts of the supply chains from other sectors are considered (Figure 7). Taking the diesel passenger car from above as an example not only the CO_2 emissions of the operation phase are accounted for, but also the impacts from the oil chain as well as further impacts in the supply chains such as the production and disposal of the car. The LCA method is shortly described in Box 1.

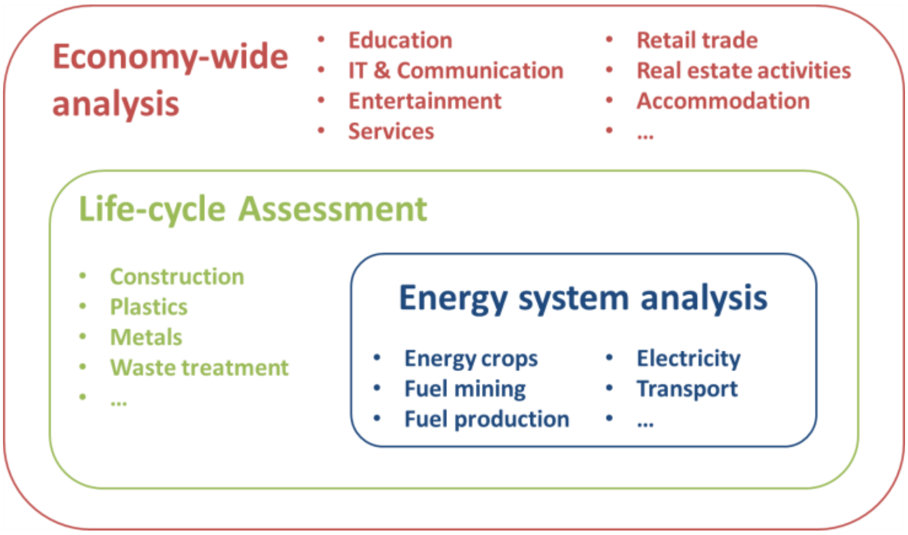


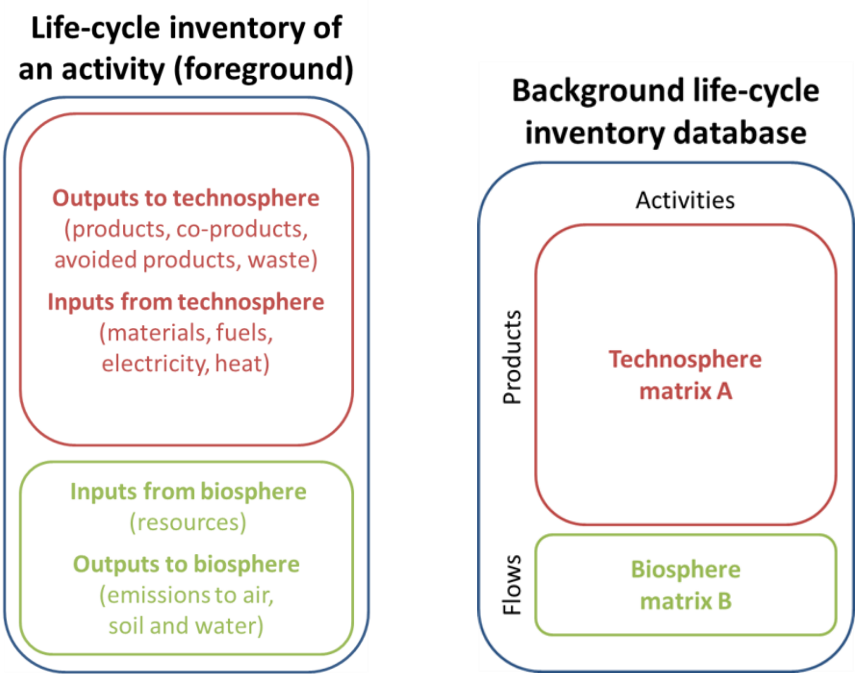
Figure 7: Illustration of the sectoral coverage of an energy system analysis, life-cycle assessment (LCA) and economy-wide analysis

Box 1: Life-cycle assessment (LCA)

Life-cycle assessment (LCA) has become the dominant tool for determining environmental and human health damages of products and services [29]. It is often applied for comparative environmental evaluations and considers all impacts from cradle to grave. The method is ISO-standardised [30] and consists of four steps:

1) Goal and scope definition
2) Inventory analysis
3) Impact assessment
4) Interpretation

The first step aims to frame the analysis by specifying its aim and its temporal, spatial and technological characteristics. The second step includes the collection of the input and output data, i.e. the generation of the (foreground) life-cycle inventories (LCI) for the considered activities as illustrated below. So-called background LCI databases such as ecoinvent [16] are comprehensive collections of LCI datasets. The study-specific LCI, i.e. the foreground information specified in the second step, can be linked to a background LCI database which provides the information for the supply chains. For an LCA of a building for example, the amounts of concrete and steel are collected specifically for the building under consideration (foreground), while the information on the steel and concrete production in the supply chains can be drawn from the background LCI database.



In the third step, the cumulative environmental impacts of the activities (h) are calculated based on the following formula:

$$h = BA^{-1}f$$

where B is the biosphere matrix, A is the technosphere matrix and f is the functional unit, i.e. the demand, as depicted above. If of interest, these cumulative impacts can be characterised with so-called Life-cycle Impact Assessment (LCIA) methods, such as the IPCC LCIA method for the quantification of the GHG emissions in kg of CO_2-equivalents. The fourth step consists of the interpretation of the results.

The quantification of LCA-based indicators for bottom-up ex-post multi-criteria analysis of energy systems on the end-use technology level leads to double-counting the impacts of the energy used in the end-use technologies' energy and supply chains. For example, the life-cycle impacts of a Swiss gas-fired industrial furnace not only include the direct (on-site) impacts (e.g. pollutant emissions) but also the impacts of the Swiss coal-fired industrial furnace used to produce the steel for this gas furnace. As the heat provided by coal-fired industrial furnace is already modelled by the Swiss industrial energy demand in the energy system model, the impacts of the coal-fired industrial furnace are double-counted.

In general, if all energy and supply chains lie within the modelling region(s) of a single- or multi-regional energy system model, all impacts of the energy used in the supply and energy chains are double-counted. If the energy system model instead excludes certain world regions, double-counting only occurs for impacts of the energy and supply chains which lie within the considered region(s).

The second option for considering the whole energy chain is used for indicators that cannot be quantified with LCA. These indicators are quantified in such a way that they take into account all impacts along the energy chain of the corresponding end-use technology. Taking the industrial coal furnace from above as example, the risk for severe accidents is not only defined for the end-use technology but over the whole coal energy chain.

2.3.2.2. Uncertainties in indicator quantification

The specific indicator values for the end-use energy technologies and the techno-economic data for the PE energy system model are usually taken from different data sources. In this case, their technology characteristics do usually not match perfectly, so the impacts of the end-use energy technologies of the PE energy system model are quantified with some uncertainty. The combined method aims to analyse future scenarios, i.e. at one or more future time periods, but the specific indicator values used to describe the end-use technologies are typically available for current or even outdated technologies. If these specific indicator values are applied to future time periods or if they are projected, further uncertainty is introduced to the indicator value estimations. This also applies to information from background databases, which are used to model the impacts of energy and other supply chains.

2.3.2.3. Regional allocation of impacts

PE energy system models calculate the minimum cost combination of resource extraction, conversion and end-use technologies which satisfy the exogenous energy service demands. They do not differentiate whether the energy service demand is due to domestic actors or by foreign actors as a consequence of cross-border supply chains. While passenger car transport and residential energy demands of a region are mostly induced by domestic actors, freight transport and industrial energy demands can be caused by foreign actors’ demands. For example, the industrial energy demand of China is partially caused by demands for products in the rest of the world. The way that PE energy system models and thus the combined method are laid out, the impacts are all allocated to the region that satisfies the energy service demand, independent of the region that caused the respective energy service demand. As opposed to this production-oriented perspective, a consumption-oriented perspective would require allocating the impacts to the regions which are actually responsible for the demand, i.e. the impacts would be differentiated according to the domestic and foreign shares in the respective energy service demands. Taking China as an example, a certain share of the impacts caused by the Chinese industry would be allocated to Europe.

Furthermore, the combined method leads to the allocation of all energy chain- and LCA-based impacts to the region of the end-use technology, independent of where they actually occur. While the direct (on-site) impacts of the end-use technologies obviously occur in the local region under consideration, energy chain and LCA-based impacts can occur in other regions.

2.3.2.4. Possibility for MCDA

MCDA, as a part of the fourth step described in Section 2.3.1, is only possible for the comparison of scenario variants, i.e. scenarios with the same energy service demands but different policy assumptions or technology alternatives. This includes for example the comparison of scenario variants with and without CCS technologies, or the comparison of scenario variants with and without a CO_2 emission cap. In contrast, if different scenarios, i.e. pathways with *alternative* energy service demands, are compared, MCDA, which is a tool for the comparison of products or services *serving the same purpose,* is not applicable.

2.3.2.5. Comparison with existing literature

Bottom-up ex-post multi-criteria analysis of energy system scenarios has been applied in a set of studies such as those listed in Appendix, Table 24. However, most of the listed studies quantify indicators for the electricity sector only, i.e. they do not cover the whole energy system from the resource to the end-use. Some of the listed studies perform an analysis of the whole energy system, but without quantifying the indicators from a LCA perspective [31-34]. But among the latter studies, Eckle et al. [33] take into account the energy chain when quantifying the indicators for severe accidents in the energy chains.

The consideration of the impacts along the energy chains is facilitated by quantifying the indicator values on the energy system technology level instead of only the end-use technology level. The bottom-up ex-post multi-criteria sustainability analysis of energy systems on both the supply and end-use technology levels is discussed in the next section. Further, an approach for avoiding double-counting when using LCA-based indicators is proposed. This approach cannot be applied on the end-use technology level because it does not explicitly account for the energy chain impacts.

2.4. Bottom-up ex-post multi-criteria analysis of energy systems on the supply and end-use technology levels

For bottom-up ex-post multi-criteria sustainability analysis of energy systems on the technology level, the sustainability indicators are quantified on the resource, conversion and end-use technology levels as depicted in Figure 8 instead of only the end-use technology level. A set of sustainability indicators is quantified for each technology and aggregated to total indicator values for each scenario. These total indicator values are compared with or without full MCDA.

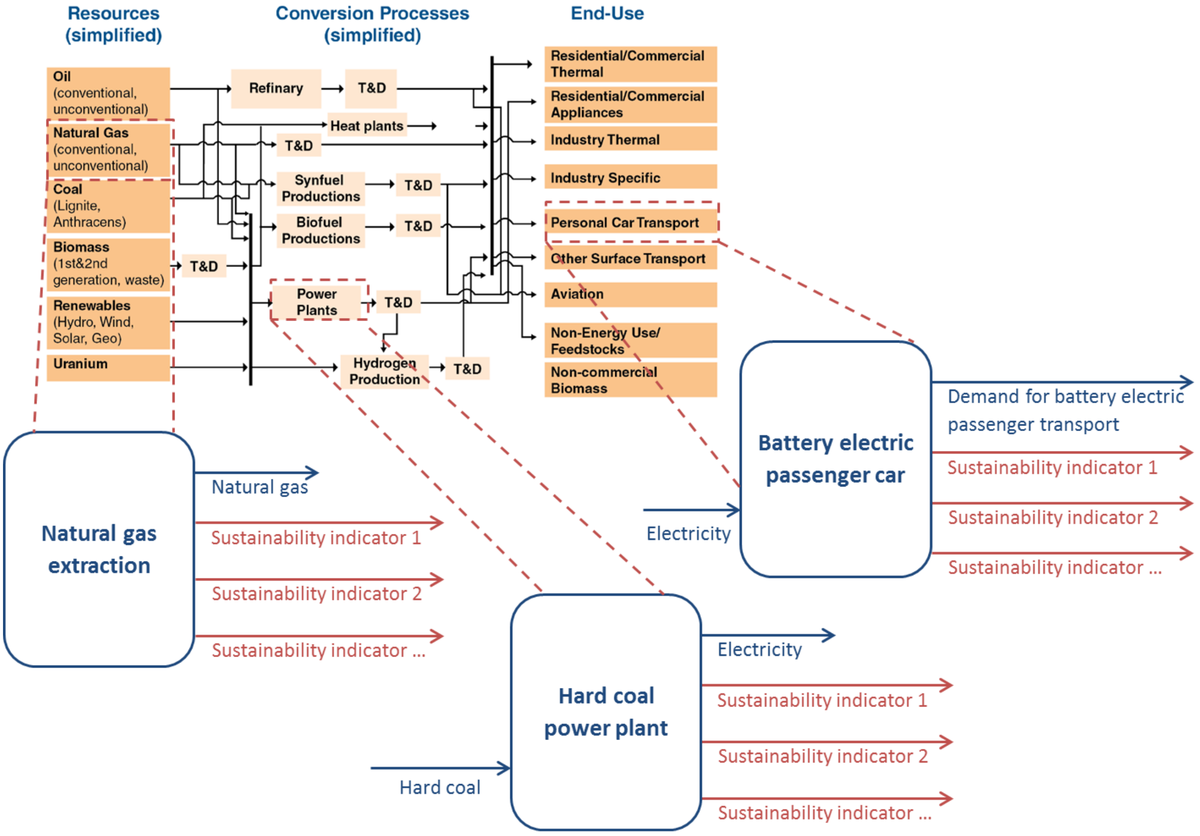


Figure 8: Illustration of the bottom-up quantification of sustainability indicators on the supply and end-use technology levels based on a simplified reference energy system from [18]

2.4.1. Formalisation of the combined method

The process of performing a bottom-up ex-post multi-criteria sustainability analysis of energy systems on both the supply and end-use technology levels can be broken down into the following four steps (Figure 9), which are described in more detail in the subsequent paragraphs:

1) Scenario description
2) Technology data selection, criteria definition and specific indicator quantification for each supply and end-use technology
3) Scenario quantification based on cost minimisation
4) Total indicator value quantification per scenario, possible calculation of MCDA results, and interpretation of results

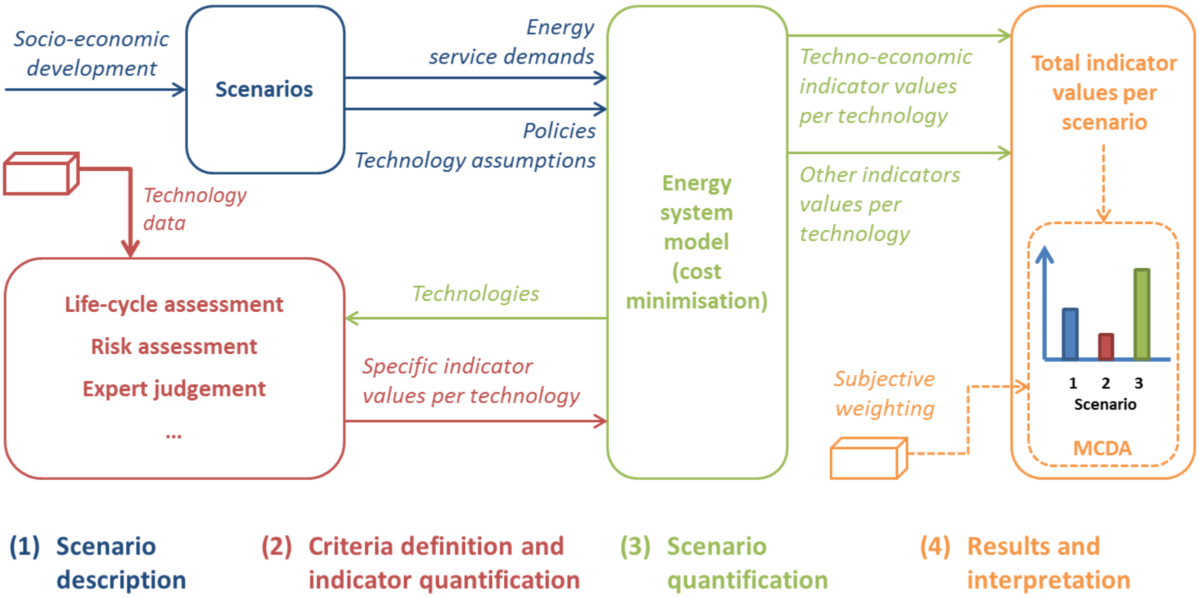


Figure 9: Illustration of the methodological steps of the bottom-up multi-criteria sustainability analysis of energy systems on the supply and end-use technology levels. The result calculation with MCDA is indicated by dashed lines.

As a first step, the energy system scenarios are developed. Together with technology and policy assumptions, the derived energy service demands are implemented into the energy system model. In the second step, the sustainability criteria are defined and corresponding specific indicator values are quantified. As the indicator values are quantified on the technology level, they can be integrated in the energy system model framework using its existing features for the quantification of environmental indicators (Section 2.1). Depending on the features of the applied energy system modelling framework, it is possible to specify the impacts of each energy system technology per activity, investment and capacity.

The scenarios are quantified using the energy system model in the third step, taking into account the corresponding policies and technological constraints. This step includes the quantification of the sustainability indicators for each supply and end-use technology (e.g. the air pollutant emissions of a technology). In the fourth step, the total indicator values are extracted from the energy system modelling results. Further sustainability indicators can be drawn from the techno-economic results of the energy system model itself (e.g. investment costs and energy carrier imports). In addition to the trade-off analysis of the total indicator values, it is also possible to carry out a full MCDA. In doing so, the total indicator values per scenario are normalised and weighted and the scenarios are ranked by aggregating the normalised and weighted total indicator values. This step is only possible for the comparison of scenario variants, i.e. scenarios with the same energy service demands but different policy and technology assumptions (Section 2.3.2.4).

2.4.2. Discussion of the combined method

2.4.2.1. Avoiding double-counting impacts with LCA indicators

As described in Section 2.3.2.1, bottom-up quantification of LCA indicators for energy system technologies leads to double-counting (parts of) the impacts of the energy inputs if standard LCA calculation schemes are applied. Therefore, an approach is proposed, which avoids double-counting and which can be divided into the following steps:

1) Matching energy system technologies with their corresponding Life-Cycle Inventory (LCI) datasets
2) Subdividing LCI datasets according to the life-cycle phases
3) Constructing a background LCI database without the energy system of the considered region(s)
4) Calculating the cumulative LCI and conducting Life-Cycle Impact Assessment (LCIA) (if required)

As the first step for the calculation of the LCA-based indicators, one LCI dataset is allocated to each technology in the energy system model. The LCI dataset matches the energy system model technology as closely as possible regarding technical, geographical and temporal characteristics. In the second step, the selected LCI datasets are subdivided into the upstream input from technosphere on the one hand and the residual technosphere inputs and biosphere flows on the other hand (Figure 10a). The upstream contribution is removed from the LCI dataset in this bottom-up approach, as the impacts of the upstream energy chain are represented by the other processes in the energy system model. For example for hard coal power generation this means that impacts resulting from hard coal extraction and transport are separated.

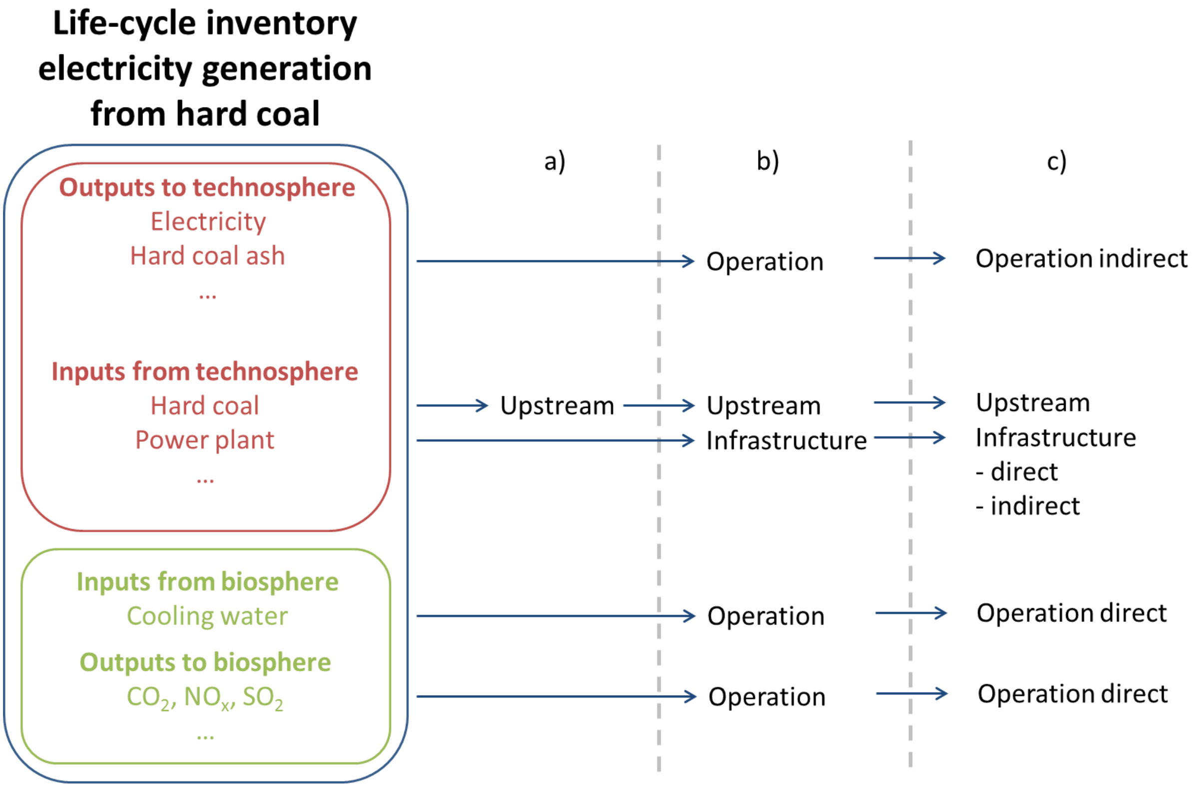


Figure 10: Illustration of the disaggregation of LCI datasets for the bottom-up quantification of LCA-based indicators

If it is of interest for the study, the modified LCI dataset can be subdivided into upstream, operation and infrastructure contributions (Figure 10b). Impacts from operation occur whenever the energy technology is used, while the infrastructure impacts occur whenever there is investment in the respective energy technology. For example in the case of hard coal power generation the infrastructure contribution includes the land use for the power plant, contributions from the materials used to build the plant, and residues from decommissioning, while the operation contribution consists of natural inputs, smokestack emissions, ash production as well as additional processes and materials used for power generation. The operation and infrastructure impacts can be further subdivided into direct impacts that occur on-site and indirect impacts that occur elsewhere (Figure 10c). The natural inputs and emissions from operation produce direct impacts, while materials and wastes produce indirect impacts from operation. The direct impacts related to infrastructure include land use as well as emissions related to construction. The indirect impacts of infrastructure include the materials and waste from constructing and decommissioning the power plant.

The third step represents the preparation of the background LCI database so that double-counting the impacts from the energy system is avoided, i.e. the technosphere matrix A is modified so that it excludes the contributions for the energy system(s) of the region(s) under consideration. All energy inputs to all activities in the technosphere matrix are set to zero as illustrated in Figure 11. These energy inputs include industrial electricity and heat generation, freight transport and feedstocks, which are – as opposed to residential and commercial energy, passenger car transport and non-commercial biomass – potential inputs to the construction and operation of energy system technologies.

The general LCA formula (Section 2.3.2.1, Box 1) for the calculation of the cumulative environmental impacts h as the fourth step is thus changed to:

$$h' = BA'^{-1}f$$

where A’ is the modified technosphere matrix, B is the biosphere matrix, f is the functional unit and h’ is the corresponding vector of cumulative environmental impacts. The LCA-based indicators can then be implemented in the energy system model according to Section 2.1.

2.4.2.2. Uncertainties in the indicator quantification

The energy system technologies and sustainability indicators are modelled with data from different sources. This can lead to uncertainties in the indicator quantification due to deviations in the underlying assumptions. While the energy system model includes techno-economic data for all future time periods and regions under consideration, the corresponding information for other sustainability indicators may be rough regarding the required regional and temporal resolution. This also includes data from background databases. If projections are required, further uncertainties are introduced.

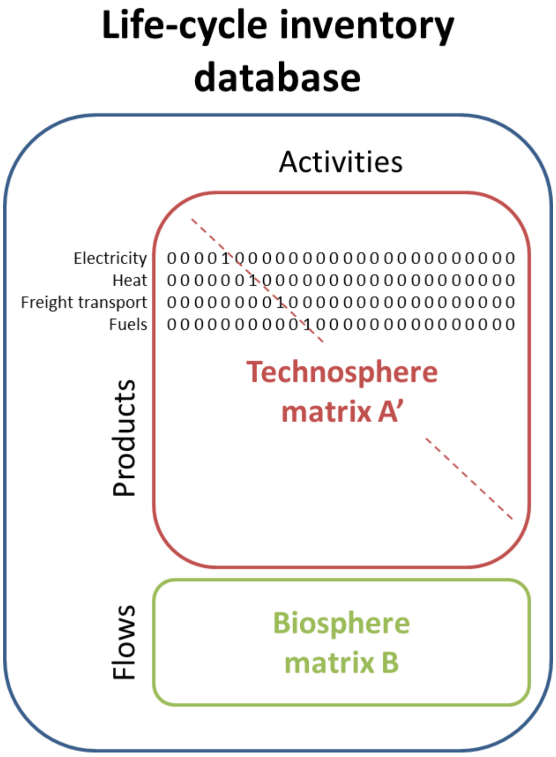


Figure 11: Illustration of the modified technosphere matrix A' in the background LCI database

2.4.2.3. *Regional allocation of impacts*

This combined method allocates the impacts from a production perspective: i.e. all impacts are allocated to the technology and region that satisfies the energy service demand, independent of which region causes this demand. The life-cycle and energy chain impacts are allocated to the region in which the direct (on-site) impacts occur. This is analogous to the discussion in Section 2.3.2.3.

2.4.2.4. *Literature review*

In addition to the bottom-up ex-post multi-criteria analysis of energy system scenarios studies discussed in Section 2.3.2.5 and Appendix, Table 24, there are dedicated bottom-up ex-post LCA studies of energy system scenarios (Appendix, Table 25). Except for Brand et al. [35], the listed studies focus on the electricity sector, and only two mention double-counting environmental impacts: Garcia-Gusano et al. [36] propose to allocate the LCA-based indicators to the generating capacity level and Brand et al. [35] apply an approach by Stroemman et al. [37] for hybrid life-cycle inventories to avoid double-counting. In the European NEEDS project, Loulou et al. proposed two approaches for integrating LCA-based indicators in the TIMES model of the European electricity system: (i) endogenous modelling of the amounts of materials and fuels directly consumed in the construction, dismantling and upstream phase, or (ii) integration of the cumulative impacts of construction and dismantling and their upstream chains [38]. Eventually, approach (ii) was selected, which does not fully avoid double-counting.

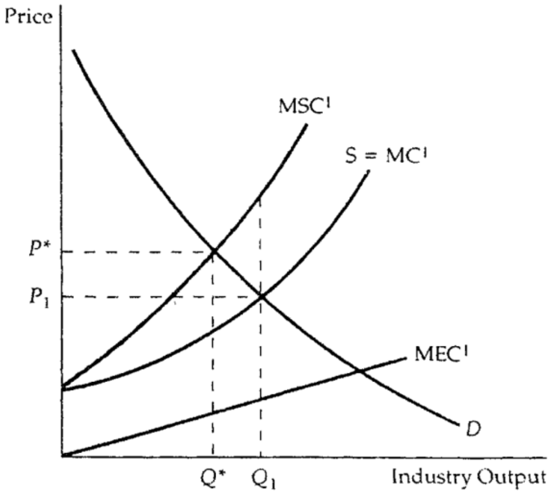
While some sustainability indicators such as investment cost are specified in monetary terms by the PE energy system model, other indicators such as environmental and human health impacts due to pollutant emissions are quantified in physical terms or on other scales. This prevents direct comparisons of such impacts with the economic sustainability indicators, energy system costs, and important economic measures such as the GDP. It also prevents aggregation of the multiple sustainability indicators without normalisation. The monetisation of impacts enables such economic comparisons, allows for direct aggregation of multiple indicators and makes physical flows more comprehensible. The combination of PE energy system models and monetised environmental flows is therefore discussed in the subsequent section.

2.5. Bottom-up ex-post external cost analysis of energy systems

Environmental flows (resource and land use as well as emissions according to Box 1) can lead to damages to human health, materials and ecosystems. With the previous combined method, flows such as the emission of pollutants from the energy system to the air, soil and water were quantified in physical units. Complementarily, environmental flows can be assessed with so-called external costs that reflect the damages they cause in monetary terms. External costs are costs which affect a party, which did not choose to incur that cost, in other words, external costs are costs that not paid by the polluter but by society. The internal costs and the external costs add up to the total costs of an energy system pathway. The economic theory of external costs is shortly described in Box 2.

Box 2: Economic theory of externalities

Externalities are market inefficiencies and an important source of market failure. In the case that externalities are present, the prices do not reflect the social value of a good. This is depicted in the figure from Pindyck and Rubinfeld below [5]. In an imperfect market, the price P_1 and quantity Q_1 of a good produced by an industry is determined by the intersection of the marginal demand curve (D) and the marginal cost curve (MC) of that industry. In the case of externalities, a marginal external cost curve (MEC) is present, leading to the marginal social cost curve (MSC) which lies above the MC. The intersection of MSC with the marginal demand curve (D) gives the socially optimal price P* and quantity Q*. This price is generally higher and the corresponding quantity is lower compared to the price and quantity in an imperfect market.



2.5.1. Formalisation of the combined method

The bottom-up ex-post external cost analysis can be described in four steps (Figure 12):

1) Scenario description
2) Definition and quantification of environmental flows and external costs for each technology
3) Scenario quantification
4) Total cost quantification and interpretation of results

In the first step, the scenarios are described according to Section 2.1. As second step, the environmental flows for the study are selected and quantified for each technology represented in the energy system model. Specific external costs are quantified for each of the selected environmental flows using the same socio-economic and technology assumptions as in the scenario description. The specific environmental flows and specific external costs are implemented in the energy modelling framework using its existing features (Section 2.1).

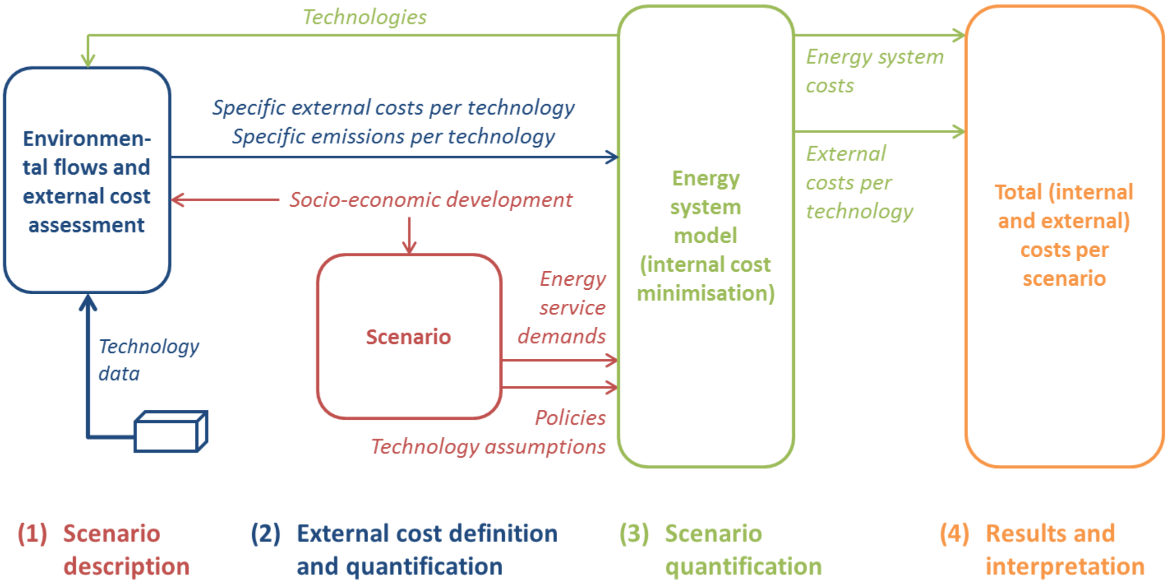


Figure 12: Illustration of the methodological steps of a bottom-up ex-post external cost assessment of energy system scenarios

The third step, the quantification of the scenarios, is based on cost minimisation of only *the internal costs* and leads to an estimation of the external and internal costs of the scenarios under consideration. In the fourth step, the total costs of the energy system pathways are calculated by aggregating all internal and external costs, and the results are interpreted. With the monetisation, the aggregation of environmental flows is enabled and they are implicitly weighted by the specific external costs. Therefore, no full MCDA with normalisation and weighting is envisaged for this combined method.

2.5.2. Discussion of the combined method

2.5.2.1. Regional allocation of the external costs

Global air pollutants such as GHG are dispersed in the whole atmosphere and cause damages around the world, independent of the location of the emission. In contrast, local air pollutants (LAP) as well as resource and land use cause local or regional damages. With the combined method presented, the external costs of both LAP and GHG are allocated to the technology, region and environmental flows causing them, i.e. they are defined from a production perspective. This is independent of where the energy service demand is actually located. The quantification of external costs for LCA-based indicators is discussed in Section 2.5.2.2.

2.5.2.2. Quantification of external costs for LCA-based indicators

LCA-based impacts of energy technologies can be quantified according to Section 2.4.2.1 and valued with specific external costs. By doing so, all life-cycle impacts are assumed to occur within the technology's region, i.e. all impacts are monetised with the specific external costs of the region in which the direct (on-site) impacts of the technology occur. Considering today's global supply chains and the different impacts that the same environmental flow can cause in different regions, this is not necessarily realistic.

One solution to overcome this issue is to split the total LCA-based impacts into the regional contributions and value them with the respective regional specific external costs. For this purpose, the equation from Section 2.4.2.1 is changed to

$$h_i' = B\, A_i'^{-1} f$$

where B is the biosphere matrix, A_i' is the modified technosphere matrix, f is the functional unit, h_i' is the vector of the cumulative environmental impacts of region i and i is the region under consideration. For the calculation of h'_i, the technosphere matrix is modified so that the inputs to all activities of all regions except the ones from region i are set to zero as illustrated in Figure 13.

For a global energy system model, the regions i correspond to the modelling regions and the contribution of each region i is valued with its respective specific external costs. For models, which cover only a part of the world, the approach for the modelled region(s) is the same as for the global model. For the parts of the world which are not modelled, assumptions on the foreign regions and their specific external costs are required.

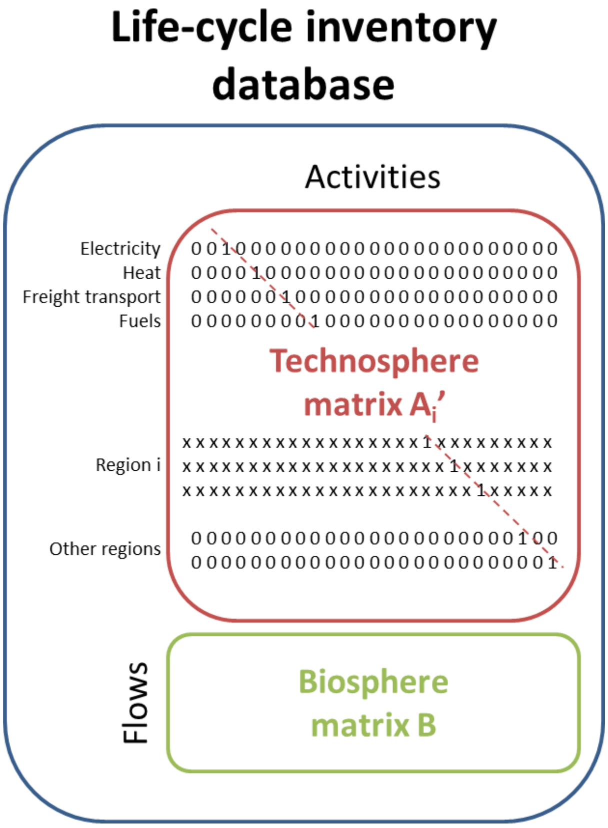


Figure 13: Illustration of the modified technosphere matrix A_i' in the background LCI database. “x” indicates elements, which are not set to zero.

In practice, this can be a very complex task due to the regional inconsistency of the energy system modelling regions and the background LCI database regions: region i may not have a one-to-one corresponding region in the background LCI database. Therefore, each regional environmental impact h_i' must be quantified by disaggregation or aggregation of regional inputs in the background database.

2.5.2.3. Uncertainties in the external cost quantification

For external cost assessments in the context of energy system models, technology- and region-specific rather than process-specific external cost data are needed. Therefore, external cost assessments with energy system models usually include some level of aggregation and simplification compared to dedicated external cost studies such as ExternE [39]. The external costs of environmental flows are not physical properties and are therefore based on monetary valuation. This step includes value choices, such as discounting and equity weighting, which can be made in different ways. Thus, the monetisation of environmental flows bears value-related uncertainties in addition to the uncertainties related to the quantification of the environmental flows, which are described in Section 2.4.2.2.

2.5.2.4. Literature review

An overview of studies which have integrated externalities in PE energy system models is presented in Appendix, Table 26. Most of the listed studies focus on one country or region, while the studies by Rafaj [15] and Kypreos et al. [40] are based on a multi-regional model. The majority of the listed studies address LAP as well as GHG emissions, but Kosugi et al. [41] also analyse the externalities related to land use. There are studies focussing on the electricity sector [15, 42-46], while others address the entire energy sector [40, 47, 48] or even the whole economy [41]. Roeder instead focuses on the external costs of the passenger car sector [49]. The modelling of the emissions is either based on direct (on-site) emissions [15, 42, 47], LCA [40, 41, 43-45, 48, 49] or upstream and operating emissions [46]. Many studies presented in Appendix, Table 26 use external cost data from the European research projects ExternE and NEEDS. The other studies draw information from their previous work or other sources.

The three combined methods discussed so far (Sections 2.3 to 2.5) are based on a cost minimisation framework, in which a single internal cost objective is optimised and other indicators are calculated ex-post. With these combined methods, the same (set of) energy system transformation(s) can be analysed based on different types of indicators. The endogenisation of sustainability indicators in the PE energy system model instead leads to a new (set of) energy system transformation pathway(s), which is quantified for each (set of) objective(s). This combined method is described and analysed in the next section.

2.6. Endogenisation of sustainability indicators in energy system models

PE energy system models are based on cost minimisation, which is expected to approximate the real world decisions and developments (Section 2.1). Energy system pathways based on the optimisation of (combined) sustainability indicators instead represent developments under different policy objectives. The endogenisation of sustainability objectives such as energy carrier imports or CO_2 emissions leads to new scenarios, which can be compared with each other and the least-cost pathway, if the other boundary conditions remain unchanged.

2.6.1. Formalisation of the combined method

Endogenisation of sustainability indicators in PE energy system models can be formalised as follows (Figure 14):

1) Definition and quantification of the sustainability indicators for each technology
2) Scenario description
3) Scenario quantification with single or multiple objectives
4) Result calculation and interpretation

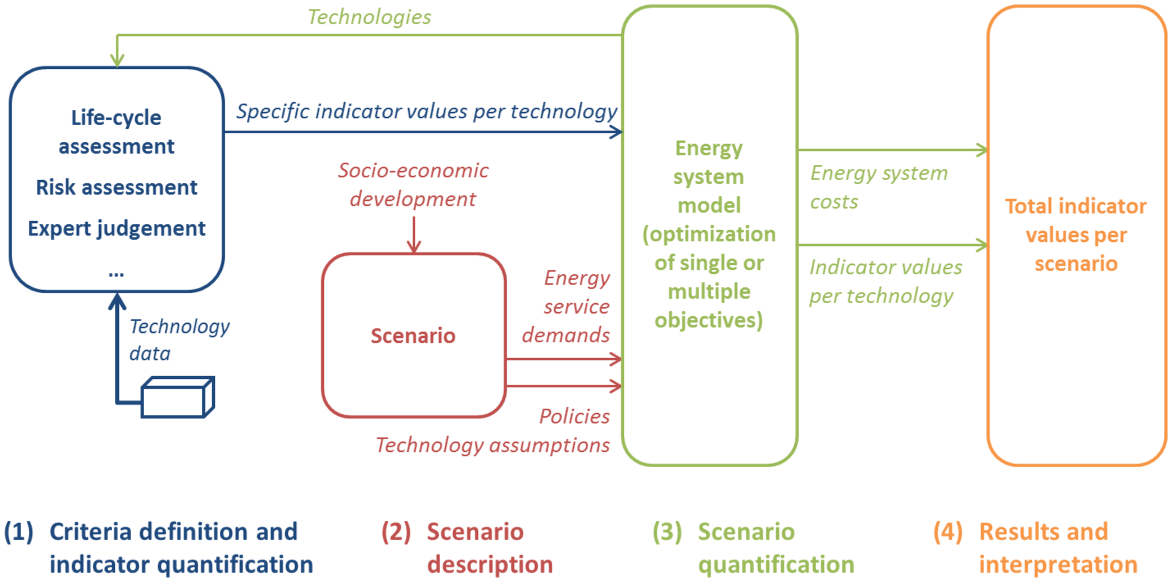


Figure 14: Illustration of the methodological steps for the endogenisation of sustainability indicators in energy system models

The approach for endogenisation of sustainability criteria in energy system models is set up analogous to the bottom-up multi-criteria analysis of energy system scenarios presented in Section 2.4: In the first two steps, the scenarios are described and the sustainability indicators are quantified on technology level and introduced in the energy system model using its features for the consideration of environmental aspects (Section 2.1). But, as opposed to the ex-post analysis, the indicators are endogenised, i.e. introduced in the objective function of the PE energy system model. Accordingly, the objective function is altered to allow for the optimisation of (combinations of) the respective sustainability objectives. After the scenario quantification in the third step, the total indicator values are aggregated to scenario level and interpreted in the fourth step.

2.6.2. Discussion of the combined method

2.6.2.1. Regional allocation of impacts

The impacts are quantified and implemented as described in Section 2.4.2.3. Therefore, the impacts are allocated to the region in which they actually occur, i.e. they are not defined from a consumption perspective.

2.6.2.2. Endogenisation of the energy system's own energy use

PE energy system models allocate energy supply technologies to exogenously defined energy service demands based on cost minimisation. The energy service demands are derived from socio-economic drivers and are assumed to include all energy demands of the respective regions, i.e. also all demands for the production and disposal of the energy system technologies. The energy used for the operation of the energy system (the energy system's own energy use) is either also included in the exogenous energy service demands or in the energy system processes themselves (e.g. in transport and distribution (T&D) efficiencies)[2].

Alternatively, the energy use of the energy system technologies can be endogenised using an LCA-based approach. If – for example – the direct (on-site) CO_2 emissions of the energy system are optimised, low-CO_2 conversion technologies such as photovoltaic (PV) power plants are expected to be part of the optimal solution as they do not emit CO_2. Nevertheless, they require energy for the production of the components and the installation. In order to better represent such developments, the energy system's own energy use (including both operation and infrastructure contributions) can be endogenised in the energy system model. If such an approach is taken, the energy used in the supply chains of each energy system technology is explicitly repre-

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[2] According to 2011 statistics, the average own energy use for the operation of the energy sector was 7 % of the total produced electricity (observed range 0%-44%) and 7% of the total produced heat (observed range 0-39%) [50].

sented as a set of energy inputs (electricity, heat, freight transport and feedstock demands) as illustrated in Figure 15.

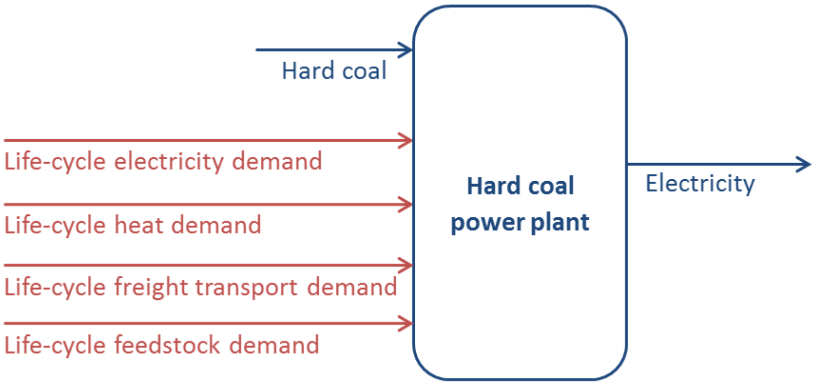

Figure 15: Illustration of the endogenous life-cycle energy inputs on technology level

The life-cycle energy inputs can be derived from the standard formulation of LCA indicators (Box 1 in Section 2.3.2.1):

$$s = A^{-1} f$$

where s is the supply vector, A is the technosphere matrix and f is the demand vector. The supply vector represents the cumulative inputs from technosphere required to satisfy one unit of demand. By summing up over the electricity, heat, freight transport and feedstock inputs, respectively, the life-cycle energy inputs can be calculated. Analogous to Section 2.5.2.2, it is further possible to disaggregate the cumulative energy inputs into to the regional contributions by summing up only over the respective regional energy inputs.

For the implementation in the energy system model, industrial electricity and heat, freight transport and feedstock end-use technologies and according energy carriers are defined, which represent the mixes of the respective time period and region. An illustration of the approach is presented in Figure 16.

If such an approach is implemented, the energy service demands must be adapted: The energy service demands of the base year are lowered according to the life-cycle amounts of energy used by the energy system technologies to avoid double-counting the energy flows related to the energy system technologies. For the future time periods, an assumption about the share of the energy service demands due to energy technologies is required for each time period and region. This share can – for example – be estimated based on the cost optimal scenario (without endogenous energy flows). After these adjustments, the scenarios can be quantified based on other objectives and the residual energy service demands and the energy demands from the energy technologies are satisfied.

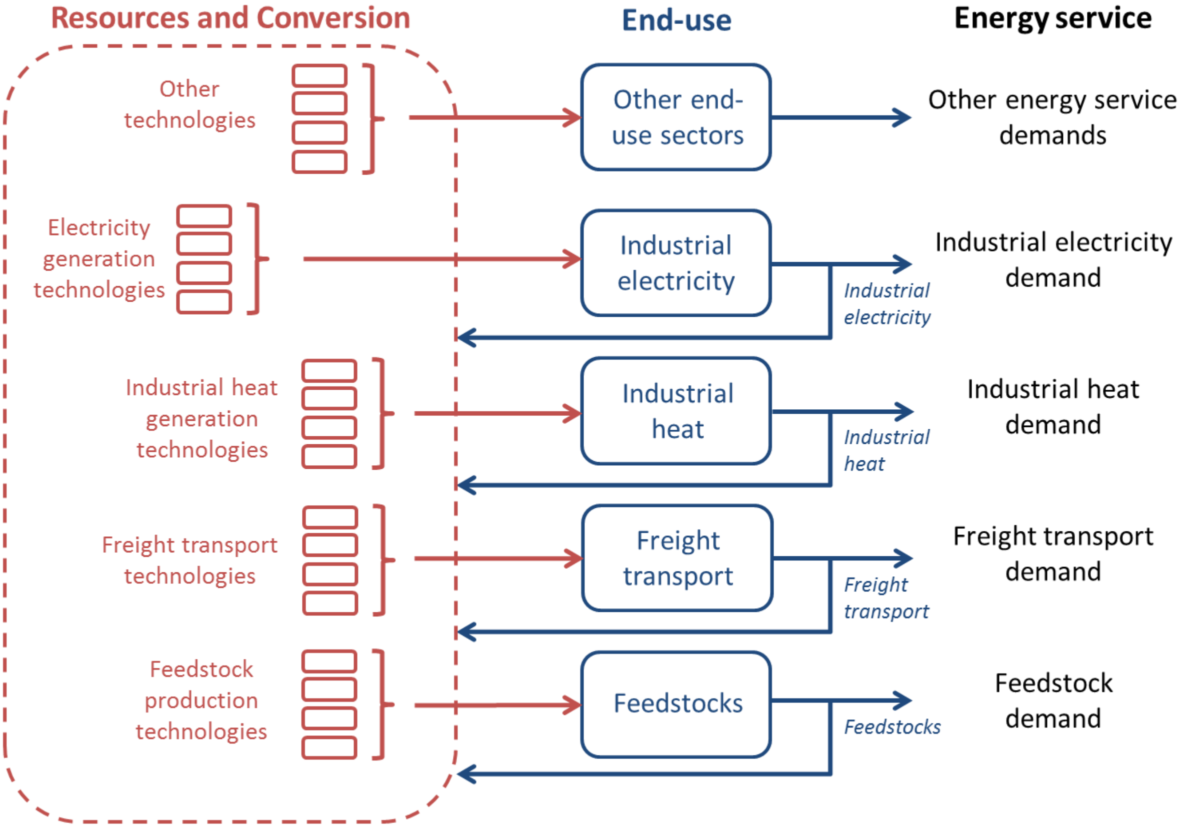

Figure 16: Illustration of the modelling of the endogenous energy inputs on energy system level

2.6.2.3. Modelling uncertainties and limitations

There are uncertainties in the indicator quantification in bottom-up analysis as listed in Section 2.4.2.2. Further modelling limitations could also be determined, which are described in the subsequent paragraphs.

TIMES- and MARKAL-based PE energy system models are directed to cost minimisation and thus have detailed cost characteristics implemented on technology level. This ensures that the solving algorithms lead to cost-efficient solutions without dissipation ("leakages"), although the modelling equations are formulated inequalities. If the modelling paradigm is changed to the optimisation of another sustainability objective, leakages can occur as the costs are no longer (the only) part of the objective function and the modelling equations are still formulated as inequalities. For example, a CO_2 minimal solution can include the construction of electric capacity which is not used. The reason is that the capacity does not have sustainability impacts (no direct, i.e. on-site, CO_2 emissions) and that its construction costs are not included in the objective function so that the technology is selected even though it is not required to satisfy the electricity demand. Such leakages must be avoided to reach credible results. One approach is to change the model's inequalities to equalities. But in large-scale models such as the GMM model, this approach leads to difficulties for the solver to find feasible solutions due to numerical problems even if it has been proven that feasible solutions exist.

For the optimisation of multiple weighted objectives in the objective function (analogous to the WSA in MCDA), the weighting is carried out *concurrent* to the optimisation. The individual objectives usually must be scaled as it is likely that they are not on the same scale. Without scaling, the objective with the largest order of magnitude would dominate the other objectives and thus the solution. These scaling factors however not only influence the results of the modelling but they also interfere with the weighting factors so that no robust results for such a WSA application could be found.

The introduction of new technologies on the end-use level (e.g. more end-use technologies) in existing large models such as the GMM model changes the results as the model has more opportunities to satisfy the respective energy service demand. The induced changes in one end-use sector can in turn influence other end-use sectors. Similarly, if new end-use technologies such as the ones for industrial electricity and heat as well as freight transport are implemented in exiting models, the previous end-use technologies are shifted to the conversion sector (Figure 16). Such modifications change the interactions between conversion technologies, end-use technologies and energy service demands, and lead to changes in the modelling results.

2.7. Summarising remarks and introduction to the case studies

Long-term PE energy system modelling and multi-criteria sustainability analysis can be combined on different levels of integration from ex-post analysis to endogenisation of indicators. All the combined methods presented allow for long-term multi-criteria sustainability analysis of energy systems, but they also face limitations and uncertainties, for example regarding spatial and temporal aspects, regarding value choices and regarding practical implementation in full-scale energy system models. The first three combinations are ex-post analyses and based on cost minimisation, and can therefore be applied for the analysis of the same energy system pathways. The forth method, which is based on the optimisation of other sustainability objectives instead leads to different energy system pathways.

In the next chapters, the four combined methods presented in Sections 2.3 to 2.6 are applied to case studies. The goal is to gain practical experience by applying the combined methods, and to derive insights for the investigated region(s).

In the first case study, the approach for bottom-up ex-post multi-criteria analysis of energy systems on end-use technology level is applied. Namely, three scenario variants for the future Swiss energy sector are quantified with a Swiss energy system model. The resulting end-use technology mixes are – ex-post – compared according to multiple sustainability criteria as well as under different subjective preferences.

The second case study is based on bottom-up multi-criteria analysis of energy systems on the supply and end-use technology levels. Three energy system scenarios are analysed with a global energy system model, in which all energy chains are fully represented.

The third case study extends the second one by monetising sustainability aspects, namely the human health damages caused by LAP emissions. Bottom-up ex-post external cost analysis of the three energy system scenarios is applied for scenarios quantified with a global energy system model. The external costs due to the LAP emissions are compared with the external costs of GHG emissions, energy system costs and GDP.

The fourth case endogenises sustainability indicators in the global energy system model. The objective function of the least-cost optimisation modelling framework is altered so that not only energy system costs but also other sustainability indicators (CO_2 emissions, energy carrier imports) can be optimised. Three global energy system pathways are quantified, which represent the perspective of three different sustainability objectives.

An overview of the characteristics of the four case studies is presented in Table 1.

Table 1: Overview of the four case studies presented in Chapters 3 to 6.

Chapter	Case study	Regional scope	Time horizon	Optimisation objective(s)
3	Multi-criteria Sustainability Analysis of Swiss Nuclear Phase-out Scenario Variants	Switzerland	2035	Total discounted energy system cost
4	Bottom-up Sustainability Analysis of the World Energy Scenarios	World	2010-60	Total discounted energy system cost
5	External Costs of Human Health Damages from Air Pollution in the World Energy Scenarios	World	2010-60	Total discounted energy system cost
6	Optimisation of Multiple Objectives for the Global Energy System	World	2010-60	Total discounted energy system cost CO_2 emissions Energy carrier imports

3. Multi-criteria Sustainability Analysis of Swiss Nuclear Phase-out Scenario Variants

Switzerland expects a transformation of its energy system in the coming decades: On the one hand, Switzerland has decided to contribute to the mitigation of climate change and the international efforts to limit the global temperature rise to 2°C by reducing its domestic GHG emissions by 20% by 2020 compared to the 1990 level. The emission reduction target is described in the law on CO_2 emissions[3] and it is likely to be tightened further[4]. On the other hand, the Swiss Federal Council decided in 2011 that Switzerland will gradually phase-out domestic nuclear power

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[3] Federal Act on the Reduction of CO_2 Emissions (CO_2 Act) [51].

[4] The advisory body of the Swiss federal council in climate change issues (OcCC) recommended a more stringent Swiss GHG emission reduction target of 60% by 2050 [52]. This recommendation has been tightened to minus 80-95% by 2050 [53].

generation [54][5]. Assuming a 50 year lifetime for the reactors[6] and constant electricity demand, about 40% of the Swiss electricity supply must be replaced by either additional domestic power generation or electricity imports in the year 2035.

The Swiss energy system transformation includes the replacement of nuclear power by other low-carbon electricity generation such as renewable energies and possibly CCS technologies. But, in order to reach the ambitious GHG emission reduction target, emission reductions in the other energy sectors are also foreseen, for example with biomass, geothermal and solar heating systems, alternative transportation fuels and energy efficiency measures. Furthermore, the Swiss Federal Council also has other energy policy targets such as preventing human health and ecosystem damages and assuring security and affordability of the energy supply [55]. In order to analyse possible transformation pathways for the Swiss energy system in view of sustainability and under the new boundary conditions described above, a bottom-up ex-post multi-criteria analysis on end-use technology level is conducted for the year 2035, when nuclear power is expected to be phased out[6].

3.1. Literature review

Bottom-up ex-post multi-criteria analysis of energy system scenarios has been applied before (Appendix, Table 24). This study complements the existing literature by combining the following aspects: the whole energy system is encompassed; an established full-scale energy system model is used for the quantification of future scenarios; the case study explicitly addresses Switzerland; an estimation of the sustainability impacts of energy saving measures in the residential sector is made; all indicators are quantified based on a life-cycle perspective; the issue of double-counting impacts related to the use of LCA-based indicators is discussed; and the sustainability impacts of the deployment of CCS technology are explicitly addressed.

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[5] There has been a referendum on the new Swiss energy policy and on the nuclear phase-out in particular.

[6] The safety-related lifetime is subject to continuous evaluation by the authorities and thus may be shorter or longer than 50 years. The economic lifetime is decided by the utilities operating the nuclear plants.

3.2. Method and data

3.2.1. Scenario definition

Three variants of the Swiss nuclear phase-out scenario from Weidmann [11] are selected for this case study. They reflect different policies regarding the reduction of GHG emissions and the availability of the low-carbon technology CCS according to Table 2.

Table 2: Description of the three scenario variants based on their key policy assumptions

Scenario variant	Climate policy	CCS technology
Ref	no climate policy (CO_2 law is ignored)	not available
Clim	CO_2 emission reduction target of 20% by 2020 and more stringent 40% by 2035 compared to the emission level of 1990 This target is an interpolation of the 20% reduction in 2020 [51] and the 60% reduction target for the year 2050 which was recommended by OcCC [52] for reaching the 2°C target.	not available
Clim+CCS	same as in *Clim*	available from 2030

3.2.2. Scenario quantification

The scenario quantification is carried out with the most recent version of the SMM as described in Section 2.1.1 and in Weidmann [11]. The energy service demands in the residential sector are provided by electricity and heat. The heat demand for hot water and space heating may be supplied by biomass, oil, district heat, natural gas, electricity, and solar energy, while the heat for cooking may be supplied by electricity, natural gas and wood (Appendix, Table 27). The hot water demanded for washing machines and dish washers is included in the district heating demand. The SMM's commercial sector is also defined by its heating and electricity demand. The heating demand is supplied by the same fuels as in the residential sector (Appendix, Table 27). The industrial sector of the SMM demands electricity, process heat and space heating. The process heat demands are supplied by coal, oil, natural gas, district heat and biomass and waste (Appendix, Table 28). The transport sector of the SMM encompasses passenger and freight transport on rail, on the road and in the air. It is fuelled by kerosene, natural gas, diesel, gasoline, electricity and hydrogen (Appendix, Table 28).

The scenario quantification with the SMM provides end-use energy demands per end-use sector (Figure 17) and domestic power generation mixes (Figure 18).

The total end-use energy demand for all scenario variants consists of similar contributions from the residential, commercial and industrial sectors, while the share of the transport sector is larger. In the *Ref* variant, the two major contributors to the residential end-use energy demand are electricity and natural gas, and energy savings are also substantial. In the two climate scenario variants, the amount of electricity consumed is still high but the large natural gas share of the *Ref* case is replaced by district heating, solar energy and more energy savings, more pronounced in the *Clim* than in the *Clim+CCS* variant. The commercial end-use energy demand is mainly supplied by electricity, natural gas and biomass. For the two climate scenario variants, there is a shift from electricity to biomass compared to the *Ref* variant. All other energy carriers play a minor role in the commercial sector.

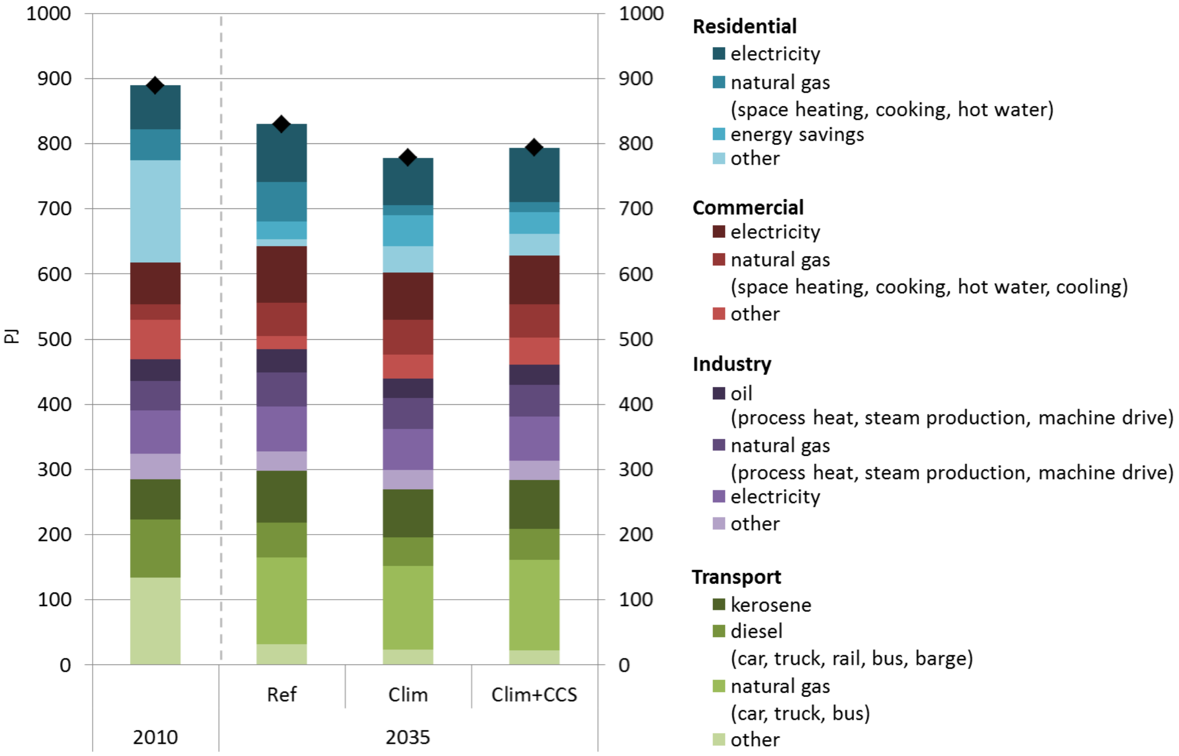

Figure 17: Swiss end-use energy demands per end-use sector for the three scenario variants in 2035 as quantified with the SMM

The industrial end-use energy demand is mainly satisfied by oil, natural gas and electricity, while the minor coal contribution is the same in all three variants. The absolute contributions of all other energy carriers drop in the two climate scenario variants compared to *Ref*, except for the contribution of district heating, which is slightly higher. The transport sector heavily relies on fossil fuels, namely jet kerosene, diesel, gasoline and natural gas. Compared to the *Clim* variant, the availability of CCS (and the resulting lower CO_2 emissions in the electricity sector) allows for higher fossil fuel use in the transport sector while still meeting the CO_2 target. Battery electric transport plays a minor role and is most important in the *Clim* variant. Hydrogen fuel cell-based transport is only present in the two climate scenario variants, when the climate target leads to a fuel shift from diesel and gasoline cars to battery electric, hydrogen fuel cell and natural gas cars (the latter only in the *Clim+CCS* variant).

The phased-out nuclear power is mainly replaced with natural gas-fired power generation (*Ref*), renewable power generation (*Clim*) and renewable energies and natural gas-fired generation with CCS (*Clim+CCS*), while the contribution of hydro power is similar in all three scenario variants (Figure 18). The *Clim* scenario variant has lower overall electricity production compared to *Ref* due to the constraints on renewable energy production and high-carbon power generation. To meet the stringent CO_2 target with the required (comparatively small) natural gas power, fossil fuels in other sectors must be replaced, e.g. fossil-fuelled passenger cars are replaced with hydrogen fuel cell and battery electric cars. Overall, the CO_2 emissions of the *Clim* scenario variant are shifted from the residential and transport to the power sector.

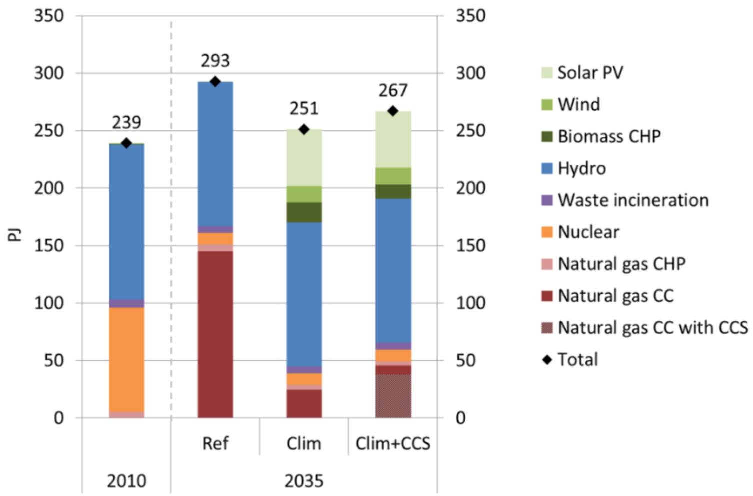

Figure 18: Swiss domestic power generation[7] in 2035 per scenario variant as quantified with the SMM. PV = photovoltaics, CHP = combined heat and power, CC = combined cycle, CCS = carbon capture and storage

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[7] In spite of the nuclear phase-out that is considered in all three scenario variants, nuclear energy is present in the quantification results for 2035. The SMM considers five-year time periods, i.e. reference year is the temporal centre of

The availability of the CCS technology in the Swiss power sector (*Clim+CCS*) allows avoiding (more expensive) power generation from renewable energy sources and a higher overall electricity production compared to *Clim*, while still reaching the GHG emission target. Given the lower CO_2 emissions in the power sector in this case, expensive CO_2 mitigation such as efficiency measures in the transport (hydrogen fuel cell and battery electric cars) and residential (district heating, heat pumps and energy savings) can be partially or mostly avoided. The lower deployment of efficiency measures in the *Clim+CCS* scenario variant results in higher end-use energy demand compared to the *Clim* variant.

3.2.3. Criteria selection and indicator quantification

The criteria and corresponding indicators for the comparison of the sustainability of the three scenario variants are an adjusted and simplified set derived from the one presented in Volkart et al. [39]. The criteria represent all three dimensions of sustainability (Section 1.1) as well as security of supply, and they represent the aspects which are considered important for the new Swiss energy strategy by the Swiss Federal Council [56]. They are described in Table 3 and Table 4. In total, 27 end-use energy demands are quantified with the SMM for each scenario variant. For this case study, they are assumed to be supplied by 43 end-use technologies according to Appendix, Table 27 and Table 28. The specific indicator values for each of these 43 end-use technologies are quantified and listed in Appendix, Table 32 to Table 35.

The quantification of the LCA-based specific indicator value requires the matching of the 43 end-use technologies with corresponding LCI datasets. The datasets are selected from the ecoinvent background LCI database [57] and previous work at PSI according to Appendix, Table 27 and Table 28. Technologies such as space heating, process heat, cooking, hot water and conventional technologies are assumed to be mature and thus unchanged in 2035. The 2030 LCI datasets of Bauer et al. [58] are assumed to be representative for 2035, while the 2035 values for technologies described in Volkart et al. [59] are calculated from a linear interpolation of the results for 2025 and 2050.

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a time period starting in July 2033 and ending in June 2037. So from 2030 to 2035 there is still some nuclear power generation expected in Switzerland.

Table 3: Environmental and economic criteria and indicator hierarchies and definitions. LCA = life-cycle assessment, SMM = Swiss MARKAL Model, RA = risk assessment, ExpJ = expert judgement.

CATEGORY	Sub-category	Indicator	Unit	Optimal	Method	Description
ENVIRONMENT	Resources	**Metal depletion**	kg Fe-eq/ MJ	min	LCA	Total use of metals in the entire energy chain (LCA), expressed in iron (Fe)-equivalents (considers specific scarcity of the individual metals in relation to the scarcity of the reference metal iron); ReCiPe method [60]
		Fossil energy depletion	MJ/MJ	min	LCA	Total amount of coal, peat, natural gas and oil used in the entire energy chain (LCA) in terms of primary energy equivalents of the consumed fossil energy carriers
	Ecosystems	**Ecosystem damages**	species*y/ MJ	min	LCA	Impacts on ecosystems expressed as loss of species in the entire energy chain (LCA) due to terrestrial ecotoxicity and acidification, freshwater ecotoxicity and eutrophication, marine ecotoxicity and land use; not site specific; excl. climate change effects; ReCiPe method [60]
	Climate	**Greenhouse gas emissions**	kg CO_2-eq/ MJ	min	LCA	Total GHG emissions in the entire energy chain (LCA), expressed in terms of CO_2-equivalents; representing all potential negative impacts of climate change; IPCC 2007 method [61]
ECONOMY	Financing	**Investment cost**	M$	min	SMM	Annualised investment cost
	Operation	**O&M cost**	M$	min	SMM	Annual total operation and maintenance (O&M) cost

Table 4: Social and security of supply criteria and indicator hierarchies and definitions. LCA = life-cycle assessment, SMM = Swiss MARKAL Model, RA = risk assessment, ExpJ = expert judgement.

CATEGORY	Sub-category	Indicator	Unit	Optimal	Method	Description
SOCIETY	Normal operation	**Human health damages**	DALY/MJ	min	LCA	Impacts on human health in the entire energy chain (LCA) expressed as Disability adjusted life years (DALY) due to human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation; not site specific; excl. climate change effects; ReCiPe method [60]
	Severe accidents	**Expected mortality**	fatalities/ (TJ_{final}*y)	min	RA	Expected number of fatalities in severe accidents in the energy sector including 5 or more dead persons; based on historical accidents reported in the ENSAD. The indicator is expressed per TJ of fuel used in the end-use sector and comprises all steps of the energy chain from the extraction via transport to conversion. The estimates do not include road traffic fatalities.
	Waste	**Chemical waste**	m^3/MJ	min	LCA	Total volume occupied by special chemical wastes requiring storage in underground repositories for the entire energy chain (LCA); impacts on human health and ecosystems are included in the respective indicators; cumulative life-cycle amounts of "Volume occupied, underground deposit"
	Social stability	**Conflict potential**	Ordinal scale	min	ExpJ	Potential of technology induced conflicts; aspects considered based on historic evidence: willingness of NGOs and other citizen movements to act against realisation; mobilisation potential; conflicts on local/regional/national/international level; necessity of participative decision-making processes; includes perceived risks, noise, aesthetics, landscape, and conservation.
SECURITY OF SUPPLY	Resource supply	**Resource autonomy of the supply chain**	Ordinal scale	max	ExpJ	The indicator measures the resource autonomy of the technology. Better technologies are based on a domestic and/or storable resource, whereas worse technologies depend on a foreign and/or non-storable resource.
	Reliability	**Resource variability**	Ordinal scale	max	ExpJ	This indicator corresponds to the "dispatchability" in power generation. Less variable technologies function independently of temporarily varying weather and time of the day, while more variable technologies are heavily dependent on the weather conditions and the time of the day.

The SMM quantifies the electricity production mix for each scenario variant for 2035. For the quantification of the indicator values for electricity however the Swiss supply mix, which also considers electricity imports according to “Modell 2” in Ménard et al. [62], is used. The imported electricity is assumed to correspond to the European electricity mix according to Blesl et al. [63]. The LCI datasets used to quantify the specific indicator values for the electricity generation technologies are presented in Appendix, Table 29 and Table 30. Appendix, Table 36 and Table 37 list the specific indicator values for electricity mixes which are not based on LCA.

The SMM also quantifies space heating savings in the residential sector based on marginal cost curves for different types of houses as presented in Weidmann [11]. This case study provides estimates for the specific indicator values of these energy saving measures. Using information on U-values[8], the renovation rates for single- [64] and multi-family [65] houses[9], the shares of the insulation materials in the Swiss construction sector [66] and the material properties [57, 64, 65], the required number of windows and the amounts of insulation material to achieve the energy savings in each scenario variant are quantified. Together with the corresponding LCI datasets, the estimates are presented in Appendix, Table 31.

The quantification of the LCA-based specific indicator values considers the whole energy chains, consistent system boundaries and background data by using the LCI database ecoinvent v2.2 [57]. The temporal consistency of fore- and background data is ensured by reflecting technological progress in selected processes in the energy chains and in other economic sectors by 2035 according to Volkart et al. [59] after ESU-services/IFEU [67]. The LCA calculations are carried out according to ISO standards [30] using the SimaPro software version 7.3.3 [68] with the LCIA methods as implemented in this version.

The expected fatalities in severe accidents in the energy sectors are derived from the Energy-related Severe Accident Database (ENSAD)[10]. The economic indicators are extracted from the SMM, and expert judgement is applied to quantify the remaining specific indicator values.

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[8] The U-value is the overall heat transfer coefficient that describes how well a building element (e.g. walls or windows) conducts heat from the inside to the outside. It is expressed as the rate of transfer of heat (in W) per m^2 of a structure and temperature difference (in K) across the structure.

[9] Values for the time period 2030 to 2040 for houses built between 1985 and 2000 were used.

[10] The Energy-related Severe Accident Database (ENSAD) comprehensively covers energy-related accidents from all world regions. It is built on historical experience, probabilistic safety assessment (PSA) and hybrid approaches, which combine available data with modelling and expert judgement [69].

After the quantification of the specific indicator values for all 43 end-use technologies, they are aggregated to the twelve total indicator values for each scenario variant. The LCA-based specific indicator values are multiplied with the end-use energy demand and summed over all end-use technologies. For indicators based on risk assessment and expert judgment, the specific indicator values are weighted with the corresponding end-use energy demands and summed over all end-use technologies.

3.3. Results

There are two types of results presented for this case study: First, a comparison of the total indicator values of the three scenario variants is carried out. Second, a full MCDA is conducted in order to create rankings of the scenarios variants under different weighting profiles.

The total indicator values derived from the indicator quantification are presented in Appendix, Table 38. The normalised total indicator values are displayed in Figure 19. The total indicator values for the *Ref* variant are either best or worst among the three scenario variants, while the total indicator values for *Clim+CCS* are mostly between the two other values. The performance of the two climate scenario variants regarding fossil energy depletion, GHG emissions, expected mortality in severe accidents, conflict potential, and resource autonomy of the supply chain is better than the one of the *Ref* variant. For chemical waste and resource autonomy of the supply chain the total indicator values differ substantially between the scenario variants while the differences for others are small (O&M costs, conflict potential and resource variability).

The contributions of the end-use energy demands to the total end-use energy demand and the total indicator values are presented in Table 5 and Table 6 for all scenario variants. Usually, high shares in the total end-use energy demand lead to high shares in the total indicator values (underlined values; Table 5 and Table 6). Green cells in Table 5 and Table 6 indicate end-use energy demands that contribute less than their corresponding shares in the total end-use energy demand (e.g. district heating and energy savings in the residential sector, district heating in the commercial sector and renewables/waste and district heating in industrial sector). In contrast, red cells in Table 5 and indicate end-use energy demands which contribute more than their corresponding shares in the total end-use energy demand (e.g. biomass and wood pellets in the residential sector, coal in industry and diesel, gasoline and natural gas in the transport sector). Also electricity contributes substantially to the total end-use energy demands and many indicator values. The results presented in Table 5 and Table 6 are discussed in more detail in the subsequent paragraphs.

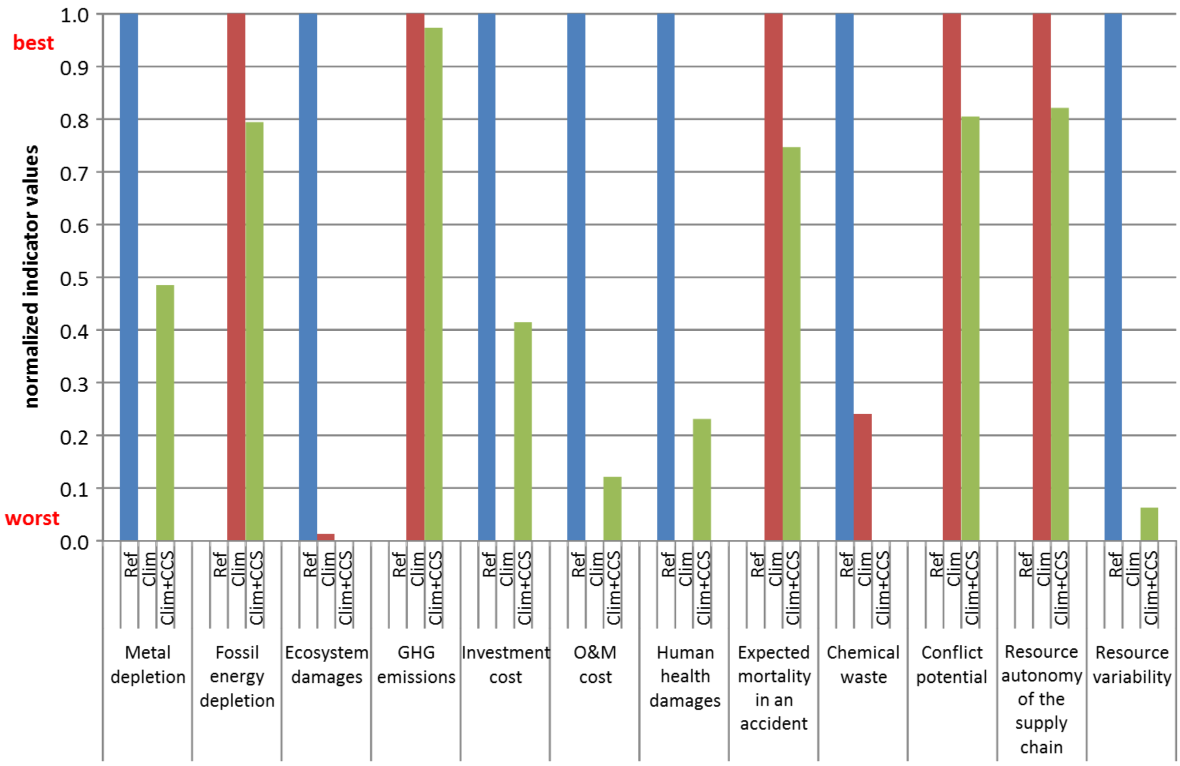


Figure 19: Normalised total indicator values for the three scenario variants. Zero indicates the worst performer and one indicates the best performer among the scenario variants for each indicator. GHG = greenhouse gas, O&M = operation & maintenance

LCA-based indicator values

The *metal depletion* indicator values are driven by the electricity supply (copper in the transmission and distribution network) and transport technologies (metals in railway tracks as well as in vehicles). The contributions of diesel and gasoline vehicles in the *Ref* variant are replaced by the ones from battery electric and hydrogen fuel cell vehicles in the *Clim(+CCS)* variants.

The major contributors to *fossil fuel depletion* are electricity (natural gas-fired power generation), residential, commercial and industrial appliances (natural gas and oil) and transport (kerosene, diesel and natural gas). The contribution of electricity is higher in the *Ref* variant than in the others due to more natural gas-fired power generation.

Table 5: Absolute end-use energy demands in the residential and commercial sectors per scenario variant, their relative contribution to the total end-use energy demand and relative contributions of the end-use energy demands to the total indicator values. Contributions of ≥ 5% are underlined. Higher/equal/lower shares in the total indicator values than indicated by respective shares in the total end-use energy demand are indicated in red/orange/green colour.

		End-use energy demand [PJ]			Metal depletion			Fossil energy depletion			Ecosystem damages			Greenhouse gas emissions			Human health damages			Chemical waste		
Sector		Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS
Residential	**Biomass**	2.24 (0%)	2.00 (0%)	3.44 (0%)	0%	0%	0%	0%	0%	0%	2%	3%	3%	0%	0%	0%	1%	1%	1%	0%	0%	0%
	Light oil	0.00 (0%)	0.00 (0%)	0.04 (0%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Electricity	88.66 (11%)	72.04 (9%)	83.01 (10%)	22%	21%	21%	11%	7%	7%	6%	7%	7%	11%	4%	4%	11%	12%	12%	11%	18%	18%
	District heat	5.89 (1%)	25.41 (3%)	18.72 (2%)	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	1%	1%	0%	0%	0%
	Natural gas	60.23 (7%)	16.33 (2%)	15.33 (2%)	2%	0%	0%	8%	3%	3%	2%	0%	0%	7%	3%	3%	2%	0%	0%	7%	1%	1%
	Wood pellets	2.15 (0%)	1.86 (0%)	1.41 (0%)	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Solar energy	0.87 (0%)	12.00 (2%)	9.89 (1%)	0%	3%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	3%	3%
	Energy savings	27.49 (3%)	46.80 (6%)	33.45 (4%)	2%	2%	2%	1%	1%	1%	1%	1%	1%	0%	1%	1%	2%	2%	2%	1%	1%	1%
Commercial	**Biomass**	13.09 (2%)	29.81 (4%)	34.17 (4%)	0%	1%	1%	0%	0%	0%	13%	27%	27%	0%	0%	0%	3%	6%	6%	0%	1%	1%
	Light oil	1.97 (0%)	2.09 (0%)	1.93 (0%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Electricity	86.66 (10%)	72.02 (9%)	74.93 (9%)	21%	19%	19%	11%	6%	6%	5%	7%	7%	10%	4%	4%	11%	11%	11%	10%	16%	16%
	District heat	4.24 (1%)	4.69 (1%)	4.94 (1%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Heavy fuel oil	0.46 (0%)	0.16 (0%)	0.19 (0%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Natural gas	50.69 (6%)	53.52 (7%)	51.00 (6%)	1%	1%	1%	6%	9%	9%	2%	1%	1%	6%	9%	9%	1%	1%	1%	5%	4%	4%
	Solar energy	0.00 (0%)	0.00 (0%)	0.00 (0%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 6: Absolute end-use energy demands in the industrial and transport sectors per scenario variant, their relative contribution to the total end-use energy demand and relative contributions of the end-use energy demands to the total indicator values. Contributions of ≥ 5% are underlined. Higher/equal/lower shares in the total indicator values than indicated by respective shares in the total end-use energy demand are indicated in red/orange/green colour.

	Indicator	End-use energy demand [PJ]			Metal depletion			Fossil energy depletion			Ecosystem damages			Greenhouse gas emissions			Human health damages			Chemical waste		
Sector		Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS	Ref	Clim	Clim+ CCS
Industry	Coal	2.40 (0%)	2.40 (0%)	2.40 (0%)	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟧 0%	🟥 1%	🟥 1%	🟥 1%	🟥 1%	🟥 1%	🟧 0%	🟧 0%	🟧 0%
	Oil products	36.19 (6%)	29.92 (4%)	31.40 (4%)	🟩 0%	🟩 0%	🟩 0%	🟩 5%	🟥 6%	🟥 6%	🟩 2%	🟩 1%	🟩 1%	🟧 6%	🟥 7%	🟥 7%	🟥 8%	🟥 8%	🟥 6%	🟩 0%	🟩 0%	🟩 0%
	Natural gas	52.65 (4%)	46.95 (6%)	49.02 (6%)	🟩 1%	🟩 1%	🟩 1%	🟥 7%	🟥 9%	🟥 8%	🟩 2%	🟩 1%	🟩 1%	🟥 6%	🟥 8%	🟥 8%	🟩 2%	🟩 2%	🟩 1%	🟥 5%	🟩 4%	🟩 4%
	Electricity	68.60 (8%)	63.42 (8%)	66.81 (8%)	🟩 4%	🟩 5%	🟩 6%	🟧 8%	🟩 3%	🟩 5%	🟩 3%	🟩 6%	🟩 5%	🟩 7%	🟩 3%	🟩 3%	🟩 4%	🟩 4%	🟩 5%	🟩 7%	🟥 11%	🟥 13%
	Renewables / Waste	21.68 (3%)	19.61 (3%)	20.45 (3%)	🟩 1%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 1%	🟩 1%	🟧 3%	🟧 3%	🟧 3%	🟩 1%	🟩 0%	🟩 0%
	District heat	5.71 (1%)	6.93 (1%)	7.04 (1%)	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%	🟩 0%
Transport	Jet kerosene	78.77 (9%)	73.62 (9%)	75.08 (9%)	🟩 1%	🟩 1%	🟩 1%	🟧 9%	🟥 13%	🟥 12%	🟧 9%	🟩 6%	🟩 6%	🟥 11%	🟥 15%	🟥 15%	🟥 12%	🟥 12%	🟥 11%	🟩 3%	🟩 2%	🟩 2%
	Diesel	53.72 (6%)	44.46 (6%)	47.92 (6%)	🟥 11%	🟥 7%	🟥 9%	🟥 8%	🟥 10%	🟥 10%	🟥 13%	🟥 8%	🟥 9%	🟥 9%	🟥 10%	🟥 11%	🟥 15%	🟥 15%	🟥 13%	🟥 9%	🟧 6%	🟧 6%
	Electricity	10.93 (1%)	13.62 (2%)	11.43 (1%)	🟥 3%	🟥 15%	🟥 5%	🟩 0%	🟩 1%	🟧 1%	🟥 3%	🟥 5%	🟥 3%	🟩 0%	🟩 1%	🟧 1%	🟥 2%	🟧 2%	🟥 3%	🟥 2%	🟥 7%	🟥 3%
	Gasoline	21.00 (3%)	3.91 (1%)	9.61 (1%)	🟥 4%	🟧 1%	🟥 2%	🟧 3%	🟧 1%	🟥 2%	🟥 5%	🟧 1%	🟥 2%	🟧 3%	🟧 1%	🟥 2%	🟥 4%	🟥 4%	🟥 2%	🟥 4%	🟧 1%	🟧 1%
	Natural gas	133.4 (16%)	128.0 (16%)	138.7 (17%)	🟥 28%	🟥 22%	🟥 27%	🟥 22%	🟥 31%	🟥 30%	🟥 28%	🟥 21%	🟥 23%	🟥 20%	🟥 28%	🟥 29%	🟥 19%	🟥 19%	🟥 18%	🟥 35%	🟥 27%	🟥 27%
	Hydrogen	0.00 (0%)	6.51 (1%)	1.42 (0%)	🟧 0%	🟥 7%	🟥 2%	🟧 0%	🟧 1%	🟧 0%	🟧 0%	🟥 3%	🟥 1%	🟧 0%	🟧 1%	🟧 0%	🟧 0%	🟩 0%	🟥 1%	🟧 0%	🟥 3%	🟥 1%
Total		830 (100%)	778 (100%)	794 (100%)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

The contributions of electricity (land use for natural gas production and transport for power generation and land use for wood cultivation for biomass power generation), biomass heating in the commercial sector (land use for wood cultivation), kerosene-, gasoline-, diesel- and natural gas-fuelled transport (land use in crude oil and natural gas extraction and land use for roads), and electricity-based transport (land use for operation of rail tracks and roads) dominate the *ecosystem damages*. Due to additional deployment of biomass power generation in the two climate scenario variants, their ecosystem damages related to electricity are higher than in the *Ref* variant.

The *GHG emissions* are driven by the direct emissions from operation of natural gas and oil technologies in residential, commercial and industrial sectors as well as fossil-fuelled (kerosene, diesel and natural gas) transport technologies. Due to the high share of natural gas-fired power generation in the *Ref* scenario variant, electricity contributes more than 5% to the total GHG emissions. In the two *Clim* variants, natural gas in the residential sector is replaced with district heating, solar energy and more energy savings.

In all three scenario variants, the majority of the *human health damages* can be allocated to electricity (copper production for the transmission and distribution networks and wood power generation), biomass heating (direct emissions and heavy metal emissions from ash disposal), oil heating (direct emissions from operation), transport fuelled by kerosene and diesel (direct emissions from operation), and natural gas-based transport (metal production for vehicles, direct emissions from operation).

Electricity (waste from natural gas production and power generation and waste from PV cell production), natural gas heating (waste from natural gas production) as well as diesel (waste from metal production for vehicles), natural gas (waste from metal production and from natural gas production) and battery electric vehicles (waste from metal production for vehicles and railway tracks) are responsible for the majority of the *chemical waste*. The electricity contribution is lower in *Ref* variant than in the *Clim* scenario variants.

Cost indicators

As solar PV electricity generation technologies (compared to conventional fossil-based), hydrogen-fuelled and battery electric cars (compared to gasoline and diesel), and energy efficiency measures in the building sector have relatively high *investment costs,* the two climate scenario variants perform worse than the *Ref* case. Furthermore, the use of O&M cost-intensive hydrogen cars in the two climate scenarios and the higher O&M cost of gas combined-cycle technologies with CCS (compared to natural gas combined cycle plants without CCS) in the two climate scenario variants leads to higher O&M costs compared to the *Ref* scenario variant despite the low O&M costs of solar and wind energy.

Other indicators

As opposed to the cost- and LCA-based indicators, the residual indicators are driven by their weighted contributions to the end-use energy demands. Hence, the presentation of percentage contributions such as the ones in Table 5 and Table 6 is omitted, but the subsequent paragraphs describe the insights regarding the residual indicators.

Solar thermal energy and energy savings have a very low *expected mortality in severe accidents* as they do not have energy chains. For the biomass and waste energy chains and particularly for the fossil energy chains, the specific indicator values are high. Due to the high share of fossil fuels in all sectors, the *Ref* scenario variant has high expected mortality in severe accidents in the energy chains compared to the two climate scenario variants.

The societal *conflict potential* is worst for coal and nuclear power generation as well as power generation with CCS. It is very low for solar and waste energy and energy savings. With the deployment of more renewable energies and energy savings in the two climate scenario variants, they perform better than *Ref* case regarding societal conflicts.

Fossil fuels have the worst *resource autonomy of the supply chain* in this Swiss case study. On the contrary, domestic biomass and hydrogen energy, waste and solar energy and energy savings perform best for this indicator. As the *Ref* and the *Clim+CCS* variants have higher fossil fuel shares, the *Clim* variant with more renewable energies with full resource autonomy performs better.

The *Clim* case includes more solar energy than the other two scenario variants. As the *resource variability* of solar energy (and also wind energy) is high, the *Clim* variant performs worse than the variants which have more fossil fuels, biomass and energy savings.

The second type of results, i.e. the results for the full MCDA, is based on the total indicator values as described above and includes subjective weighting of the criteria. This case study does not include stakeholder interaction. Thus, a set of three artificial weighting profiles is defined, which represents possible subjective preferences (Table 7).

The first profile puts 15% weight each on the indicators which are relevant for fossil energy use, namely fossil energy depletion, GHG emissions, expected mortality in severe accidents in the energy chains, conflict potential and resource autonomy. The remaining criteria are weighted with 3.6% each. Profile 2 emphasises the strengths of CCS technologies compared to renewable technologies with 15% weight each on metal depletion, investment cost, O&M cost, human health damages and resource variability. Again, the remaining criteria are weighted with 3.6% each. The third profile represents one possible interpretation of the goals of the Swiss government, which puts strong emphasis on GHG emission (climate policy) and societal conflict potential (reason for the nuclear phase-out), but also considers the reduction of fossil energy use, affordability, and resource autonomy and reliability as being important [55]. This is translated into 20% weight on GHG emissions and conflict potential, 10% weight on the other mentioned aspects and 0% weight the remaining criteria.

Table 7: MCDA weighting profiles

Indicator	Unit	Profile 1	Profile 2	Profile 3
Metal depletion	kg Fe-eq/ MJ	3.6%	15.0%	0.0%
Fossil energy depletion	MJ/MJ	15.0%	3.6%	10.0%
Ecosystem damages	species*y/ MJ	3.6%	3.6%	10.0%
Greenhouse gas emissions	kg CO_2-eq/ MJ	15.0%	3.6%	20.0%
Investment cost	M$	3.6%	15.0%	10.0%
O&M cost	M$	3.6%	15.0%	10.0%
Human health damages	DALY/MJ	3.6%	15.0%	10.0%
Expected mortality	fatalities/ (TJ_{final}*y)	15.0%	3.6%	0.0%
Chemical waste	m^3/MJ	3.6%	3.6%	0.0%
Conflict potential	Ordinal scale	15.0%	3.6%	20.0%
Resource autonomy of the supply chain	Ordinal scale	15.0%	3.6%	5.0%
Resource variability	Ordinal scale	3.6%	15.0%	5.0%

The MCDA results are calculated based on min-max normalisation, i.e. by linearly scaling the indicator values between the worst and the best performer for each indicator. This normalisation induces a loss of proportionality. There are other normalisation methods, e.g. the ones mentioned in Rowley et al. [70], but – as this case study compares indicators for which the zero is not a realistic indicator value and for which the absolute maximum is not known – min-max normalisation is applied. Further, the case study focuses on the differences between the scenario variants, i.e. the range of actual performances is of interest and no theoretical range. The WSA is selected for weighting and aggregating the normalised indicator values. This algorithm is commonly used in MCDA studies [71] because it provides a transparent way to create rankings, i.e. it allows stakeholders to clearly understand the impact of each weighting set. This is particularly important in applications for policy decisions with (political) stakeholders. There are other weighting algorithms, which are for example described in Granat et al. [72], Huang et al. [73], Steele et al. [74] and Triantaphyllou [71] each with specific advantages but also disadvantages such as mathematical complexity and thus low understandability. The MCDA results are presented in Figure 20.

Profile 1 favours the *Clim* scenario variant, but it also indicates adverse side-effects of the climate policy related to metal depletion, ecosystem damages, investment and O&M costs, human health damages and resource variability. Profile 2 leads to a preference for *Clim+CCS* over *Clim*. While there are benefits related to metal depletion, investment and O&M costs, human health damages and resource variability, *Clim+CCS* performs worse regarding fossil energy depletion, ecosystem damages, GHG emissions, expected mortality in severe accidents, chemical waste, conflict potential and resource autonomy of the supply chain. Profile 3, which represents one interpretation of the goals of the Swiss government, gives the best results for the *Clim* scenario variant. Compared to the other two variants, it has lower fossil energy depletion, lower GHG emissions, lower conflict potential and higher resource autonomy.

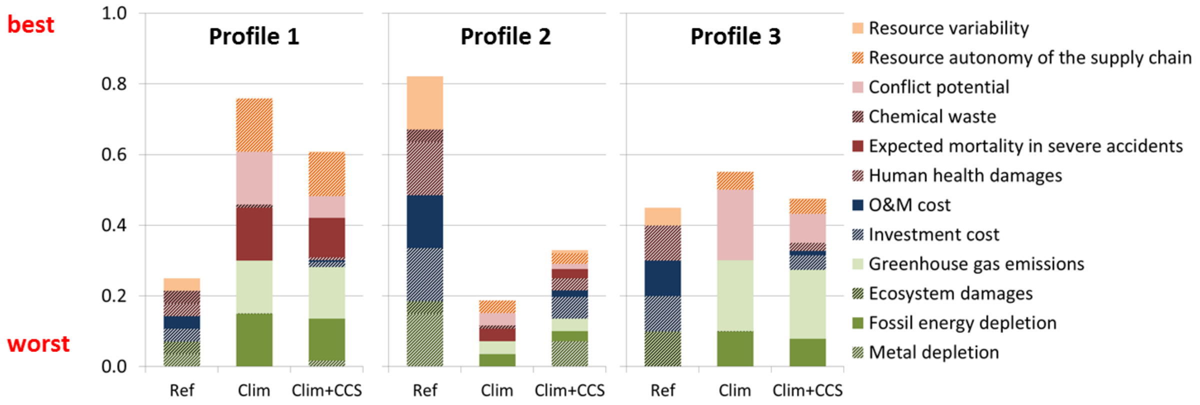


Figure 20: MCDA results for the three weighting profiles presented in Table 7

3.4. Discussion

3.4.1. Effects of the Swiss climate policy

Switzerland is expected to gain the following co-benefits from its climate policy: The deployment of more renewable energies leads to a reduction in the use of fossil resources (-34%) and fatalities in the fossil fuel chains (-13%). The deployment of well-accepted solar and waste energy and energy savings instead of natural gas technologies leads to less societal conflicts. The resource autonomy of Switzerland is enhanced with the domestic implementation of energy technologies based biomass and biogenic hydrogen, waste and solar energy, and energy savings.

The drawbacks of the Swiss climate policy are found to be threefold: First, the investment costs of low-carbon technologies are expected to be higher than the conventional ones in 2035 (+21%). Second, the PV cell production and the waste from metal production for vehicles lead to increased chemical waste production (+30%). Third, the intermittent solar energy increases the overall resource variability of the climate scenario variants.

3.4.2. Effects of CCS availability

If CCS technologies become available, the following benefits are expected: As expensive CO_2 mitigation options (e.g. energy savings, hydrogen fuel cell and battery electric cars) can be avoided, the investment costs are lower (-7%). The same holds true for the O&M costs which are lower as some cost-intensive low-carbon end-use technologies such as hydrogen cars can be avoided (-0.4%). The resource variability is reduced due to less intermittent energies in the power sector.

The drawbacks of the deployment of CCS technologies are that less fossil resources are preserved (+11%) and fewer fatalities in the fossil fuel chains can be avoided (+4%) compared to the *Clim* variant, which is less based on natural gas. Furthermore, societal conflicts are expected as CO_2 storage as part of the CCS chain can trigger public opposition. Despite the decrease of chemical waste generation from PV cell production and from metal production for vehicles, the overall amount of chemical waste is higher due to the wastes from natural gas production and chemical CO_2 capture (+7%). Because of the increased use of imported energy resources such as natural gas (power generation) and oil (transport sector), Switzerland becomes less resource autonomous.

3.4.3. General insights from the case study

Compared to the *Ref* scenario, the deployment of CCS technologies leads to less fossil energy depletion, GHG emissions, mortality in accidents, conflict potential and resource autonomy. Compared to a climate scenario variant without CCS, the deployment of CCS technologies under a climate policy leads to less metal depletion, costs, health damages from normal operation and resource variability. Except for GHG emissions, the *Clim+CCS* scenario has the co-benefits and drawbacks of a more fossil fuel-based energy system compared to the climate scenario variant without CCS.

Both *Ref* and *Clim* scenario variants have clear strengths and weaknesses, while the total indicator values of the *Clim+CCS* variant usually lie between. The indicator values change more when the climate policy is introduced than when CCS becomes available. Fossil transport fuels and the composition of the Swiss power supply are found to contribute substantially to many of the indicator values, i.e. the substitution of fossil fuels and electricity saving measures are associated with co-benefits.

3.4.4. Data quality and limitations

The case study for Switzerland is subject to some specific uncertainties and limitations in addition to the generic uncertainties listed in Section 2.3.2.2. First, the set of twelve indicators is limited compared to the total number of possibly relevant indicators. Second, the case study was conducted without stakeholder interaction, i.e. the collection of a significant sample of real opinions and preferences was out of the scope of this thesis and artificial weighting profiles were used for the MCDA. Third, some impacts (environmental and human health damages, fatalities in accidents, chemical waste, etc.) occur abroad, e.g. impacts from energy in the natural gas energy chain. Adding the geographic location of the impacts was beyond the scope of the case study.

Some indicators are found to have uncertainties due to the underlying methodology: some indicators were defined with expert judgement and for the accident risk indicators historic fatality rates are applied to a future point in time. Similarly, the LCI datasets of mature end-use technologies are assumed to be representative for the year of the case study. This neglects potential improvements (or worsening) with respect to the chosen indicators by 2035. Only electricity mixes and selected processes in the energy chains and in other economic sectors that are considered to be important in terms of contributions to cumulative LCA results are adjusted. The rest of the datasets in the ecoinvent background database [57] are assumed to still be representative for the year of the case study. This neglects potential improvements (or worsening) with regard to the impacts.

The direct atmospheric emissions data of the selected biomass heating LCI datasets from the ecoinvent database [57] have recently been reviewed and adjusted to current technology standards. Thus, there is some overestimation of the human health effects for the biomass end-use technologies in the case study. The quantification of metal depletion decisively depends on recycling rates while the selected LCA approach and the LCI data used reflect today's average recycling rates in a rough way. Furthermore, material balances are not always given and the rates assumed in the ecoinvent LCI background database [57] could be different in the year of the study. Therefore, the specific indicator values for this indicator, e.g. the electricity network and railway tracks, are subject to uncertainty.

With the standard LCIA method (ReCiPe endpoint [60]) used to calculate ecosystem damages the contribution of land use is high compared to the contributions of acidification, eutrophication and ecotoxicity. Biomass technologies (power generation and heating) are thus found to have high ecosystem damages. Assuming sustainable yield of biomass, one could argue for different weighting of the contributors to the ecosystem damages.

The human health effects of the modelled heavy metal emissions from ash disposal of biomass end-use technologies strongly depend on the type of disposal of the ash (municipal incineration, landfarming, landfilling, etc.). Using the disposal modelled in the selected ecoinvent background LCI database [57] introduces uncertainty due to the absence of predictions for future types of disposal.

According to Section 2.3.2.1, there is double-counting the energy system-related impacts of the modelling region when calculating LCA-based indicators. With the detailed analysis of the twelve indicators and the deployed end-use technologies presented in Section 3.3, the impacts are traced back to their origin:

- metal depletion mostly stems from electricity transmission and distribution grids, rail tracks and vehicles;
- fossil fuel depletion occurs in electricity generation and all fossil energy-based end-use sectors;
- ecosystem damages come from land use for biomass technologies, road and rail transport, and extraction and distribution of fossil fuels;
- GHG emissions are dominated by direct emissions from all fossil end-use technologies and electricity generation;

- human health damages are caused by direct emissions from all end-use sectors, heavy metal emissions from metal production for transmission grids and biomass ash disposal; and
- chemical waste mainly stems from the wastes of natural gas, metal and PV cell production.

The direct contributions of end-use technologies as well as from their fuel chains dominate the contributions of the energy used in the domestic supply chains of the end-use technologies. Double-counting impacts is thus negligible in this case study.

3.5. Summarising remarks and intermediate conclusions

This chapter presents a bottom-up ex-post multi-criteria analysis on the end-use technology level for possible energy system transformation pathways of Switzerland. Scenarios quantified with a Swiss bottom-up PE energy system model are analysed based on a set of twelve criteria and three weighting profiles. The goal of this analysis is the support of sustainable energy policy-making by a comparative sustainability analysis of complete and consistent bottom-up energy system scenarios with detailed end-use technology representation. The approach not only includes various sustainability aspects, but it also includes individual preferences. It thus enriches the conventional long-term energy system scenario analysis of climate and CCS policies by additional, policy-relevant indicators and subjective weighting profiles.

In principle, such an analysis can be applied in any energy system scenario study which aims to inform decision-makers and policy-makers. The set of criteria as well as the type of results can be flexibly adjusted according to the needs of the client. Depending on the set of sustainability indicators chosen, different fields of expertise and hence the possibility for interdisciplinary work are required. The effort of conducting interdisciplinary work and the gain in insights from the additional indicators form a trade-off.

The generic limitations of the combined method are described in Section 2.3.2.2, while the case study-specific limitations and uncertainties are discussed in Section 3.4.4. Two aspects are found to be of particular interest: First, the weighting allows the decision-maker to introduce subjective preferences and make well-founded personal decisions. Second, the selection of the set of indicators influences the results and the subsequent decision. The definition of indicators without overlapping, the interpretation of impacts outside the modelling region(s), and the avoidance of double-counting impacts related to LCA-based indicators are found to be important features.

Bottom-up ex-post multi-criteria analysis of energy systems could be improved by the following contributions: An approach for dealing with double-counting related to LCA-based indicators would allow for correct quantification of corresponding human health and environmental indicators. A detailed study on the quantification of indicators for energy saving measures represented in energy system models would be valuable. And, generally, case studies would profit from future indicator databases which can be adjusted so that they are consistent with the assumptions of the scenario under consideration. This not only includes LCI datasets and background LCI databases, but also indicators such as the risk of severe accidents in the energy sector and societal conflicts.

Two of the issues mentioned above dealing with the double-counting related to LCA-based indicators and handling of indicators which have impacts abroad, are addressed in the case study in the next chapter.

Acknowledgements and references

The case study presented in this chapter is published as a research article in the journal *Energy Policy* [75]. The information, the figures and the tables presented in this chapter mostly correspond to the ones presented in the manuscript. The case study was carried out in collaboration with Dr. Nicolas Weidmann, Christian Bauer and Dr. Stefan Hirschberg. Dr. Nicolas Weidmann performed the scenario description and quantification with the Swiss MARKAL model. Christian Bauer contributed to the selection of technologies and criteria, the discussion of the results and the formulation of the conclusions. Dr. Stefan Hirschberg critically reviewed the case study. I would like to thank Dr. Peter Burgherr for providing the generic accident risk indicator values.

4. Bottom-up Sustainability Analysis of the World Energy Scenarios

Today, the global energy system faces a radical transition with disruptive changes and uncertain outcome [19]. Changes in key drivers of energy demands, such as population growth, economic development, new technologies and environmental policies, have initialised the so-called "Grand Transition" of the global energy system according to the WEC [19]. The regional drivers and, accordingly, the transition will be diverse. This includes the development of the deployed resource, conversion and end-use technologies and associated sustainability aspects such as resource use, energy imports, GHG emissions and air pollution, i.e. all dimensions of sustainability. The goal of this case study is a bottom-up ex-post multi-criteria analysis of three scenarios of "Grand Transition", which can inform policy- and decision-makers from industry and governments about the sustainability of World Energy Scenarios for the time period from 2010 to 2060.

4.1. Literature review

A review of sustainability studies of energy system scenarios is presented in Appendix, Table 24. The case study presented in this chapter combines the analysis of the whole energy system, the application of a full-scale energy system model, the quantification of a comprehensive set of indicators covering all three dimensions of sustainability, the application of a consistent approach for dealing with double-counting related to LCA-based indicators and the analysis of the World Energy Scenarios. The case study thus complements the multi-criteria analysis of the World Energy Scenarios presented in the respective report [19] by incorporating further environmental and social indicators, i.e. comprehensive set of indicators is quantified that combines bottom-up indicators with indicators from the energy system model and from the scenario storylines.

4.2. Method and data

4.2.1. Scenario description

Three possible pathways in the "Grand Transition" are analysed in the case study: Modern JAZZ, Unfinished SYMPHONY and Hard ROCK. The scenarios were developed by the WEC and the corresponding storylines are described in detail in the corresponding report [19]. While the population reaches 10.2 billion people in 2060 in all scenarios, the scenarios' other socio-economic characteristics and policies differ.

Modern JAZZ attempts to provide affordable energy for all from open economies with a GDP growth rate of 3.3% p.a. There is an expanded opening of markets for unconventional oil and gas, and energy efficiency is increased based on market mechanisms. Nuclear and CCS technologies have low acceptance by markets and consumers. Wind and solar power are supported as opposed to hydro power with limited support.

The *Unfinished SYMPHONY* scenario is characterised by global governance and climate-focused policies with an annual GDP growth rate of 2.9%. Climate change mitigation policies promote renewable energies, CCS technologies and nuclear power. Energy efficiency is supported by the governments while unconventional resources are regulated.

The *Hard ROCK* scenario has fragmented economies and strong energy security policies resulting in an annual GDP growth of 1.9% p.a. The energy security policies drive renewable and nuclear power generation, unconventional oil and gas and CCS technologies. Energy efficiency continues according to historic trends.

4.2.2. Criteria definition and indicator quantification

The indicator set defined for this case study is inspired by the ones from the case study in Chapter 3, the World Energy Scenarios [19] and other studies such as [3, 23, 33, 76-78]. The criteria and indicators are selected according to the three dimensions of sustainability and the hierarchy suggested by Hirschberg et al. (Figure 1), and are presented in Table 8 and Table 9. They include indicators for the sustainability of energy supply as well as indicators representing the characteristics of the scenarios. In this case study, full MCDA is not possible because scenarios and not scenario variants are compared (Section 2.4.1). Thus, overlapping of criteria can be tolerated.

The selection of the environmental and human health indicators (WD, TA, FE, ALO, PMF, HT, POF; abbreviations are explained in Table 8 and Table 9) was guided by the comprehensive set of midpoint categories of the ReCiPe method [60]. Therefore, no indicator for the sub-category waste could be defined. Compared to the case study in Chapter 3, the metal depletion indicator is omitted due to the uncertainties related to recycling rates and material balances as described in Section 3.4.4. Global Warming Potential (GWP) and CO_2 emissions are both included to highlight the importance of considering all GHG emissions, which is often not the case in PE energy system models such as the GMM model.

The selection of the economic criteria and indicators is guided by information from the scenario quantification with the GMM model (data inputs and outputs). The *customer* sub-category is described by the GDP per capita, i.e. the ability of people to afford energy. The quantification of commodity prices was not possible as only commodity production and transport *costs* can be derived from the GMM model outputs. The *utility* sub-category is represented by the capital investments in the power sector. The *overall economy* sub-category is represented by the energy intensity (INT), the attractiveness for companies due to reliable power system infrastructure (GRID) and the vulnerability to variable oil prices (OIL). The definition and quantification of criteria and indicators for the sub-category political stability and legitimacy was beyond the scope of this case study. Overall, the set of indicators is limited compared to studies such as the one from Schenler et al. [23] but still representative.

Table 8: Environmental and economic criteria and indicator hierarchies and definitions. LCA = Life-cycle Assessment, GMM = Global Multi-regional MARKAL model, RA = Risk Assessment.

Category	Indicator	Unit	Abbreviation	Optimal	Indicator value source	Description
ENVIRONMENT						
Resources	Fossil resource use	PJ	FOSSIL	min	GMM output	Coal, oil and gas resource use measured at the TPES level; represents the use of non-renewable fossil resources
	Nuclear resource use	PJ	NUCL	min	GMM output	Nuclear resource use measured at the TPES level; represents the use of non-renewable nuclear resources
	Water use	m^3	WD	min	LCA	Amount of water from lakes, rivers, wells and unspecified natural origin used over the life cycle; according to ReCiPe methodology [60]
Climate change	Global warming potential	kg CO_2eq	GWP	min	LCA	Global warming potential expressed as GHG emissions over the life cycle; represents all potential negative impacts of climate change; according to ReCiPe methodology [60]
	CO_2 emissions	Mt CO_2	CO_2	min	GMM output	Direct CO_2 emissions of the energy system; represents the potential negative impacts of climate change caused by conversion technologies
Ecosystem damages	Terrestrial acidification	kg SO_2eq	TA	min	LCA	Life-cycle amount of atmospheric deposition of inorganic substances; represents the negative impacts of the change in acidity in the soil; according to ReCiPe methodology [60]. Major acidifying emissions are NO_x, NH_3, and SO_2 [39].
	Freshwater eutrophication	kg P-eq	FE	min	LCA	Life-cycle amount of nutrient enrichment of the aquatic environment as a result of human activities; according to ReCiPe methodology [60]
	Agricultural land use	m^2*y	ALO	min	LCA	Life-cycle amount of agricultural area occupied (in m^2) and the time of occupation (in years); according to ReCiPe methodology [60]
ECONOMY						
Customer	GDP/cap	$/cap	GDP	max	GMM inputs	Prosperity level expressed as GDP per capita; represents the average individual ability to afford energy commodities
Utility	Power generation investments	M$	CAPINV	min	GMM outputs	Investments in the power sector; represent the capital at risk
Overall economy	Oil in transport	share	OIL	min	GMM outputs	Share of oil in total fuel use for transport; represents the vulnerability of an economy to the variability of commodity prices
	TPES/GDP	PJ/M$	INT	min	GMM inputs and outputs	Energy intensity of the economy based on the ratio of TPES and GDP; represents the energy efficiency of an economy
	Grid investments	Mä/PJ	GRID	max	GMM inputs and outputs	Investments in the transmission and distribution (T&D) grid per electricity generated; represents the quality of the power supply infrastructure and thus the attractiveness of a region for business

Table 9: Social criteria and indicator hierarchies and definitions. LCA = Life-cycle Assessment, GMM = Global Multi-regional MARKAL model, RA = Risk Assessment.

Category	Indicator	Unit	Abbreviation	Optimal	Indicator value source	Description
SOCIETY						
Security and stability of supply	Import dependence	share	IMP	min	GMM outputs	Share of coal, oil products, gas products and biofuel imports in TPES; represents the dependence of foreign suppliers
	Variable renewable generation	share	RENEW	max	GMM outputs	Share of solar and wind power generation in total electricity generation; represents the challenges related to intermittent power supply
Social and individual risk	Particulate matter formation	kg PM10-eq	PMF	min	LCA	Life-cycle emissions of a complex mixture of organic and inorganic fine particulate matter with a diameter of less than 10 µm (PM10); represents damage to human health caused by local air pollution; according to ReCiPe methodology [60]
	Human toxicity	kg 1,4,-DCB-eq	HT	min	LCA	Life-cycle amount of chemicals based on their environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect; represents human health damages related to the emission of toxic chemicals; according to ReCiPe methodology [60]
	Photochemical oxidant formation	kg NMVOC-eq	POF	min	LCA	Life-cycle emissions of ozone formed as a result of photochemical reactions of NO_x and Non Methane Volatile Organic Compounds (NMVOC); represents damages to human health related to the ground level ozone; according to ReCiPe methodology [60]
	Expected mortality in severe accidents	fatalities	MORT	min	RA	Expected number of fatalities in severe accidents in the energy sector including 5 or more dead persons; based on historical experience; estimates do not include fatalities from road traffic
	Maximum credible consequences of severe accidents	fatalities	CONSQ	min	RA	Maximum credible consequences of severe accidents in the energy sector including 5 or more dead persons; based on historical experience; estimates do not include fatalities from road traffic
Quality of life	Car ownership	cars/1000 cap	CARS	max	GMM inputs	Number of cars per 1000 people; represents the access to individual mobility
	Access to clean energy	GJ/cap	ACC	min	GMM inputs	Access to clean energy expressed as non-commercial biomass per capita; represents the negative impacts of the collection of non-commercial biomass and emission of polluting and health damaging substances on household level

The indicators values are quantified based on four main sources: scenario storylines, GMM model inputs and outputs, and severe accident data from the ENSAD and LCI datasets from different sources (Table 8 and Table 9). While a set of indicators can be directly calculated or derived from GMM inputs and outputs and the scenario storylines, two other indicators are quantified bottom-up based on accident risk assessment: The first indicator is the mortality in severe accidents in the energy sector which is defined per energy chain using data from the ENSAD [69] as reported in Burgherr and Hirschberg [79]. The data is allocated to the technologies in the energy chains and regions based on their share of fatalities in the corresponding stage of the energy chain according to Appendix, Table 39. The indicator is specified per activity and adjusted according to the technologies' efficiency improvements. The transport and distribution (T&D) contribution is allocated to the importing region, i.e. the region demanding the energy carrier bears the responsibility for the fatalities. The second risk indicator quantifies the maximum credible fatalities in severe accidents in the energy sector, which are defined on a technology basis in the ENSAD. The data is allocated to the technologies in the energy chains and regions by investment (renewable energies except hydro) or by capacity (other energy chains) and adjusted according to the reference capacities (Appendix, Table 40). The choice of investment and capacity allocation, respectively, is motivated by the fact that the maximum fatality case for the renewable energies is expected during the construction phase, while the maximum fatality case of the other energy chains is expected in the operation phase. The probability of the severe accidents is not taken into account.

The residual indicators are specified bottom-up based on LCA. They are calculated according to the four steps introduced in Section 2.4.2.1, which are reported in detail in the subsequent sections for the case study.

Step 1: Matching of GMM model processes and LCI datasets

As the first step, the GMM model processes were matched with corresponding LCI datasets. For that purpose, the set of GMM technologies were screened and 44 dummy, i.e. burden-free, technologies are screened out, which can be ignored for the LCA indicator calculation. The remaining technologies were further checked for whether they are burden-free. Export technologies are considered to be burden-free and all impacts of trade are allocated to the corresponding import technology, i.e. the region demanding the energy carrier bears the burden. With this second check, another 69 technologies can be eliminated.

The remaining set of GMM technologies is compared with the available LCI datasets at PSI [24, 27, 59, 80, 81]. For 50 GMM technologies no corresponding LCI dataset is available, so the technologies were deleted from the GMM model. The vast majority of the eliminated technologies were from the large hydrogen sector for which the LCI data is sparse. Nevertheless, a representative set of hydrogen technologies remains (Appendix, Figure 83). In 16 cases, namely in the uranium chain, oil crop processing and corn production, full energy chains were not available in the GMM model, so they were added (Appendix, Figure 84 and Figure 85).

For each of the 203 GMM technologies emerging from the selection process described above, the best matching available LCI dataset was selected (Appendix, Table 42). The majority of the 203 technologies could be matched with ecoinvent datasets [82]. In the hydrogen sector, all selected LCI datasets stem from Simons and Bauer [81]. In the electricity sector, a set of technologies could be matched with LCI dataset from Roth et al. [24] and Volkart et al. [59]. In the passenger car sector, fuel cell technologies could be drawn from Simons and Bauer [81], while the hybridised technologies were newly created based on information from Hofer [27] and Bauer et al. [83]. In the freight transport sector missing LCI datasets were created based on data on fuel cells from Simons and Bauer [81], on exhaust and non-exhaust emissions from [84], on calculations based on the World Harmonized Vehicle Cycle (WHVC) driving cycle using the methodology of Hofer [27], and ecoinvent [82]. The coal and natural gas co-generation technologies are assumed to be heat-driven, i.e. 100% of the impacts are allocated to heat, and are therefore represented by heat generation LCI datasets.

The matching of technologies and LCI datasets described in the previous paragraph also includes the regional correspondence, which is documented in Table 10. For single country GMM regions, the corresponding national or larger region dataset is chosen (if available). For GMM regions for which multiple LCI datasets exist, their contributions are weighted by their current production volume. If no GMM region-specific datasets are available, the Rest of the World (RoW), global (GLO) or the only available datasets are used. The temporal correspondence is ensured by adjusting the efficiencies.

Table 10: Correspondence list of the regions in the GMM model and in ecoinvent. The GMM model regions are displayed in Figure 3. The ecoinvent regions are listed in Treyer and Bauer [86].

GMM region	ecoinvent region
ASIAPAC	TH | ID | MY
AUSNZL	AU
BRAZIL	BR | RLA
CANMEX	CA-AB | CA-BC | CA-MB | CA-NB | CA-NF | CA-NS | CA-NT | CA-NU | CA-ON | CA-PE | CA-QC | CA-SK | CA-YK | MX | RNA
CENASIA	-
CHINAREG	CN
EEUR	BA | MK | RS | TR | UA | Europe without Switzerland | RER | RER w/o DE+NL+NO
EU31	WEU | Europe without Switzerland | RER | RER w/o DE+NL+NO | AT | BE | BG | CH | CZ | DE | DK | ES | FI | FR | GB | GR | HR | HU | IE | IT | LU | NL | NO | PL | PT | RO | SE | SI | SK
INDIA	IN
JPKRTW	JP | KR | TW
LAC	RLA | PE | CL
MENA	IR | SA | DZ
RUSSIA	RU
SSAFRICA	ZA | TZ
USA	HICC | ASCC | WECC, US only | MRO, US only | NPCC, US only | RFC | SERC | SPP | TRE | US | FRCC | RNA

The ecoinvent database is a collection of process datasets. The energy sector's own energy use is thus represented on the level of processes by reduced efficiencies or by additional energy carrier inputs. The energy sector's own energy use in the GMM model stems – as does the other calibration data – from the IEA extended world energy balances [85] and is represented as follows in the model:

- The use of natural gas, diesel, gasoline and coal in the energy sectors is incorporated into their T&D efficiency, which also includes distribution losses.
- The use of natural gas in LNG production is endogenous via the efficiency of the LNG liquefaction technology.
- The use of electricity in all energy sectors is incorporated into T&D efficiency, which also includes distribution losses.
- The use of coal in blast furnaces, gas works and coke ovens is included in industry thermal demand.

By including the energy use in T&D it is assumed that the use of each energy carrier by the energy industry remains roughly proportional to the use of the same energy carrier in total final consumption.

For the calculation of the LCA-based indicators, the energy use in energy sector is ensured to be consistent with the GMM model by (i) modifying the technophere matrix in the third step, (ii) by adjusting the efficiencies of the LCI datasets to the ones of the corresponding GMM processes in the fourth step, and (iii) by adjusting the energy carrier inputs, which are not the main input of the considered GMM technologies, to the ones of the corresponding LCI datasets.

Step 2: Division of the LCI datasets into life-cycle phases

In the second step, all 203 listed LCI datasets are split into their upstream, operation and infrastructure contributions according to Figure 10b. The LCA-based indicators are calculated by activity (operation contribution) and by investment (infrastructure contribution). The indicators defined by activity are further differentiated into the direct (on-site) and indirect contributions according to Figure 10c. It must be noted that due to the modelling approaches of some LCI datasets, some direct impacts occur one step back in the supply chain and are thus allocated to the indirect impacts. For example there is an activity called “diesel burned in diesel-electric generating set“, which creates direct (on-site) emissions which are accounted for as indirect contribution. These special cases could not be considered with the developed LCA-based indicator calculation framework.

Step 3: Constructing a background database without the energy system

The technosphere matrix A’ is created in the third step by first extending the basic ecoinvent v3 database by additional, non-ecoinvent LCI datasets and their corresponding background databases. As some LCI datasets are based on ecoinvent version 2 [57], the dataset and the corresponding background database are updated to ecoinvent version 3 [82] using the available correspondence lists and – in case no information was available – expert judgement.

As described in Section 2.3.2.1, ecoinvent not only considers impacts of the energy system but also of other industrial sectors such as the construction sector, plastic production and metal production. For every LCA-based indicator calculated using the ecoinvent database, the industrial heat, industrial electricity, fuel and freight transport demand is reflected. The technosphere matrix is thus modified so that it excludes the contributions for the energy systems of the regions under consideration according to Section 2.4.2.1 and Figure 11. Specifically, 1082 electricity products, 333 heat products and 80 freight transport products are set to zero in the background database. In the structure of the ecoinvent database version 3 [82], electricity generation datasets deliver electricity to the markets of the corresponding regions. The market datasets reflect the electricity generation mix, the transmission grid and the direct impacts such as atmospheric emissions. In order to account for these impacts in the calculation of the LCA-based indicators, only the 1082 electricity generation datasets are set to zero while the electricity market datasets remain in the modified technosphere matrix (with electricity inputs of zero). The energy carriers in the GMM model are defined based on the IEA classification [87]. Using these definitions, 128 energy carriers could be identified in the ecoinvent database and set to zero in the modified technosphere matrix. The modified technosphere matrix is developed in the Brightway2 framework [88].

Step 4: Calculating the LCA-based indicator values

Based on the preparatory work in the first three steps, the LCA-based indicator values can be calculated. An Excel sheet was developed which contains the matched GMM processes and LCI datasets (Appendix, Table 42) as well as the classification of upstream and infrastructure contributions for each LCI dataset. The Excel sheet was read by the Brightway2 software and separate LCI datasets were created for operation and infrastructure contributions. Then the LCA calculations were carried out based on the modified technophere matrix and by dividing the operation contributions further into the direct and the indirect contributions according to Figure 10c. The LCA-based indicator values were calculated based on their standard functional units and output to Excel files. These results were post-processed in order to represent the efficiencies and units of the respective GMM technologies. If available, the specific energy contents from ecoinvent were used for the conversion.

4.2.3. Scenario quantification

The GMM model described in Sections 2.1.2 and 4.2.2 was used for this case study. It must be noted that due to the modifications of the GMM model described in Section 4.2.2, the scenario quantification does not give exactly the same results as in the original study [19]. The risk assessment- and LCA-based indicator values were implemented in the GMM model using its existing features for the quantification of environmental indicators (Section 2.1).

4.3. Results

The result section is divided into seven parts: Sections 4.3.1 to 4.3.3 present the global results for the three World Energy Scenarios, i.e. Modern JAZZ, Unfinished SYMPHONY and Hard ROCK. Section 4.3.4 describes the global multi-criteria sustainability assessment, and Sections 4.3.5 to 4.3.7 present three regions, CHINAREG, EU31 and SSAFRICA, in detail. The three areas are illustrative as they represent the largest region among the 15 GMM regions, a developed region and a developing world region. The GMM regions are displayed in Figure 3. The validation of the LCA-based estimates is presented in the discussion in Section 4.4.2.

4.3.1. Description of the global results for Modern JAZZ

The Total Primary Energy Supply (TPES) in JAZZ increases by 29% from 2010 to 2060, while the share of fossil fuels drops from 82% to 63% (Figure 21). The Total Final Consumption (TFC) increases by 45% from 2010 to 2060 and the share of electricity grows from 17% to 27% in the same period (Figure 22). CHINAREG is the most important contributor to both TPES and TFC. Developing regions such as ASIAPAC, INDIA and SSAFRICA have growing contributions and developed regions such as EU31 and USA have decreasing contributions to the TPES and TFC.

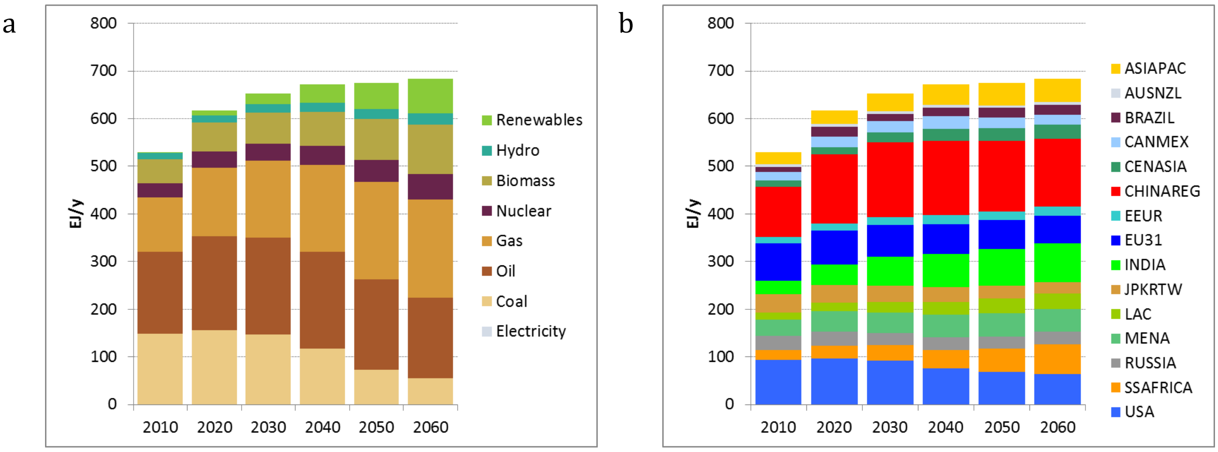


Figure 21: Total primary energy supply by resource (a) and by region (b) in the Modern JAZZ scenario

The electric capacity almost triples and electricity generation more than doubles from 2010 to 2060 (Figure 23). Renewable power generation (hydro, biomass, wind, solar, geothermal) increases from 20% in 2010 to 52% in 2060, mostly due to the expansion of solar, wind and hydro power (Figure 23).

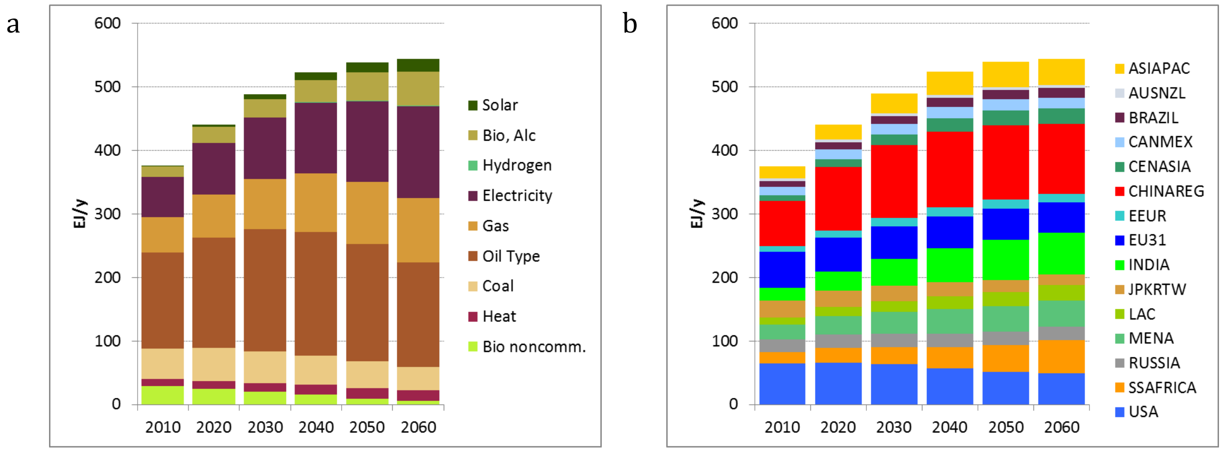


Figure 22: Total final consumption by fuel (a) and by region (b) in the Modern JAZZ scenario

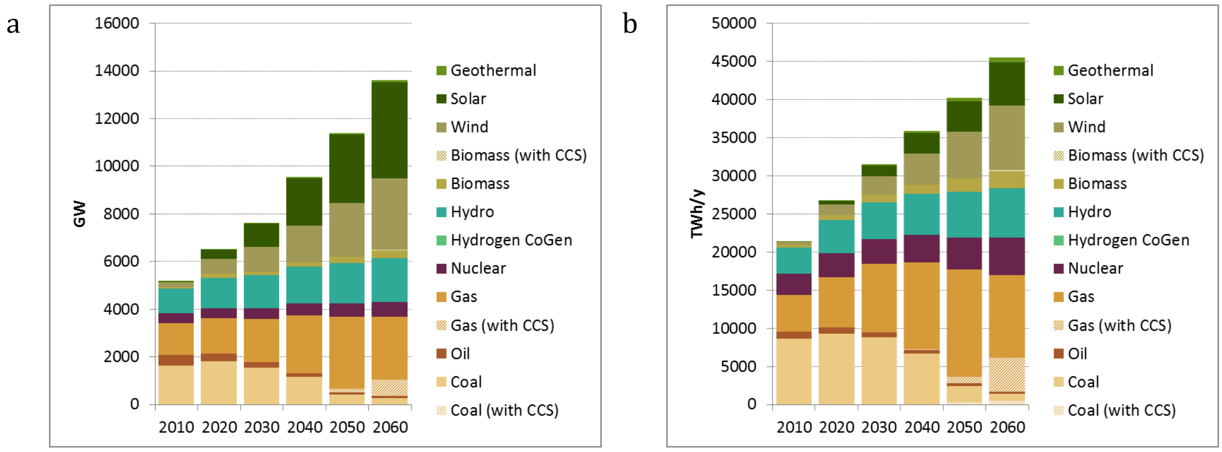


Figure 23: Global electric capacity (a) and electricity production (b) by resource in the Modern JAZZ scenario

CO_2 emissions peak in 2030 and reduce to 21.4 Gt CO_2 in 2060 (Figure 24). CHINAREG contributes the most emissions, INDIA increases its emissions and EU31 and USA decrease their emissions. CCS technologies enter the energy system towards mid-century mostly in coal power plants and store 3.3 Gt CO_2 in 2060 (Figure 24). Hydrogen production reaches 1.4 EJ in 2060, mainly from coal gasification technologies (Figure 25), and it is mostly used in freight transport (Figure 25).

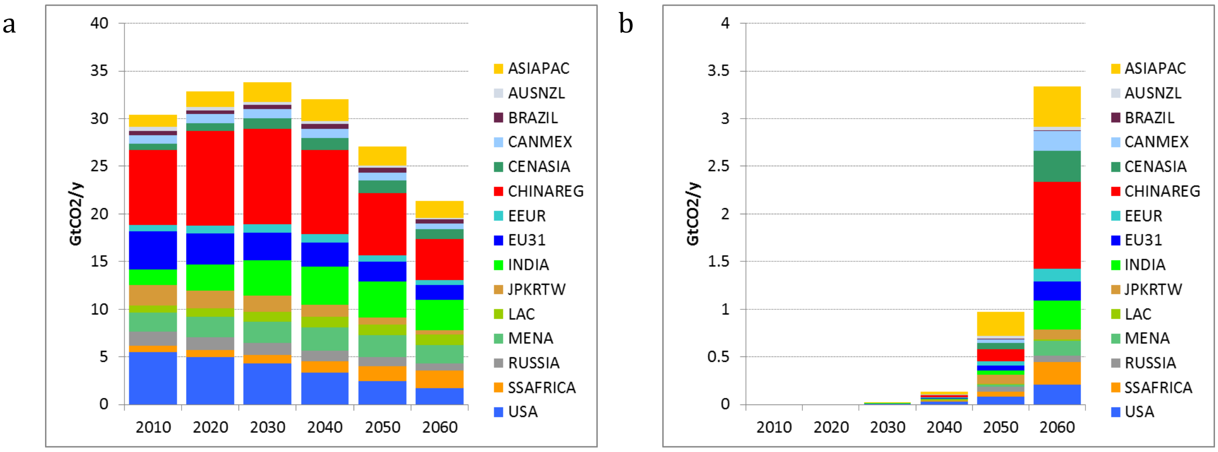


Figure 24: CO_2 emissions (a) and CO_2 captured (b) in the Modern JAZZ scenario

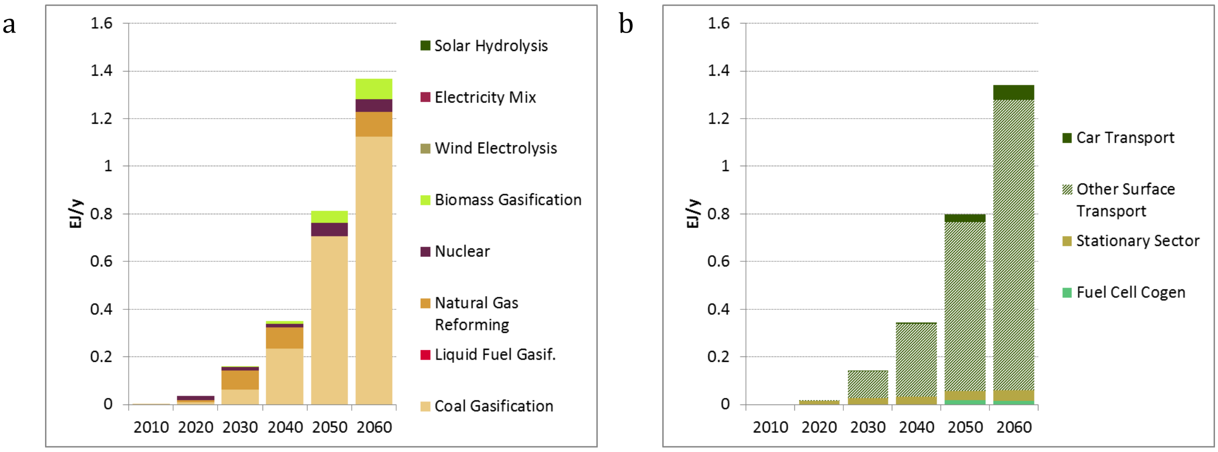


Figure 25: Global hydrogen production by technology (a) and hydrogen use by sector (b) in the Modern JAZZ scenario

4.3.2. Description of the global results for Unfinished SYMPHONY

The TPES in SYMPHONY peaks in 2030, with an increase of 15% from 2010 to 2060, while the share of fossil fuels drops from 82% to 50% (Figure 26). The TFC peaks in 2040, with an increase of 26% from 2010 to 2060. The share of electricity grows from 17% to 28% in the same period (Figure 27). CHINAREG is the most important contributor to both TPES and TFC. Developing regions such as ASIAPAC, INDIA and SSAFRICA have growing contributions to TPES and TFC and developed regions such as EU31 and USA have decreasing contributions.

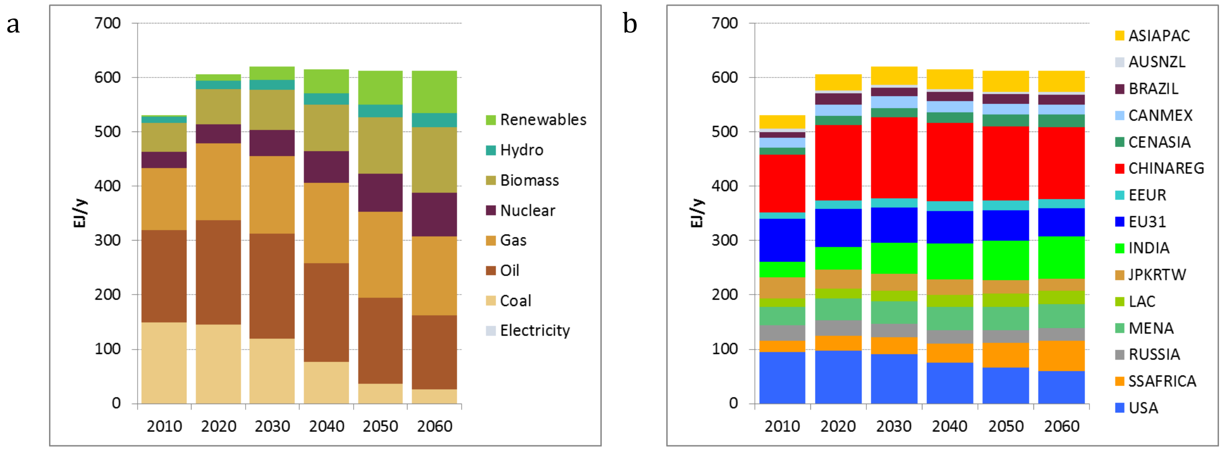


Figure 26: Total primary energy supply by resource (a) and by region (b) in the Unfinished SYMPHONY scenario

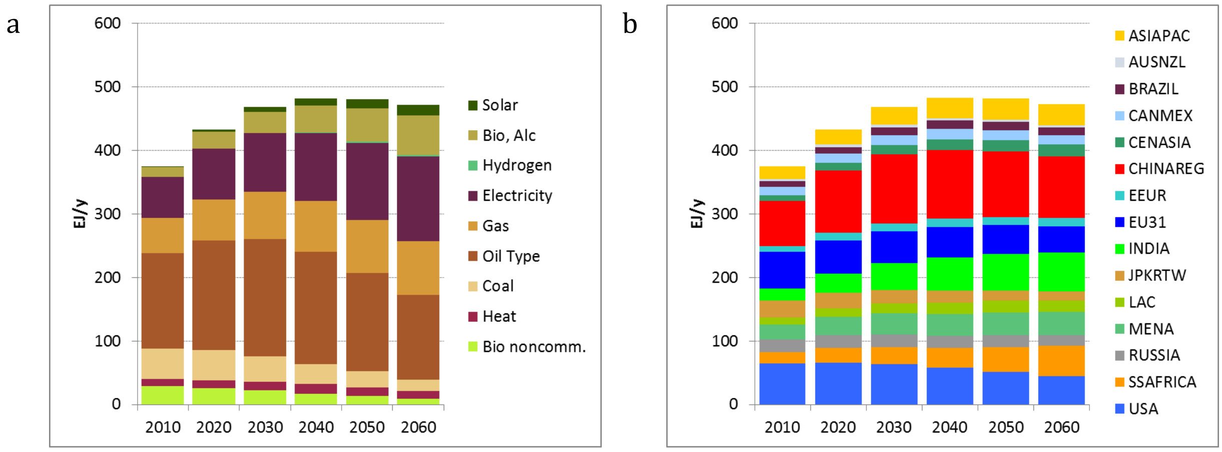


Figure 27: Total final consumption by fuel (a) and by region (b) in the Unfinished SYMPHONY scenario

The electric capacity almost triples and electricity generation almost doubles from 2010 to 2060 (Figure 28). Renewable power generation (hydro, biomass, wind, solar, geothermal) increases from 19% in 2010 to 63% in 2060, mostly due to the expansion of solar and wind energy, but also hydro power (Figure 28).

CO_2 emissions peak in 2020 and drop to 11.9 Gt CO_2 by 2060 (Figure 29). CHINAREG contributes the most emissions while EU31 and USA decrease their emissions. CCS enters the energy system towards the mid-century, reaching 4.7 Gt of stored CO_2 by 2060 (Figure 29). CCS technologies are mostly applied in natural gas power plants. Hydrogen production reaches 1.3 EJ by 2060, mainly from coal gasification technologies (Figure 30) and is mostly used in freight transport (Figure 30).

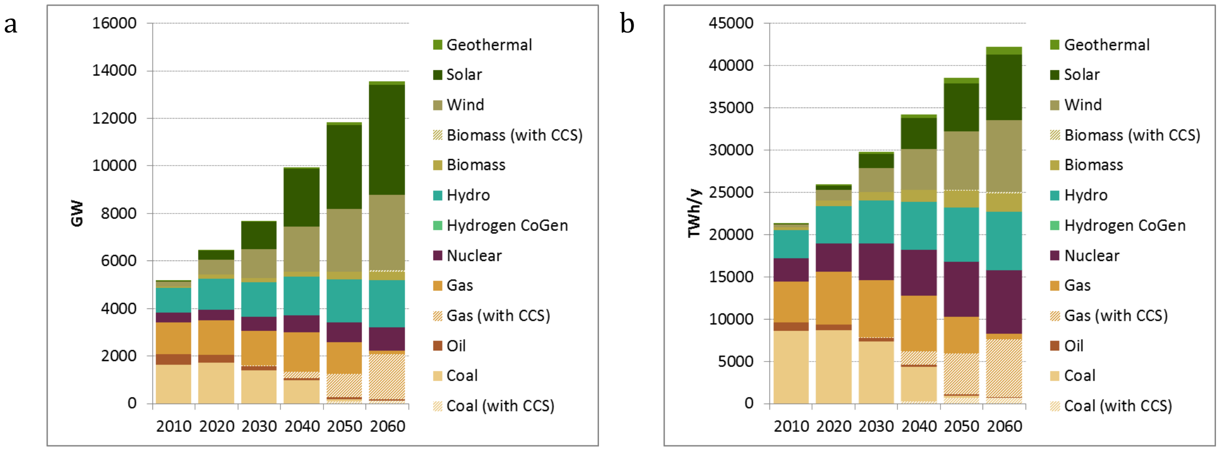


Figure 28: Global electric capacity (a) and electricity production (b) by resource in the Unfinished SYMPHONY scenario

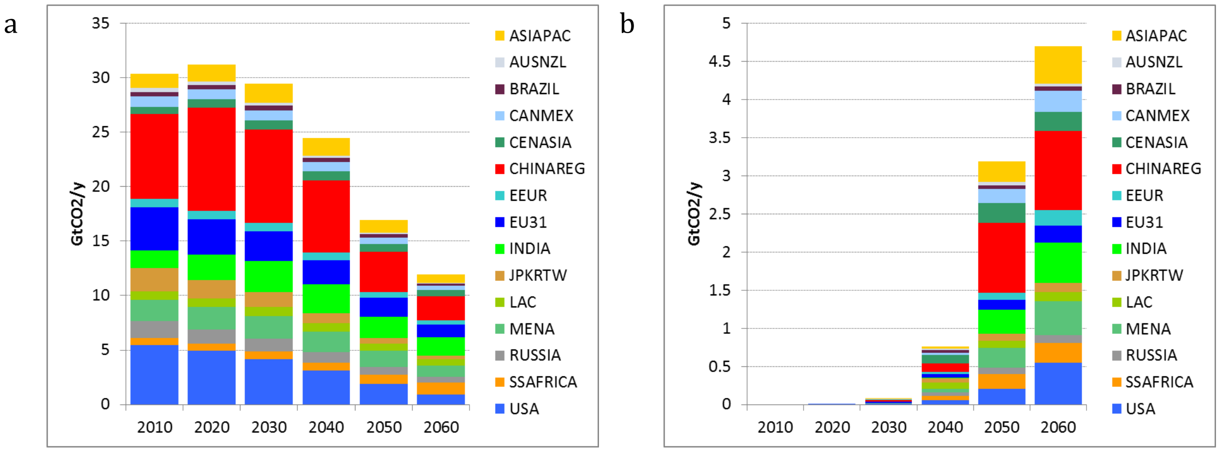


Figure 29: CO_2 emissions (a) and CO_2 captured (b) in the Unfinished SYMPHONY scenario

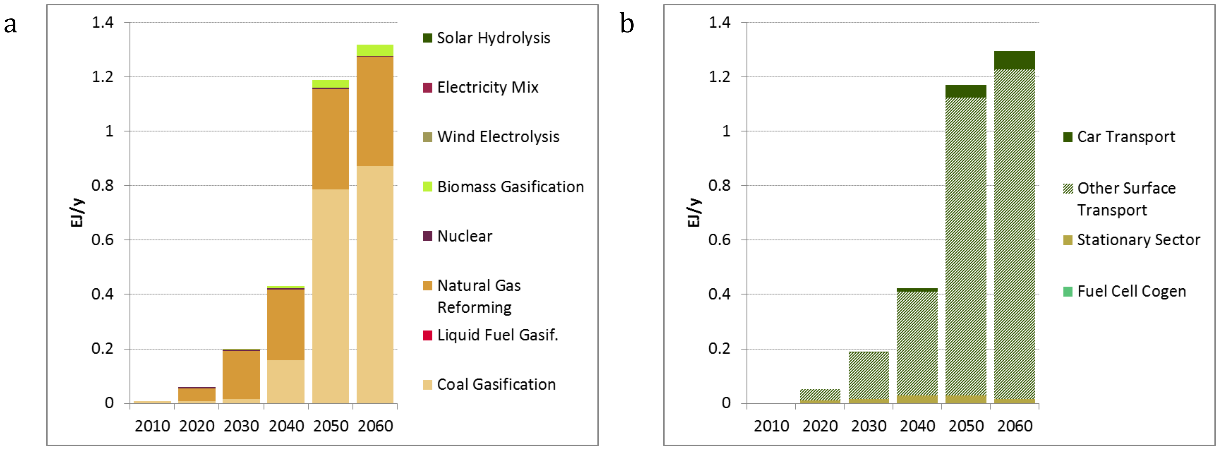


Figure 30: Global hydrogen production by technology (a) and hydrogen use by sector (b) in the Unfinished SYMPHONY scenario

4.3.3. Description of the global results for Hard ROCK

The TPES in HARD ROCK increases by 40% from 2010 to 2060, while the share of fossil fuels drops from 82% to 69% (Figure 31). The TFC increases by 54% from 2010 to 2060. The share of electricity grows from 17% to 23% in the same period (Figure 32). CHINAREG is the most important contributor to both TPES and TFC. Developing regions such as ASIAPAC, INDIA and SSAFRICA have growing contributions to the TPES and TFC and developed regions such as EU31 and USA have slightly decreasing contributions.

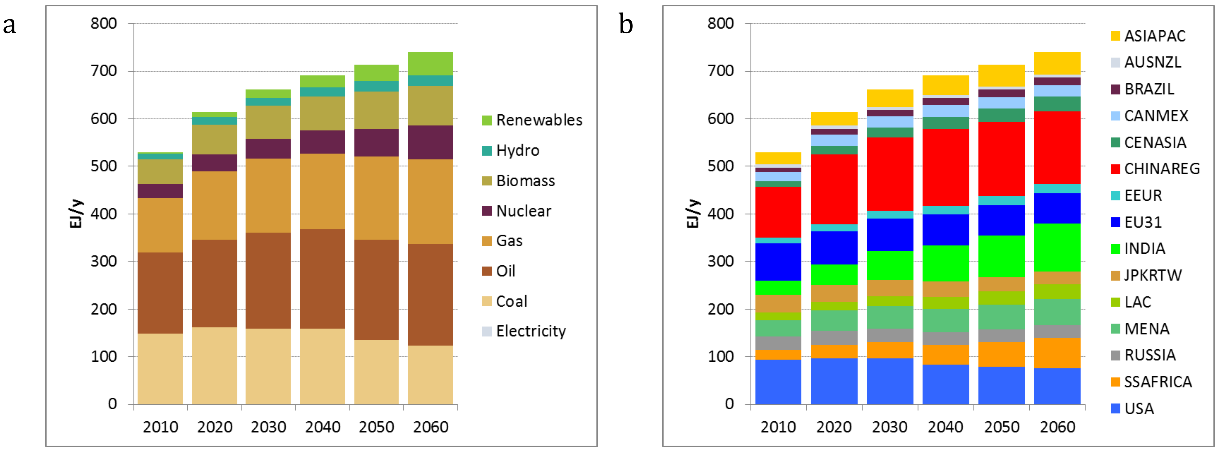


Figure 31: Total primary energy supply by resource (a) and by region (b) in the Hard ROCK scenario

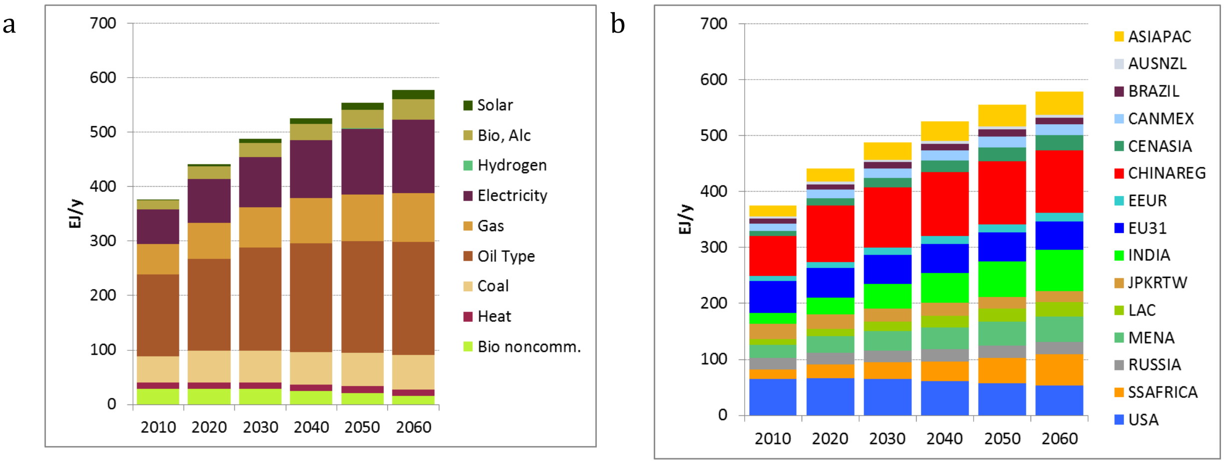


Figure 32: Total final consumption by fuel (a) and by region (b) in the Hard ROCK scenario

The electric capacity more than doubles and electricity generation doubles from 2010 to 2060 (Figure 33). Renewable power generation (hydro, biomass, wind, solar, geothermal) increases from 20% in 2010 to 40% in 2060, mostly due to the expansion of solar, wind energy and hydro power (Figure 33).

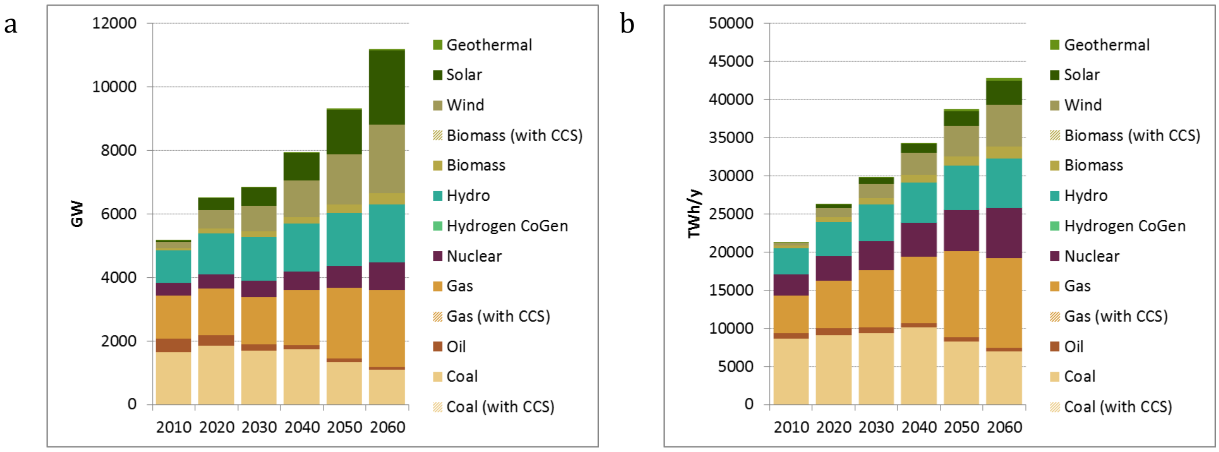


Figure 33: Global electric capacity (a) and electricity production (b) by resource in the Hard ROCK scenario

CO_2 emissions peak in 2040 and reduce to 32.3 Gt CO_2 by 2060 (Figure 34). CHINAREG contributes the most emissions and EU31 and USA decrease their emissions. There is no CCS in the HARD ROCK scenario (Figure 34). Hydrogen production reaches 0.3 EJ by 2060, mainly from natural gas, coal and biomass technologies (Figure 35) and is mostly used in car and freight transport and the stationary (heat and power) sector (Figure 35).

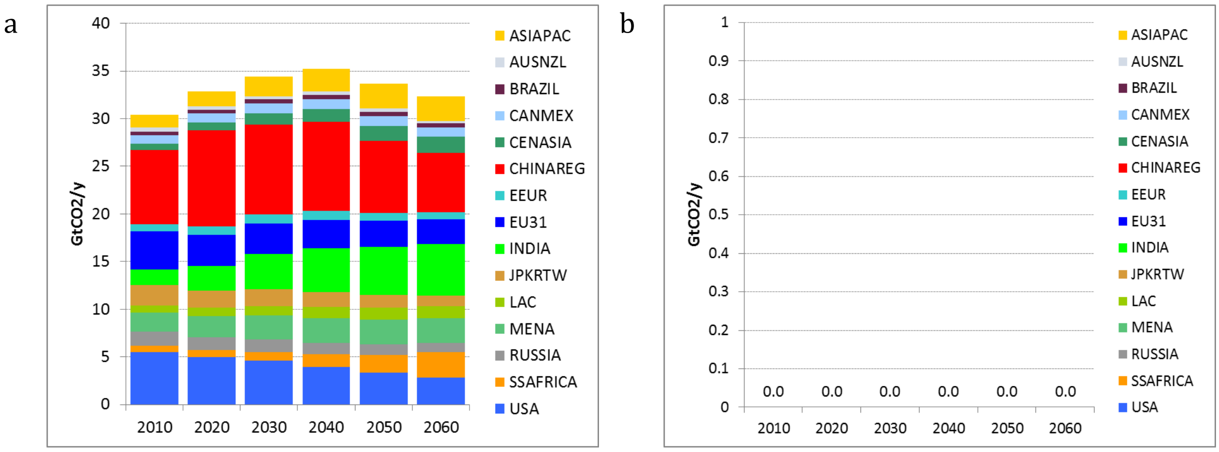


Figure 34: CO_2 emissions (a) and CO_2 captured (b) in the Hard ROCK scenario

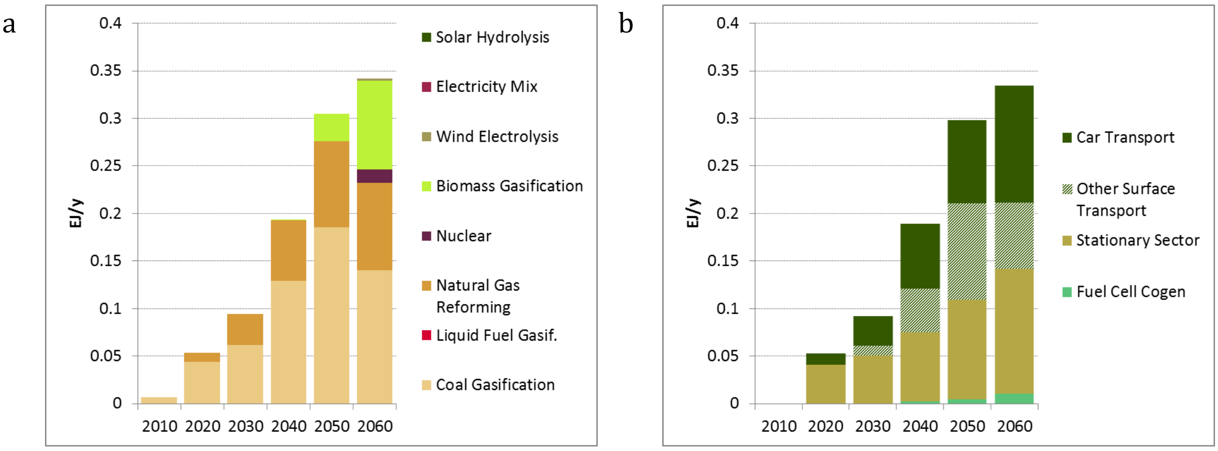


Figure 35: Global hydrogen production by technology (a) and hydrogen use by sector (b) in the Hard ROCK scenario

4.3.4. Global multi-criteria sustainability assessment

The global results for the sustainability indicators defined in Table 8 are presented in the subsequent paragraphs. The results are broken down into environmental indicators (Figure 36), economic indicators (Figure 37) and social indicators (Figure 38). The abbreviations used in the figures are listed in Table 8 and Table 9. The absolute risk assessment and LCA-based indicator values are presented in detail in Appendix, Table 43 to Table 45.

The fossil resource use (FOSSIL) reaches its peak in 2030 in Unfinished SYMPHONY and Modern JAZZ, and in 2040 in Hard ROCK. While the indicator remains on a high level in the latter scenario, it drops to 71% of the 2010 level by 2060 in Unfinished SYMPHONY. The use of nuclear resources (NUCL) increases in all three scenarios on the global level. Particularly in Unfinished SYMPHONY (+171%) but also in Hard ROCK (+138%) nuclear power generation and thus nuclear resource use expands over the time horizon considered.

ASIAPAC, CHINAREAG, EU31, INDIA and USA have large stable contributions to the global water use (WD) by the energy sector, while BRAZIL, LAC and particularly SSAFRICA have increasing contributions. Indirect water use dominates the direct use of water in the energy system and water use by infrastructure (Appendix, Table 43 to Table 45). While most of the direct water use is in coal mining, the majority of the indirect water use is by the cultivation of the biomass. Due to the increasing use of biomass, the indirect water use increases in all scenarios by 2060, particularly in Unfinished SYMPHONY (+96%).

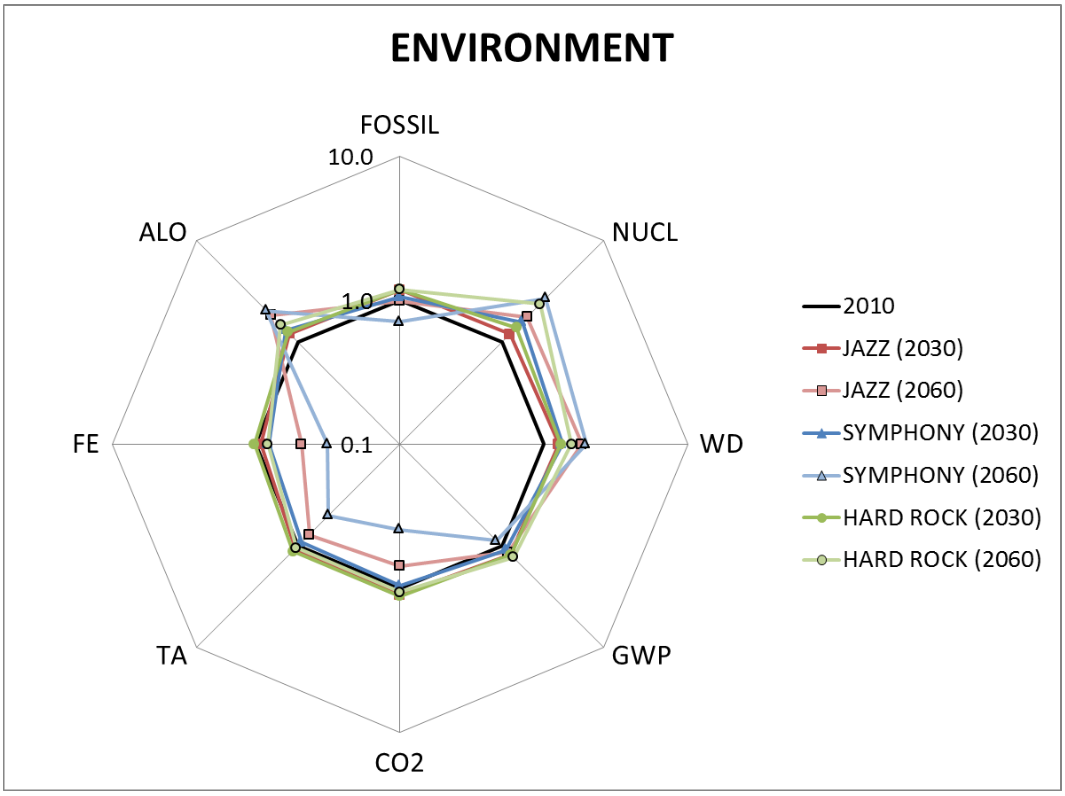


Figure 36: Performance of the three scenarios regarding environmental indicators on a global level. The abbreviations are explained in Table 8.

By 2060, the CO_2 emissions are reduced to 39% and 70% of the current values for Unfinished SYMPHONY and Modern JAZZ, respectively, while they are higher for Hard ROCK (+6%). Similarly, GHG emissions are reduced in Unfinished SYMPHONY and Modern JAZZ from 2010 to 2060, while they increase by about 29% in Hard ROCK. CO_2 and GHG emissions reach their peak in 2020, 2030 and 2040 for the Unfinished SYMPHONY, Modern JAZZ and Hard ROCK scenarios, respectively. After the peak, the direct CO_2 emissions drop due to the reduction in fossil fuel use. The GHG emissions are dominated by direct emissions (Appendix, Table 43 to Table 45) and drop slower than the CO_2 emissions as non-CO_2 GHG emissions are also considered.

Terrestrial acidification (TA) follows similar trajectories to the CO_2 emissions in the three scenarios. CHINAREG is the most important contributor, but it decreases towards the end of the time period considered. INDIA is the other major contributor, which increases strongly in Hard ROCK. The direct contributions of the energy system dominate the TA indicator (Appendix, Table 43 to Table 45) and mainly stem from coal furnaces, coal mining and coal power generation.

Unfinished SYMPHONY has the least coal use and thus lower TA (-50%) than the other two scenarios (-22% for Modern JAZZ and +4% for Hard ROCK). The development of freshwater eutrophication (FE) is similar, but this indicator is almost fully driven by indirect contributions (Appendix, Table 43 to Table 45). The impacts mostly stem from the pollution due to various spoils of the coal mining processes. Major contributors to the global FE are ASIAPAC, AUSNZL, CHINAREG, INDIA and USA.

Agricultural land occupation (ALO) mainly occurs in SSAFRICA and is driven by the area occupied by biomass planted for energy use. Therefore Unfinished SYMPHONY (+105%) and also Modern JAZZ (+84%) have higher impacts than Hard ROCK (+48%) in 2060 compared to 2010 (Appendix, Table 43 to Table 45).

The power generation capacity expansion in 2030 includes a large share of decentralised solar PV power generation which lowers the required investments in the transmission grid. Towards 2060, the T&D investment growth outpaces the growth in electricity generation leading to increased T&D investments per amount of electricity generated (GRID; +51% for Modern JAZZ, +53% for Unfinished SYMPHONY and +22% for Hard ROCK). After investing in less capital intensive power generation technologies through 2030, power generation capacity expansion (CAPINV) strongly increases by 2060, leading to high investments for that period for all scenarios.

The share of oil in transport fuels (OIL) remains high in all three scenarios, particularly in Hard ROCK with 91% in 2060. The energy intensity of the economy (INT), i.e. the TPES per GDP, decreases in all scenarios, indicating higher efficiency in transforming energy into GDP. While the indicator decreases in Hard ROCK by only 41% due to its marginal increase in GDP, in Unfinished SYMPHONY and Modern JAZZ it improves by a factor of four. Similarly, the GDP per capita indicator (GDP) only slowly increases from 2030 to 2060 in Hard ROCK (+61%), while Unfinished SYMPHONY (176%) and Modern JAZZ undergo larger improvements (+236%) over the time horizon.

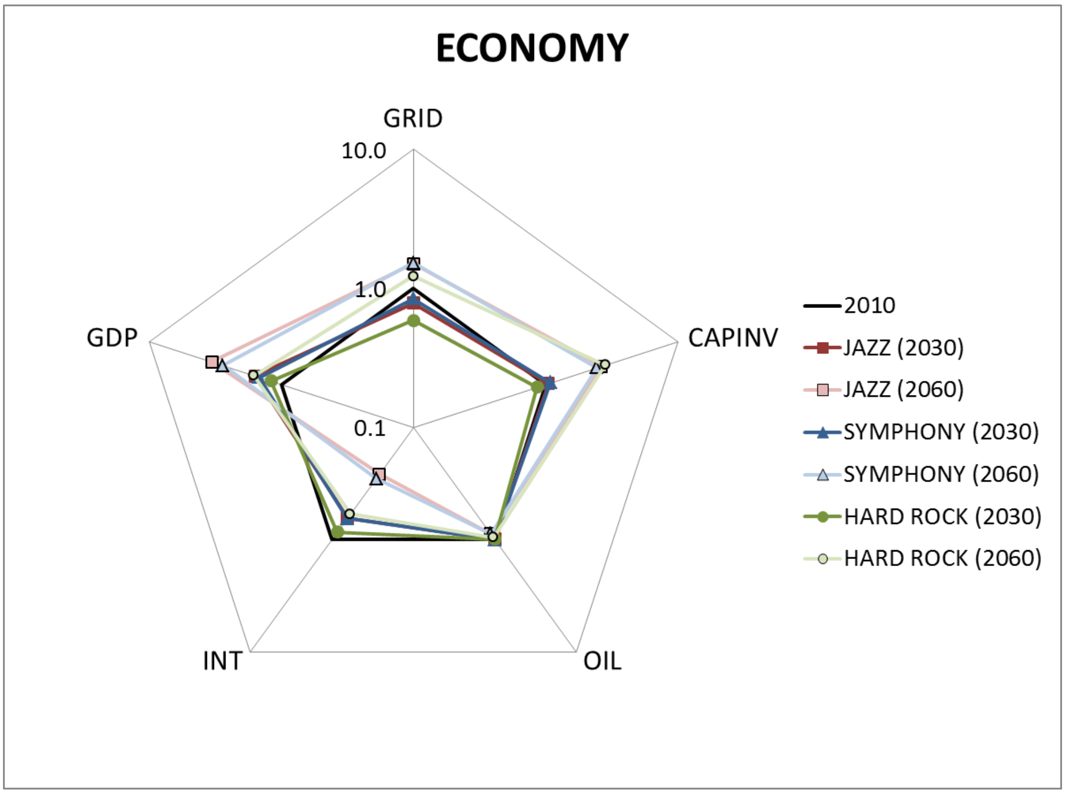


Figure 37: Performance of the three scenarios regarding economic indicators on a global level. The abbreviations are explained in Table 8.

The share of imports in TPES (IMP) decreases for all scenarios. The largest decrease is found for Hard ROCK (-55%) which is consistent with the focus on energy security in its storyline. The major importing regions are ASIAPAC, CHIANREG, EU31, INDIA and JPKRTW. Most imports are oil products, while biofuels are hardly traded. The share of renewable power generation (RENEW) steadily increases over the considered time horizon, particularly in Unfinished SYMPHONY (38% in 2060).

Particulate matter formation (PMF) peaks in 2020, 2030 and 2040 for Unfinished SYMPHONY, Modern JAZZ and Hard ROCK, respectively (Appendix, Table 43 to Table 45). Major contributors are direct emissions from coal furnaces and coal power generation and later also industrial diesel motors and wood furnaces. CHINAREG is the most important contributor, but INDIA's share is substantial and increasing. Human toxicity (HT) is more or less stable for Modern JAZZ by 2060 (-5%), but decreasing for Unfinished SYMPHONY (-19%) and increasing for Hard ROCK (+12%). CHINAREG and INDIA are the most important contributors, while the USA, which dominates in the first period, decreases its share by 2060. The indirect contributions, namely the impacts from heavy metal emissions in the spoil of coal mining and ash disposal, drive the HT impacts (Appendix, Table 43 to Table 45). Due to the trends of decreasing coal and increasing biomass use over the time horizon considered, the net change in this indicator over time is small. Photochemical oxidant formation (POF) is dominated by direct emissions from CHINAREG, INDIA, SSAFRICA and USA (Appendix, Table 43 to Table 45). It is dominated by the direct contributions of the energy system, mainly coal furnaces, coal power generation and diesel generating sets. The emissions peak in 2030 in Unfinished SYMPHONY and 2050 in Modern JAZZ. For Hard ROCK there is no peak within the considered time horizon and POF increases due to contributions from oil and gas mining, namely the combustion of gas in gas turbines at the well site and due to venting of natural gas.

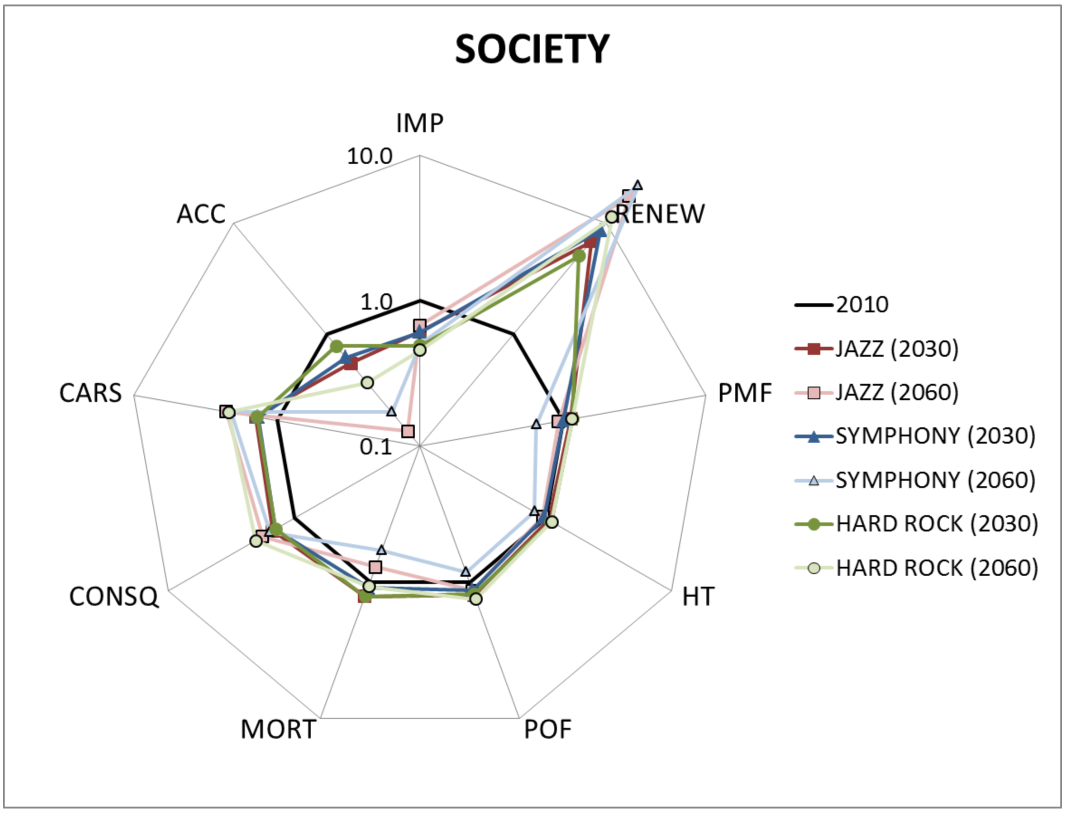


Figure 38: Performance of the three scenarios regarding social indicators on a global level. The abbreviations are explained in Table 9.

The major contributor to the indicator mortality in severe accidents in the energy sector (MORT) is the mining sector in CHINAREG. The indicator is lower in 2060 in Unfinished SYM-

PHONY (-41%) and Modern JAZZ (-23%) and higher in Hard ROCK (+7%). Besides the mining phase, also the transport and distribution phases also contribute significantly (Appendix, Table 43 to Table 45). On the global level, the maximum consequences in severe accidents indicator (CONSQ) is dominated by the oil sector (Appendix, Table 43 to Table 45). Apart from MENA, which is the major oil producer, the ASIAPAC, CHINAREG, INDIA and SSAFRICA regions also have high indicator values due to their oil imports. Based on the increase in oil consumption over the time horizon considered Hard ROCK performs worse (+102%) than the other two scenarios.

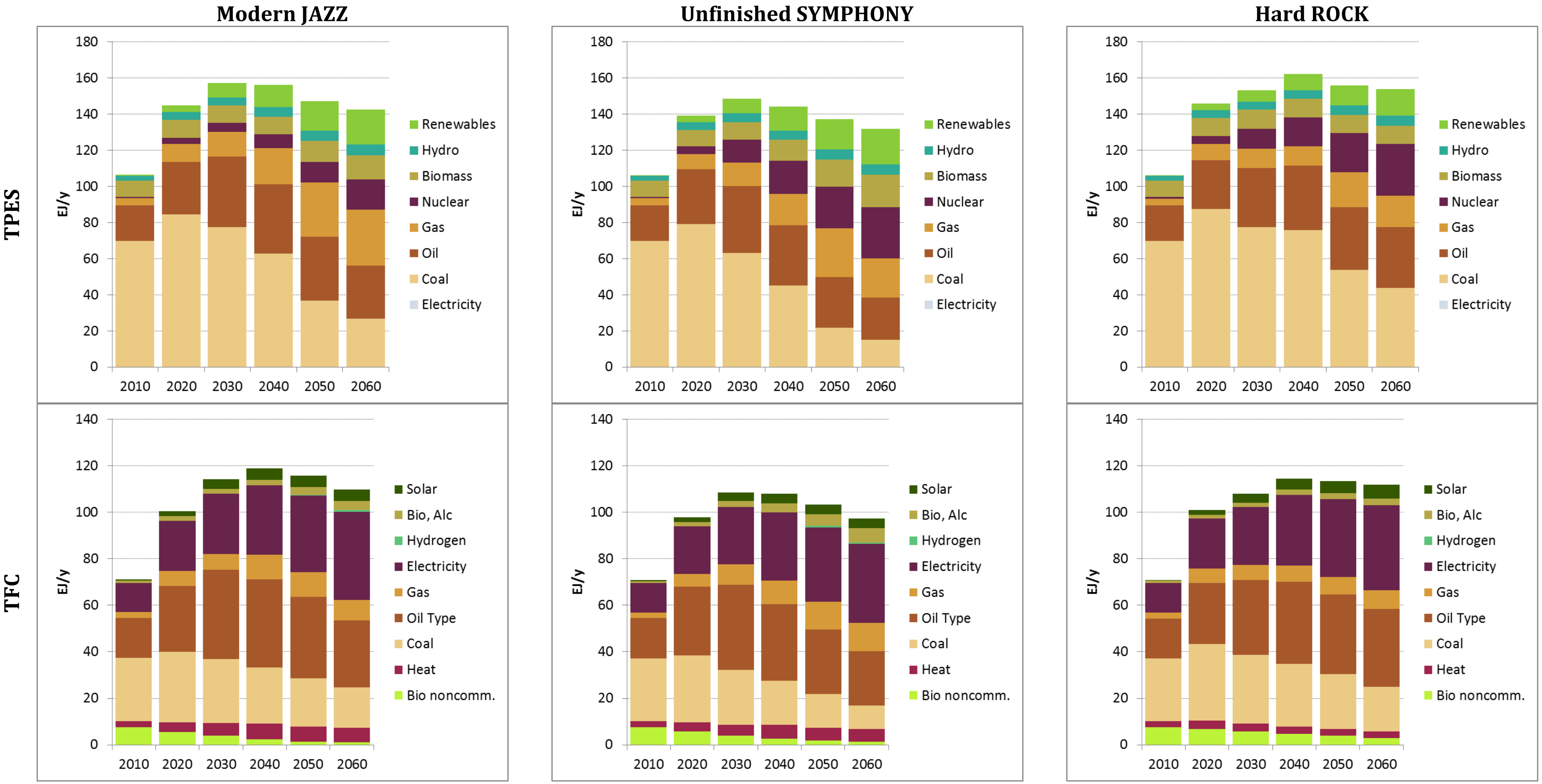
The two indicators for quality of life (see Table 9) also improve over time for all scenarios: The cars per capita (CARS) increase steadily by 2030 and 2060 (+109% and +126%, respectively) and the access to clean energy (ACC) is also improved, mostly in Modern JAZZ (+87%), followed by Unfinished SYMPHONY (+80%) and Hard ROCK (+63%).

4.3.5. Results for CHINAREG

In all three scenarios presented in Sections 4.3.1 to 4.3.3, CHINAREG had the highest contribution to the global TPES and TFC and is therefore of particular interest. The modelling region CHINAREG includes China, Macau and Mongolia. Its energy systems in the three scenarios are presented in Table 11, based on the TPES, TFC, electricity generation and CO_2 emissions. TPES and TFC peak in the time period analysed in all three scenarios. In the same period, the electricity generation grows strongly, particularly low-carbon power generation. The CO_2 emissions peak in 2020 to 2030 and decrease more or less afterwards depending on the scenario. CHINAREG's performance regarding the set of sustainability indicators is presented in Figure 39 (environment), Figure 40 (economy) and Figure 41 (society).

The fossil resource use increases in all scenarios by 2030, but decreases towards 2060 reaching lower (-36% in Unfinished SYMPHONY) or similar (Hard ROCK and Modern JAZZ) levels than in 2010. Coal use is particularly reduced towards the mid-century. The use of nuclear energy resources for power generation instead is strongly increased in all scenarios and reaches particularly high levels in Unfinished SYMPHONY and Hard ROCK.

Table 11: TPES, TFC, electricity generation and CO_2 emissions in the three scenarios in CHINAREG



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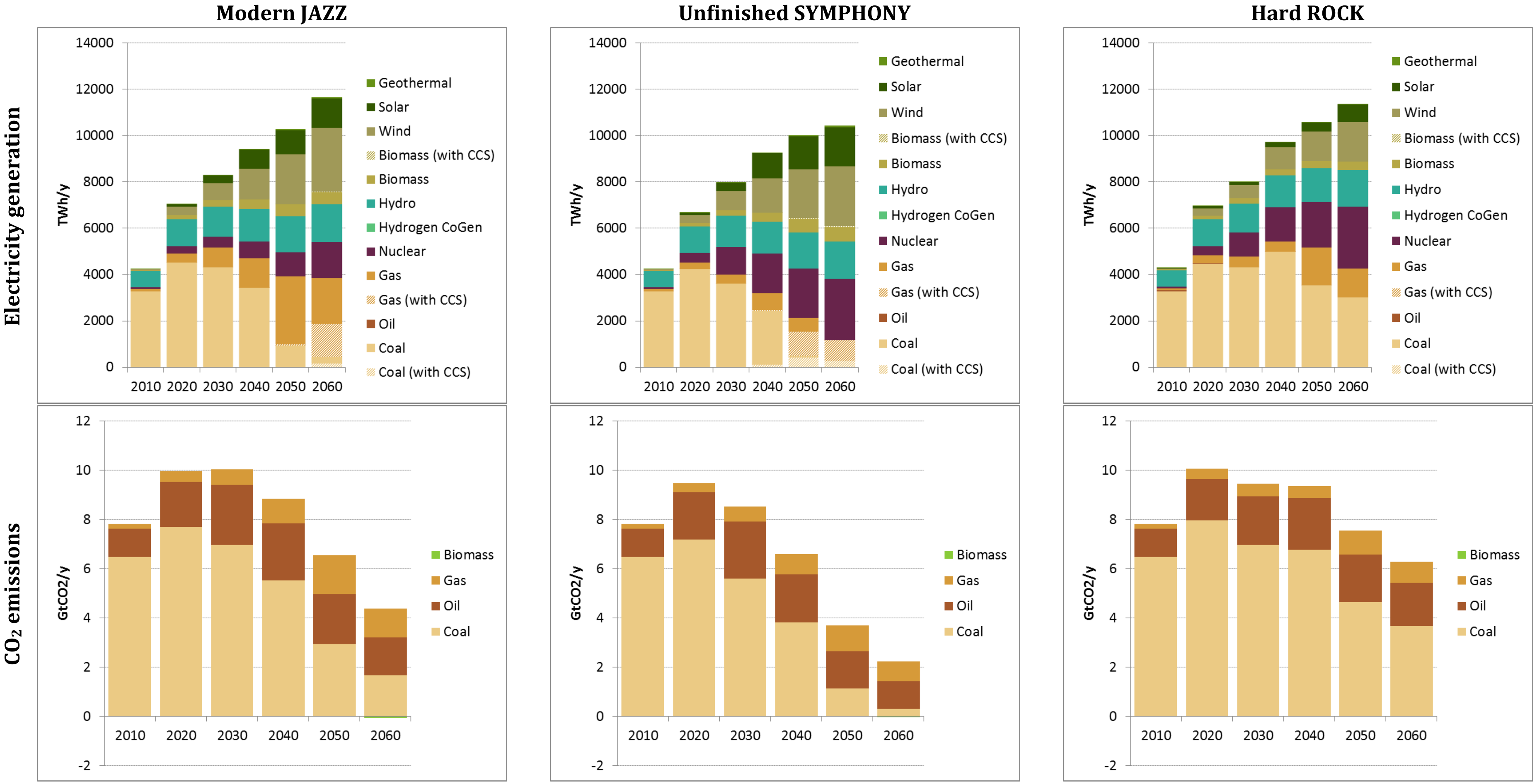


The level of water use is more or less constant in the three scenarios and over the time horizon. Direct water use, which is mainly in coal mining, is reduced over time, while the indirect contribution of biomass cultivation increases with the increase in the use of biomass technologies.

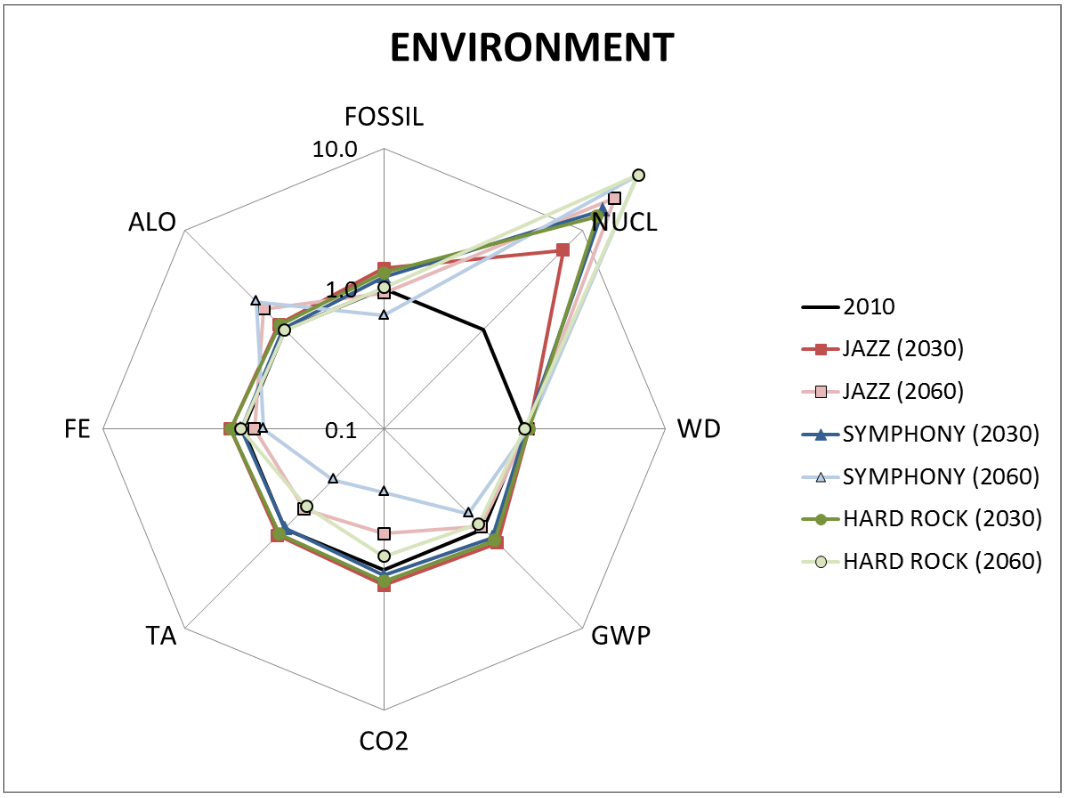


Figure 39: Performance of the three scenarios regarding environmental indicators in CHINAREG. The abbreviations are explained in Table 8.

After short-term increase in all three scenarios due to use of coal, CO_2 emissions drop towards the end of this century due to the phase-out of coal, particularly in Unfinished SYMPHONY (-72%). GHG emissions have similar trends to CO_2 emissions, but the reductions by 2060 are lower (-5% for Modern JAZZ, -29% for Unfinished SYMPHONY and -10% for Hard ROCK). TA is driven by coal use for heat and power. Due to the reduction in coal use for these purposes, the impact is reduced by 2060 (-37% for Modern JAZZ, -68% for Unfinished SYMPHONY and -40% for Hard ROCK).

Coal mining is the major contributor to FE. Therefore, the indicator is lowest for the low-coal Unfinished SYMPHONY pathway (-28% in 2060 compared to 2010) and highest for the Hard ROCK pathway (+4% in 2060 compared to 2010). ALO is highest for Unfinished SYMPHONY due to the expansion of biomass energy by 2060 (+92%). In contrast, it is almost constant for Hard ROCK (-1%) which has a stable contribution of biomass to TPES.

Compared to the other years in the time period analysed, 2030 has low investments in T&D infrastructure which leads to lower T&D investments per unit of electricity produced and transmitted. The reason for the lower investments is the decentralised solar PV power generation which makes up a large share of the capacity expansion by 2030. Compared to 2010, the T&D investments in 2060 are 22% and 19% higher for Modern JAZZ and Unfinished SYMPHONY, respectively, and 10% lower for Hard ROCK. Similarly, the capital investments in the power sector in 2030 are low compared to the other time periods due to lower investment in less capital intensive technologies (gas, solar PV, and wind instead of oil and coal). In 2060, the investments in the power sector are higher than in all previous periods.

The share of oil in transport fuels decreases by 2030 in all three scenarios. Towards 2060 alternative fuels enter the fuel mix, particularly electricity and natural gas. The share of oil-based fuels remains highest in the Hard ROCK scenario, which has the lowest CO_2 costs among the three scenarios. The energy efficiency of the economy, i.e. the ratio of TPES and GDP (INT), increases for all scenarios over the time horizon considered. Compared to 2010, Unfinished SYMPHONY and Modern JAZZ profit from increasing GDP and decreasing TPES and reduce the intensity by 85% and 86% respectively. The GDP per capita increases in all scenarios. Due to the identical population development, the difference between the scenarios is driven by the GDP development, which is highest for Modern JAZZ and lowest for Unfinished SYMPHONY.

The energy carrier imports of the Hard ROCK scenario stay low over the time horizon considered in accordance with the storyline. In Modern JAZZ and Unfinished SYMPHONY, there is an increase in oil imports and later also an increase in natural gas imports. In 2060, the import share of Unfinished SYMPHONY reaches 2010 levels, while the share stays at a high level (29%) in Modern JAZZ. All scenarios describe strongly increased and continuously growing shares of renewable power generation. Consistent with the storyline, Unfinished SYMPHONY has the highest share of renewable power generation, while Hard ROCK lags behind.

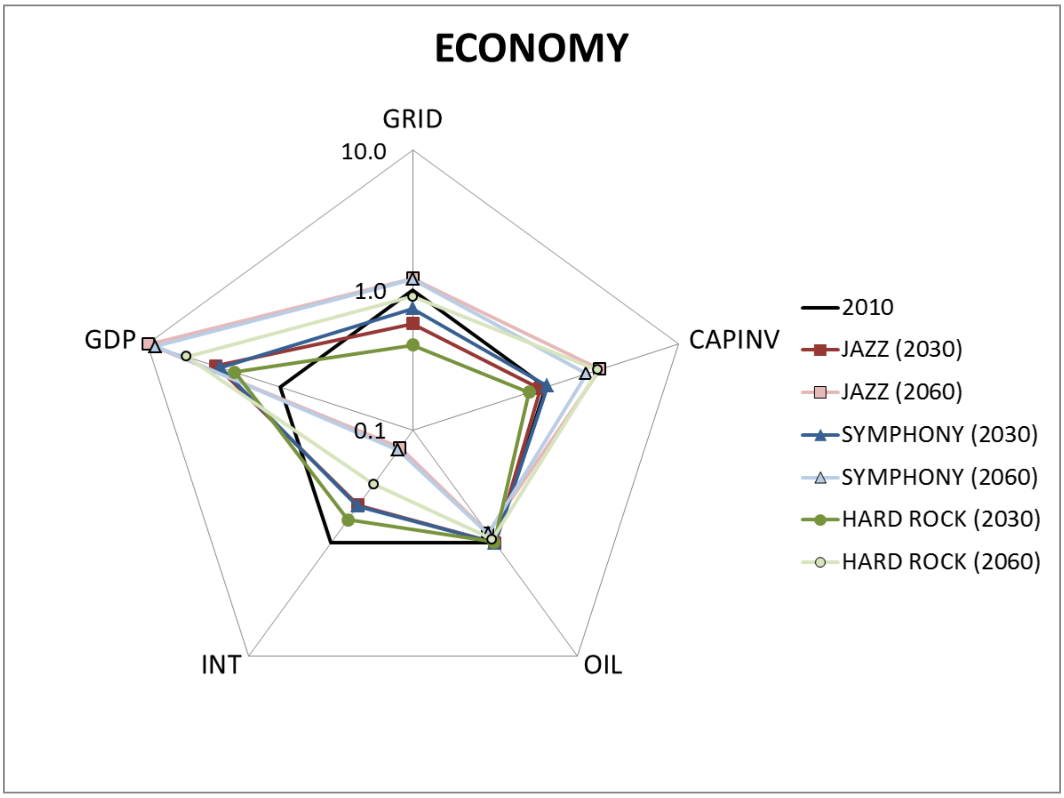


Figure 40: Performance of the three scenarios regarding economic indicators in CHINAREG. The abbreviations are explained in Table 8.

After an medium increase, PMF decreases in all scenarios by 2060. With the reduction in coal use, Unfinished SYMPHONY follows the lowest trajectory (-61% in 2060 compared to 2010). Modern JAZZ (-23%) performs worse than Hard ROCK (-36%) due to the use of more diesel generating sets. The HT level increases in Modern JAZZ (+24%), Unfinished SYMPHONY (+8%) and Hard ROCK (+19%) by 2060 compared to 2010. While the direct contribution from coal combustion decreases, the indirect contributions from coal mining (heavy metal emissions from spoils), biomass heating systems (ash disposal) and oil-based freight transport (brake wear emissions) increase. The POF is driven by the combustion of coal for heat and power and industrial diesel motors. Due to the wide application of industrial diesel motors and coal furnaces in Modern JAZZ, the overall impact is not reduced by 2060 compared to 2010 (+3%). In contrast, POF decreases in Unfinished SYMPHONY (-45%) and Hard ROCK (-28%).

The mortality in severe accidents in the energy sector in CHINAREG is mainly driven by coal mining. After an increase of mortality in 2020 and 2030 it decreases for all scenarios by 2060, particularly for the Unfinished SYMPHONY (-67%) and to a lesser extent in Modern JAZZ (-23%) due to the strong reduction in coal use. The maximum consequences of severe accidents in the energy sector are highest in Hard ROCK and dominated by the contribution of the oil sector. With the strong increase in oil consumption in the midterm, the indicator also increases temporarily for all scenarios. The quality of life indicators (according to the two indicators in Table 9) improve in all three scenarios: The level of cars per capita grows in step. The access to clean energy improves by 2060 compared to 2010, but – while Unfinished SYMPHONY (+81%) and Modern JAZZ (+85%) reach very high access levels – Hard ROCK (+63%) lags behind.

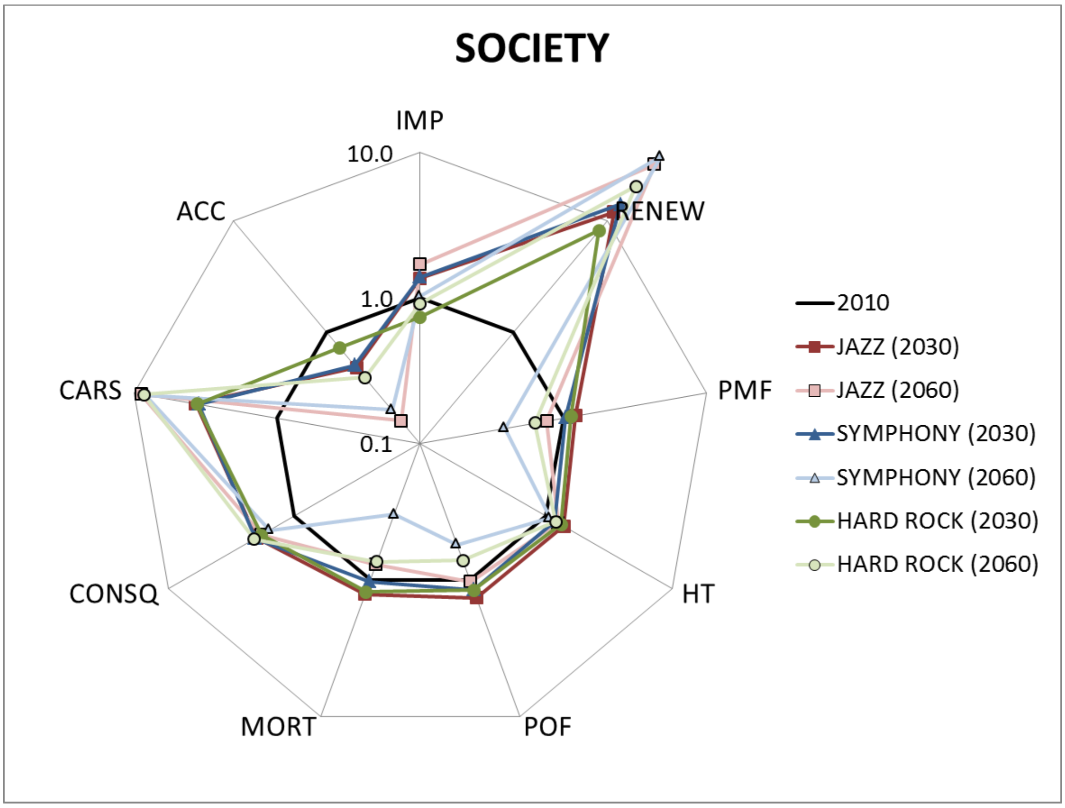


Figure 41: Performance of the three scenarios regarding social indicators in CHINAREG. The abbreviations are explained in Table 9.

4.3.6. Results for EU31

The second region which is analysed in detail is EU31 (EU28 including Switzerland, Norway and Liechtenstein) as an example of a developed region. EU31's energy systems in the three analysed scenarios are presented in Table 12 based on the TPES, TFC, electricity generation and

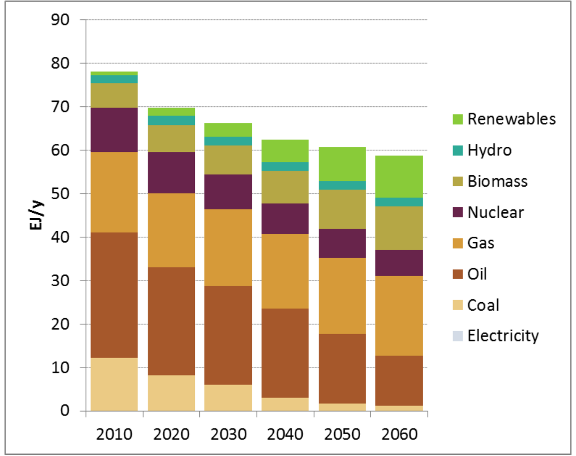
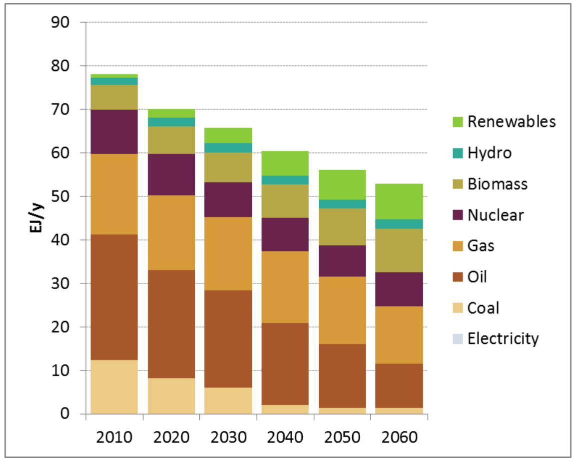
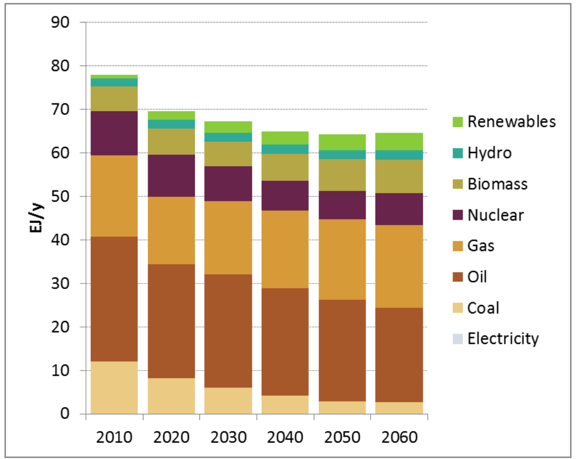
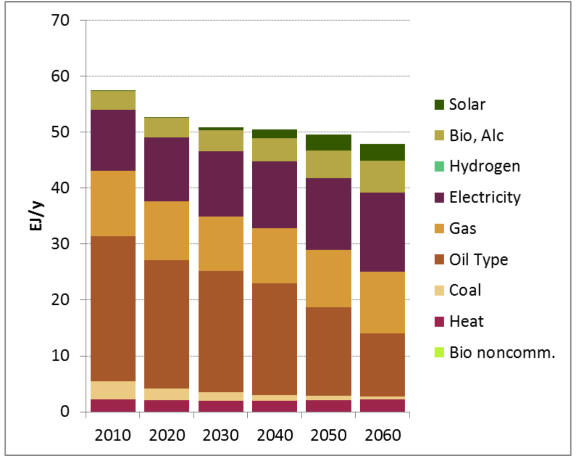
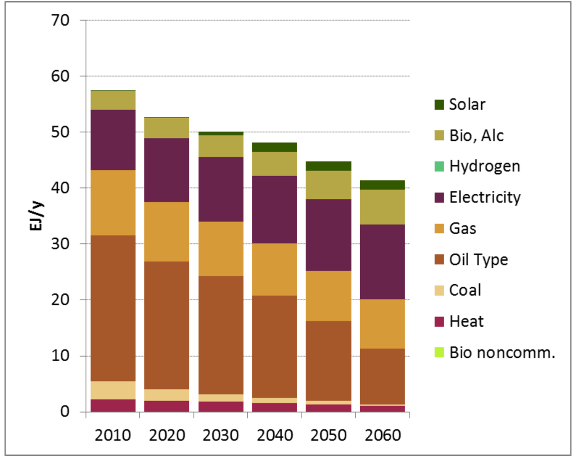
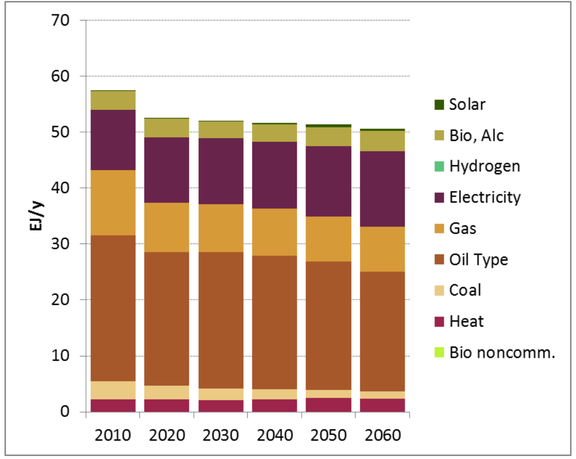
CO_2 emission. The region is characterised by decreasing TPES and TFC over the time horizon considered. Electricity generation increases slightly by expanding low-carbon generation. With the coal phase-out, CO_2 emissions decrease in all scenarios. EU31's performance regarding the set of sustainability indicators is presented in Figure 42 (environment), Figure 43 (economy) and Figure 44 (society).

The fossil resource use of EU31 is reduced in all scenarios. Unfinished SYMPHONY (-59%) and Modern JAZZ (-48%) phase out coal and oil, while natural gas remains in the mix. Hard ROCK instead keeps the oil and natural gas use almost constant, preserving a high share of fossil energy in TPES. Nuclear resource use is reduced slowly over the time period considered for all scenarios due to the reduction in nuclear power generation (-40%, -24% and -29% for Modern JAZZ, Unfinished SYMPHONY and Hard ROCK). WD increases in all scenarios by 2060. The contribution of biomass cultivation is the major source of WD and increases with the share of biomass in TPES, which is similar for all scenarios (+49% to +57% compared to 2010).

The phase-out of coal and oil use in Unfinished SYMPHONY and Modern JAZZ results in significantly lower CO_2 emissions in 2060 compared to 2010 (-71% and -61%, respectively). In Hard ROCK, the CO_2 emissions also drop by 2060, but much less than in the other two scenarios (-34% compared to 2010). There are similar trends for GHG emissions, which nevertheless decrease less than CO_2 emissions due to non-CO_2 GHG emissions.

There is a positive development of TA in all scenarios over the time horizon, particularly in Modern JAZZ (-63%) and Unfinished SYMPHONY (-67%). Fewer industrial furnaces and diesel motors contribute to the decrease in TA. The FE mainly stems from coal mining (spoils) and electric devices in the residential sector (tailings from metal mining). FE improves in all three scenarios due to the reduction in coal mining, which is least pronounced in Hard ROCK (-31% in 2060 compared to 2010). Similar to WD, ALO increases by 2060 in all three scenarios due to the expansion of biomass energy (+36%, +41% and +39% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively).

Table 12: TPES, TFC, electricity generation and CO_2 emissions in the three scenarios in EU31

	Modern JAZZ	**Unfinished SYMPHONY**	**Hard ROCK**
TPES			
TFC			

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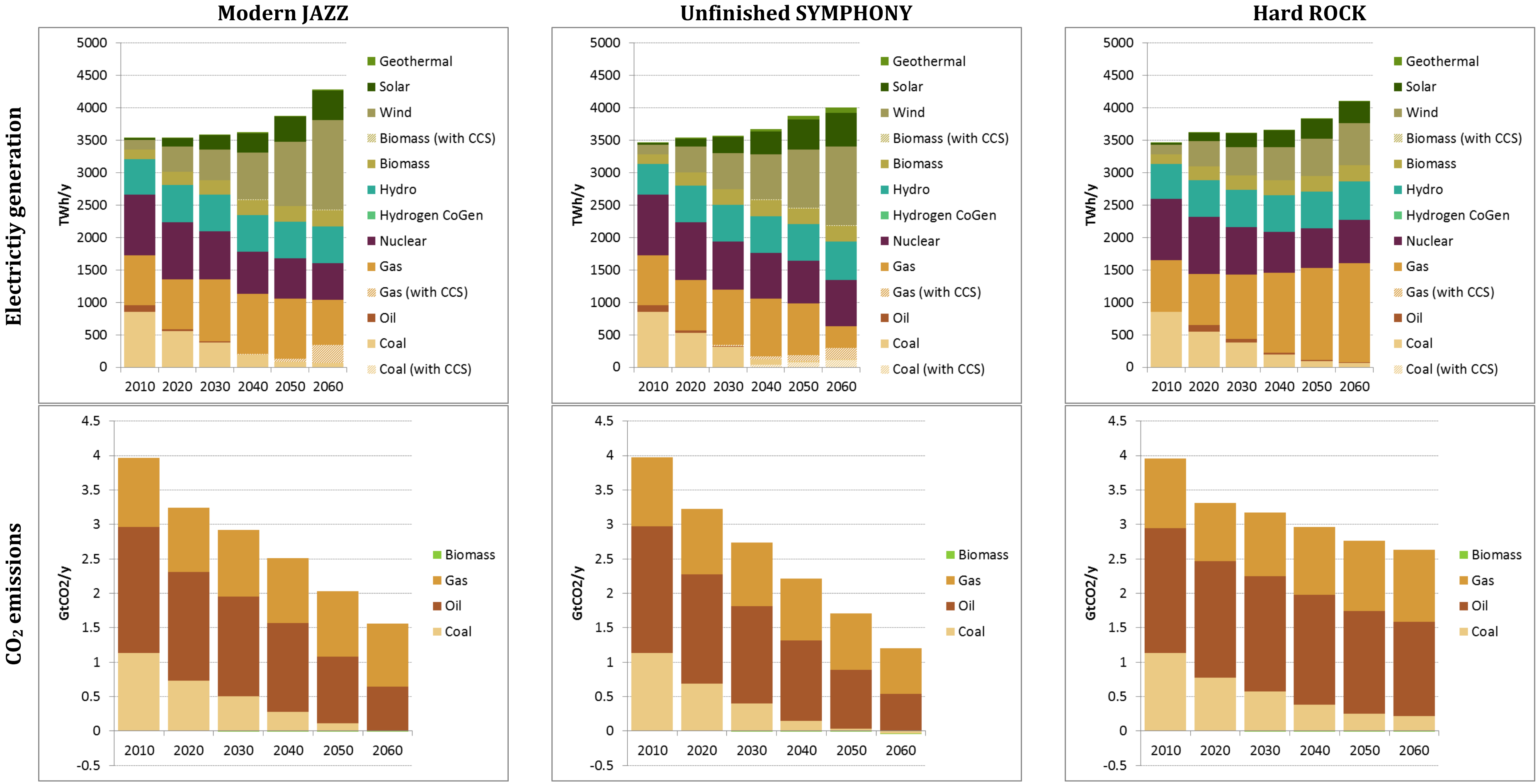


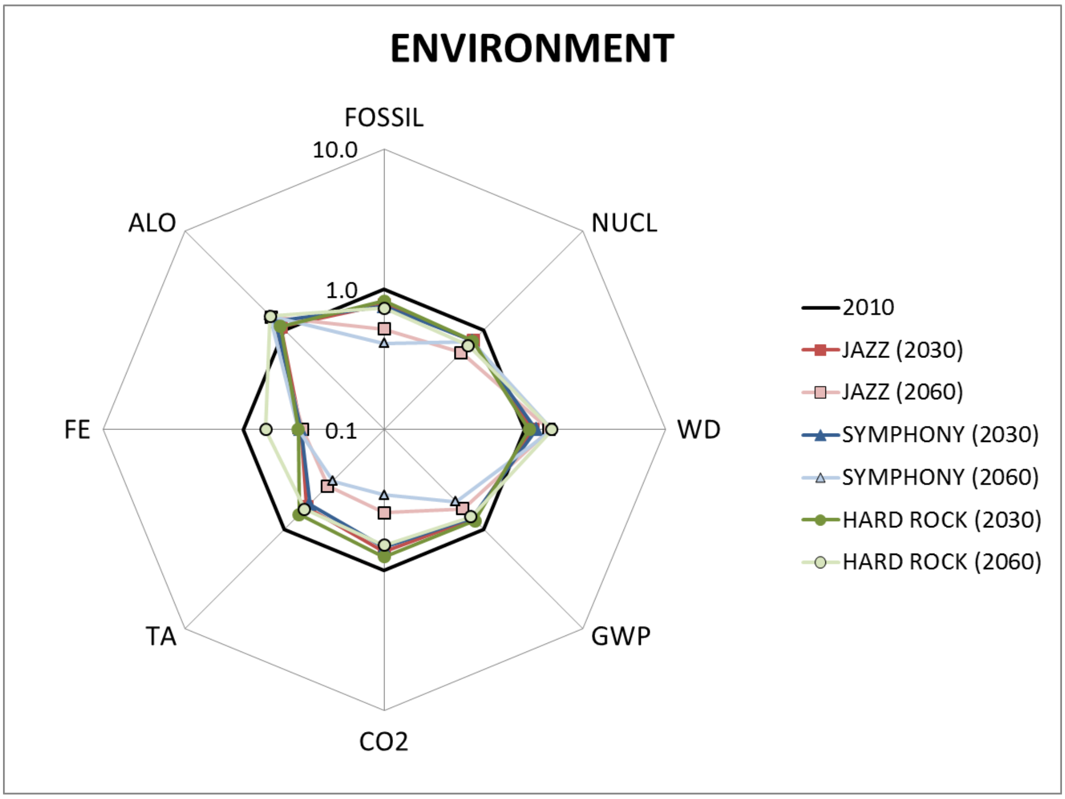


Figure 42: Performance of the three scenarios regarding environmental indicators in EU31. The abbreviations are explained in Table 8.

Grid investments in 2030 are low compared to the other time periods under consideration due to the strong expansion of decentralised solar PV power generation. Together with a slightly increase in electricity generation this leads to a lower and higher ratio in 2030 and 2060, respectively, for all scenarios (+58%, +64% and +51% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK in 2060 compared to 2010). Similarly, the capital investments in the power sector are lower in 2030 due to fewer investments and fewer investments in capital intensive technologies and higher 2060 compared to 2010.

The share of oil in transport fuels remains almost 100% in Hard ROCK. While the oil share is still high in 2030, it is significantly lower in 2060 for Unfinished SYMPHONY (82%) and Modern JAZZ (76%) when electric and gas technologies enter the transport sector. The energy intensity (INT) is strongly reduced in Unfinished SYMPHONY (-69%) and Modern JAZZ (-68%) due to the combination of decreasing TPES and increasing GDP. Hard ROCK instead lags behind due to its slow increase in GDP and slow decrease in TPES (-39%). The differences of GDP per capita between the scenarios are only influenced by the GDP, while the population development is the same. There is a stronger increase of per capita GDP over the time horizon in Unfinished SYMPHONY (+122%) and Modern JAZZ (+139%) than in Hard ROCK (+37%) in accordance with the corresponding storylines.

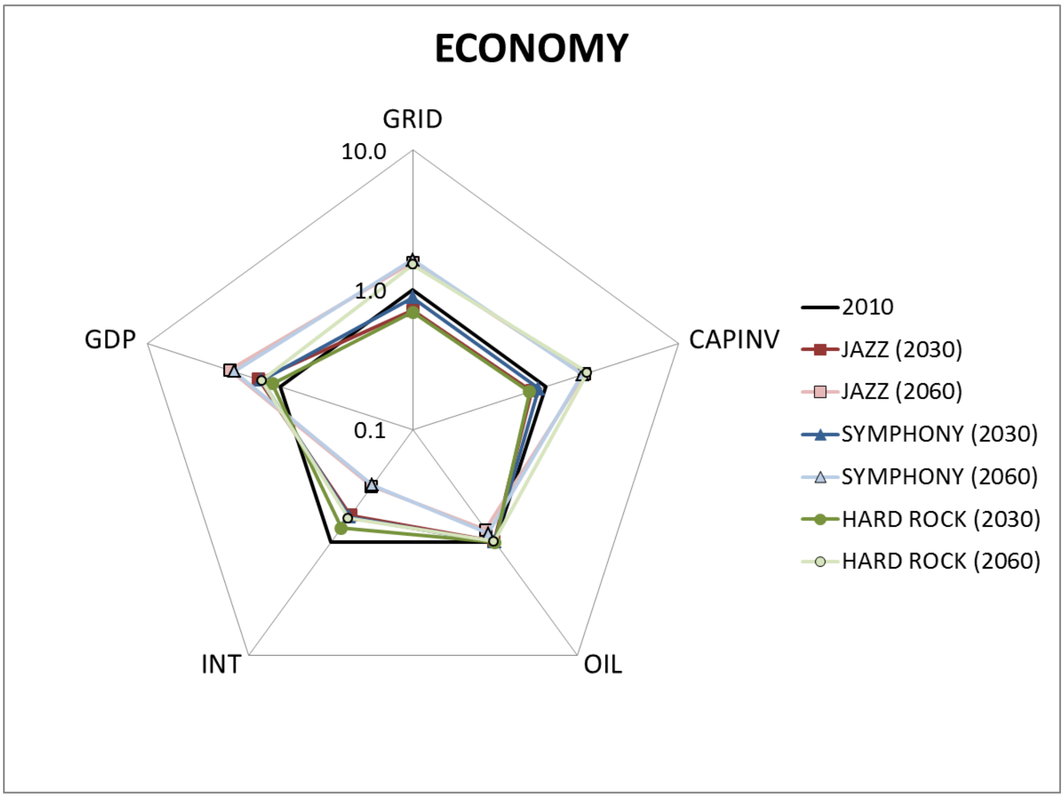


Figure 43: Performance of the three scenarios regarding economic indicators in EU31. The abbreviations are explained in Table 8.

The share of energy carrier imports is reduced in all scenarios by 2060, particularly in Unfinished SYMPHONY (38%) and Hard ROCK (39%) in which the energy carrier imports drop faster than the TPES. But for Modern JAZZ the respective share also drops from 79% in 2010 to 45% in 2060. The share of renewable power generation is higher in 2030 and 2060 for all scenarios compared to 2010. The renewable share increases to 43% in Unfinished SYMPHONY and Modern JAZZ by 2060, mainly driven by wind, but also solar energy, while Hard ROCK lags in this respect (24% in 2060).

There is a reduction of PMF over the period from 2010 to 2060 (-50%, -57% and -26% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively), which is mainly driven by the reduction of coal furnaces, but also diesel cars. The development of HT is similar in the three scenarios: While the contribution of oil-based freight transport and coal mining drops, the contributions of biomass technologies and electric devices in the household sector increase over the time horizon considered leading reduction in HT of -32%, -38% and -21% in 2060 compared to 2010. POF mainly decreases due to the reduction of coal furnaces and diesel cars by 2060. This development is less pronounced in Hard ROCK (-12%), which also faces an increase in POF due to the expansion of diesel motors in industry.

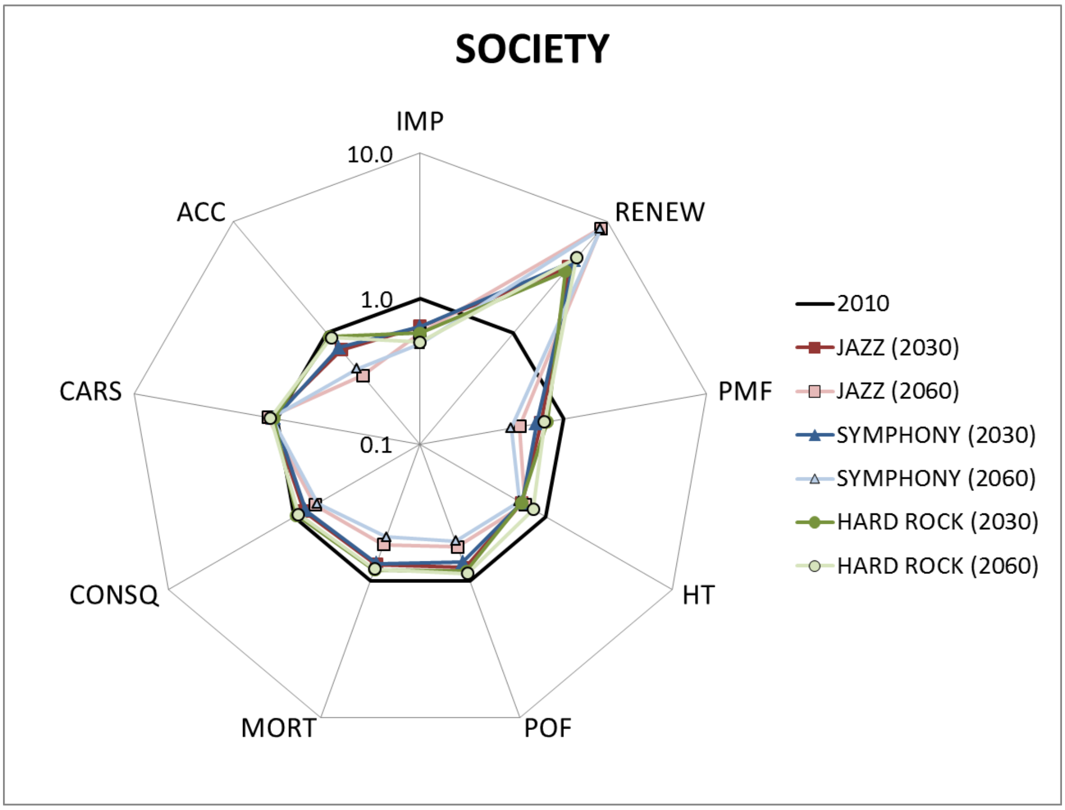


Figure 44: Performance of the three scenarios regarding social indicators in EU31. The abbreviations are explained in Table 9.

The expected mortality in severe accidents in the energy sector in Unfinished SYMPHONY (-92%) and Modern JAZZ (-45%) is reduced by 2060 due to the lower use of fossil fuels and the correspondingly reduced mortality related to extraction and T&D. In the Hard ROCK scenario, only a comparably small reduction can be observed, even in 2060 (-18%). In EU31, the maximum consequences of severe accidents are dominated by the oil sector. Nuclear power generation is another relevant contributor to this indicator, which decreases along with the decrease in nuclear power generation over the considered time horizon (-32%, -35% and -7% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively). EU31 starts from a high level of cars per capita in 2010, so the improvements are only marginal in all scenarios. The same holds true for the access to clean energy: Starting from a very high access level, the access is further improved to almost 100% by 2060.

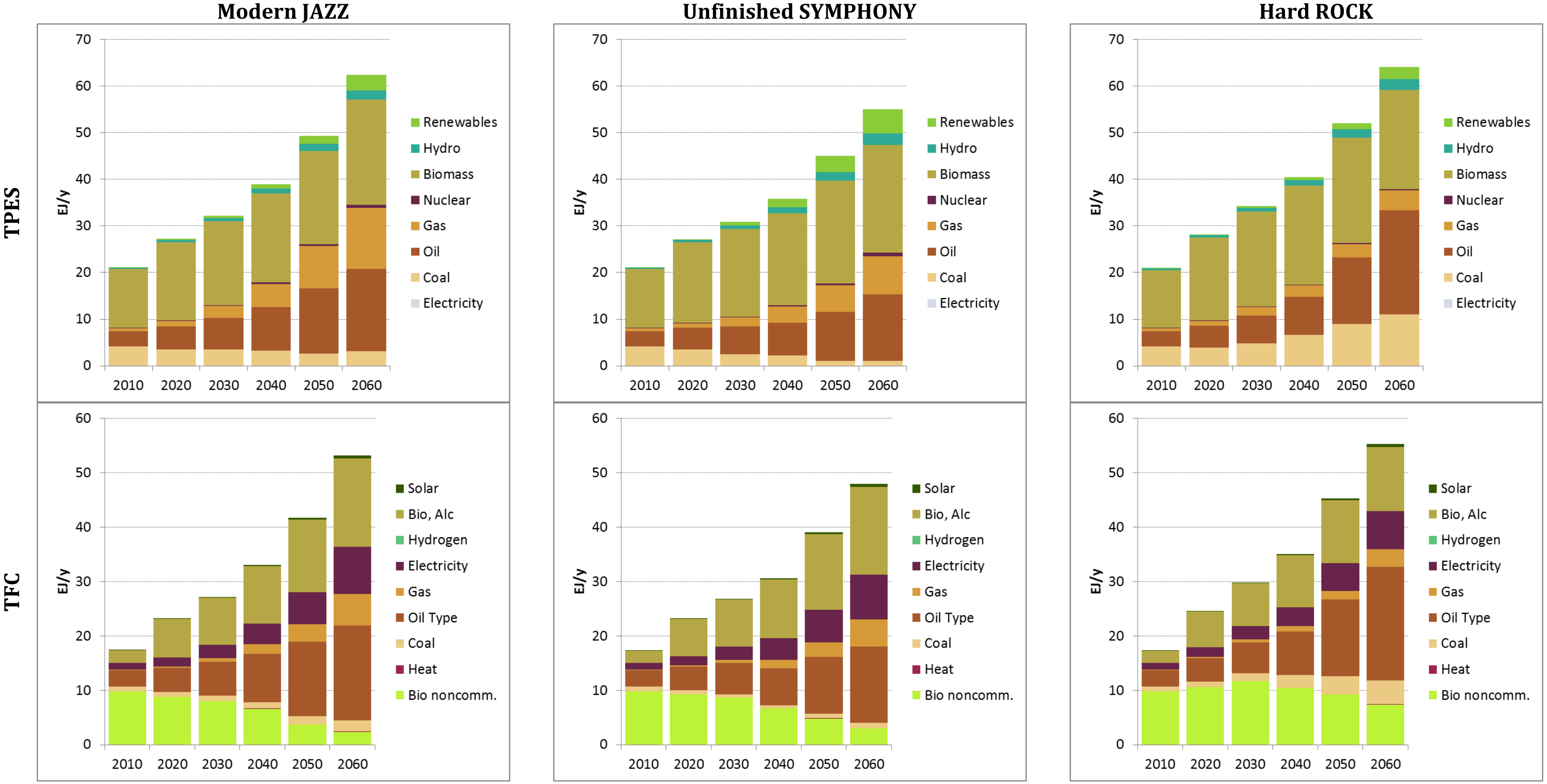
4.3.7. Results for SSAFRICA

SSAFRICA is analysed as a third region which is a developing area with an increasing contribution to both global TPES and TFC. Its energy system is described in Table 13. SSAFRICA strongly relies on biomass energy. The share of non-commercial biomass however decreases over the time horizon. Electricity generation strongly increases and the electricity mixes vary strongly between the three scenarios. Similarly, the shares of fossil fuels in TPES and the CO_2 emissions strongly depend on the scenario. The performance of SSAFRICA regarding the environmental, economic and social indicators is presented in Figure 45, Figure 46 and Figure 47, respectively.

The fossil energy use of SSAFRICA increases towards 2030 and further by 2060. The increase is particularly related to the consumption of oil and natural gas. Unfinished SYMPHONY has the lowest fossil fuel use, but the highest nuclear resource use. The level of nuclear energy is and stays at a very low level in all scenarios. WD increases strongly in all scenarios as biomass energy is an important and growing energy resource in SSAFRICA (lowest in Hard ROCK scenario).

As indicated by the fossil resource use, the increasing combustion of oil and natural gas results in higher CO_2 emissions for 2060 compared to 2010 for all scenarios (+181%, +67% and +302% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively). GHG emissions also increase – even more than the CO_2 emissions – due to the contribution of other GHG emissions. TA increases in all scenarios over the time horizon considered (+171%, +104% and +337% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively). Major contributors are coal – particularly in Hard ROCK – and biomass furnaces as well as diesel motors in industry.

Table 13: TPES, TFC, electricity generation and CO$_2$ emissions in the three scenarios in SSAFRICA



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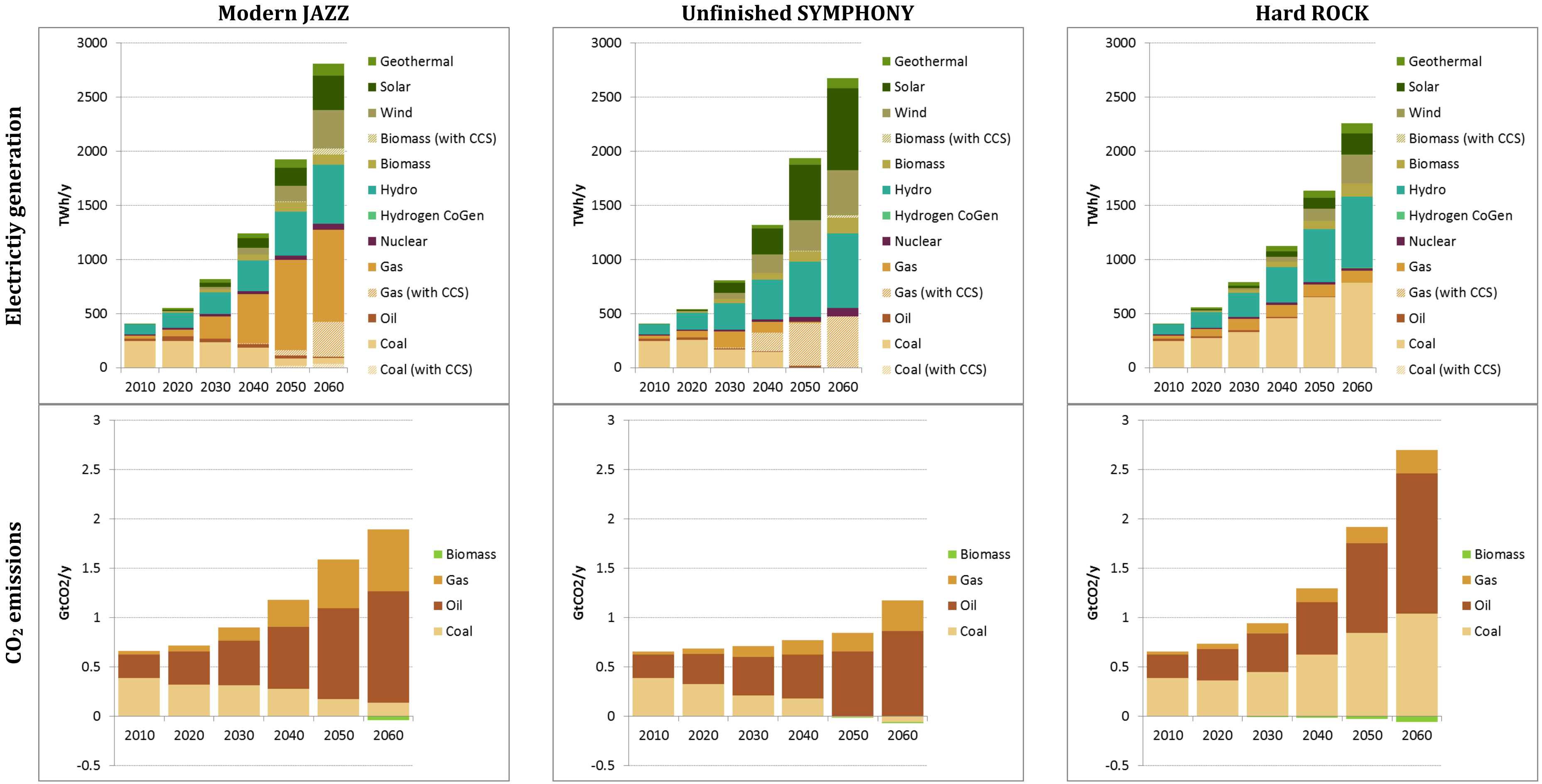


Unfinished SYMPHONY has lower FE in 2030 and 2060 (-54%) due to the reduction in coal mining compared to 2010, while Modern JAZZ has a more or less constant level of coal mining and thus a lower FE reduction over the considered time horizon (-22%). Hard ROCK instead builds on an increasing share of coal in TPES which leads to an amplified FE, particularly in 2060 (+97% compared to 2010). ALO quickly reaches a plateau based on exhausting the biomass potential of SSAFRICA.

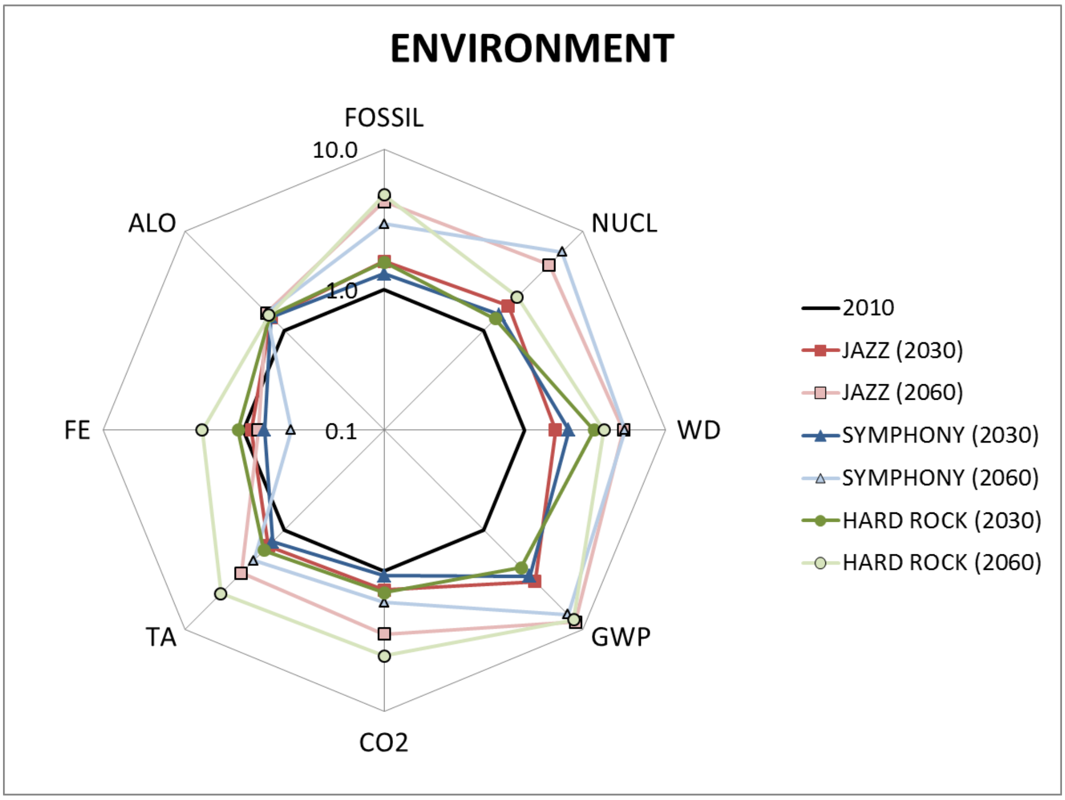


Figure 45: Performance of the three scenarios regarding environmental indicators in SSAFRICA. The abbreviations are explained in Table 8.

The grid investments are higher in all scenarios in 2060 than in 2010. The capital investments in the power sector are expanded in all scenarios over the time horizon considered due to the higher share of electricity in TFC. The fuels in transport are more than 95% oil-based for all scenarios and time periods. The energy intensity of the economy (INT) is improved over the time period considered as the increase in TPES is more than compensated for by the increase in GDP. Thus, Unfinished SYMPHONY (-88%) and Modern JAZZ (-91%) perform particularly well in 2060. The GDP per capita increases for all scenarios, but Modern JAZZ performs better than the other two scenarios.

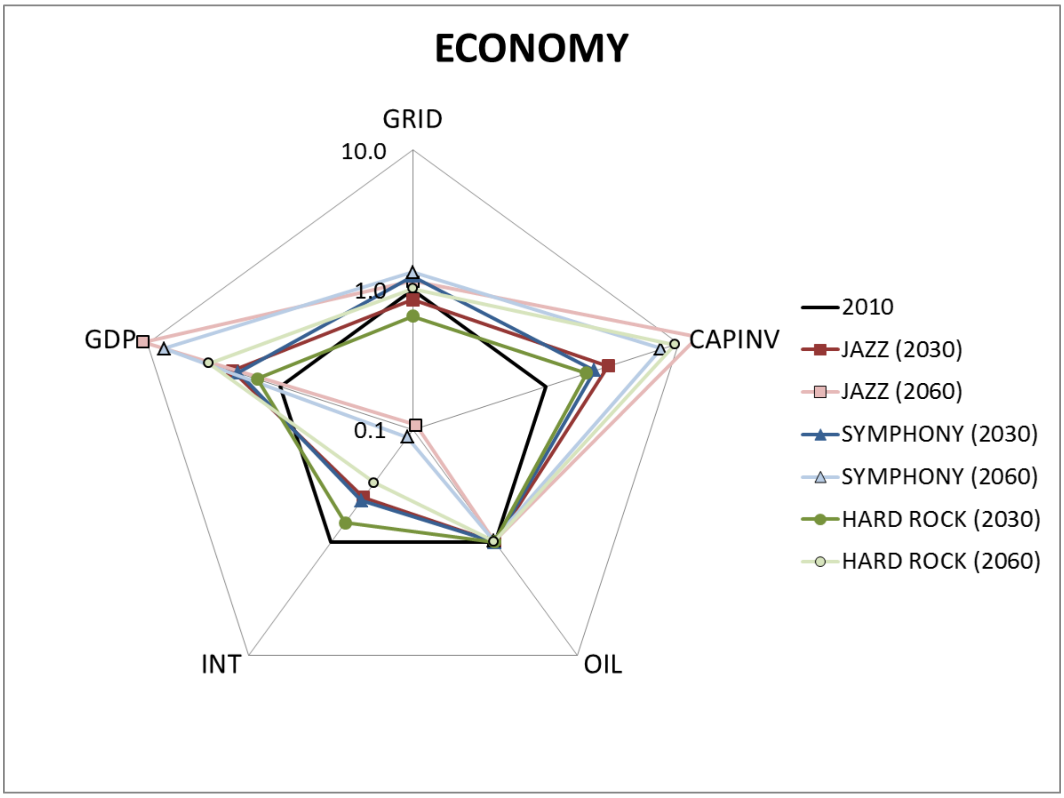


Figure 46: Performance of the three scenarios regarding economic indicators in SSAFRICA. The abbreviations are explained in Table 8.

Energy carrier imports and their share of the TPES remain on a low level for all scenarios and time steps. It is mostly oil that is imported from other world regions. Starting from a power generation system without renewable energies, their share constantly increases reaching the highest levels in Unfinished SYMPHONY (44%).

The increased deployment of biomass technologies as well as diesel motors and coal furnaces in industry increases the level PMF over the time horizon (+266% +192% and +420% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively). HT also increases by 2060 (+149%, +117% and +198% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively). Major contributors to HT are biomass combustion, oil-based freight transport and coal mining. The increase in POF can be mainly allocated to biomass technologies, which are increasingly deployed over the considered time horizon (+172%, +118% and +265% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively).

The expected mortality in severe accidents is driven by the transport of energy carriers. It increases for all scenarios by 2060 (+210%, +169% and +316% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively) particularly due to more hydro power generation and oil T&D. The indicator for the maximum consequences of severe accidents is dominated by the oil chain. It increases in all scenarios due to the strong increase in oil consumption of SSAFRICA by 2060. The region's quality of life (according to the two indicators in Table 9) also improves: The number of cars per capita increases by a factor of 5 to 6 for all scenarios from 2010 to 2060 as the number of cars grows more than the number of people. Starting from a comparably high level of people without access to clean energy, the situation has already improved in 2030 but even more so in 2060. Hard ROCK lags in this respect compared to the other two scenarios (+75% compared to +92% for Modern JAZZ and +90% for Unfinished SYMPHONY).

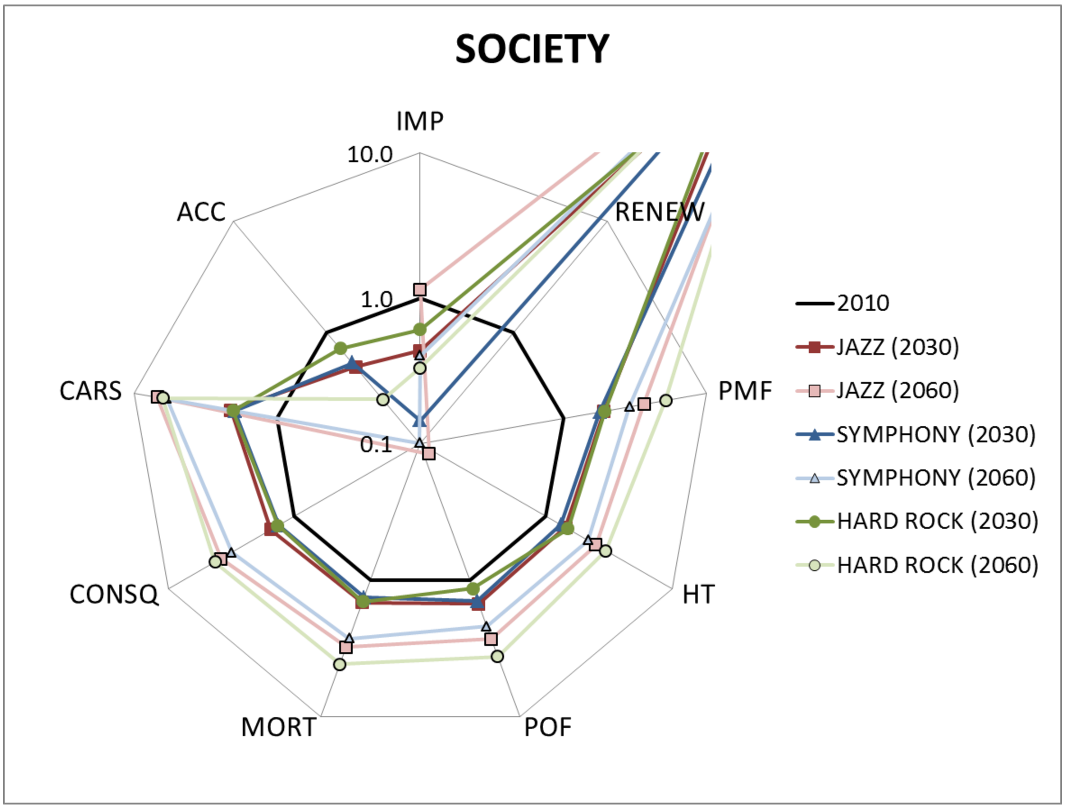


Figure 47: Performance of the three scenarios regarding social indicators in SSAFRICA. The abbreviations are explained in Table 9.

4.4. Discussion

4.4.1. Insights from the case study

In addition to the global multi-criteria sustainability analysis (Section 4.3.4), results of three illustrative regions at different stages in their development are described in detail in Sections 4.3.5 to 4.3.7. The analysis of global results gives a good overview and some general insights on the performance of the scenarios, but the global perspective averages out pronounced differences in developments on a regional scale. Therefore, and because many indicators reflect local impacts or developments, the regional results are considered as being more informative.

The regional quantification of TPES and TFC reveals that CHINAREG is and stays an important region, while EU31 and USA decrease their shares. Important emerging regions include INDIA, MENA and SSAFRICA. After reaching a peak in energy demand in 2030 or 2040, CHINAREG improves with regard to many environmental and human health indicators. Also the economic and social development is positive in the three scenarios. In contrast, the increase in oil consumption results in more potential fatalities in severe accidents, high vulnerability to variable oil prices and increased dependency on energy imports.

As stated above, the TPES and TFC of EU31 decrease by 2060. Due to the shift to more renewable energies the environmental, human health and accident risk indicators improve in all three scenarios. However, this transformation leads to more intermittent power generation, more ALO and more water use. The economic indicators and quality of life (according to the two indicators in Table 9) develop positively in EU31, starting from a very high level. Overall, the changes in the indicator values are much smaller than for CHINAREG.

In contrast, SSAFRICA as a developing region undergoes large changes in the indicator values. Despite large shares of renewable energies in its increasing TPES and TFC, all environmental, human health and risk indicators (except for FE in Modern JAZZ and Unfinished SYMPHONY) worsen. However, the development of the economy and quality of life (according to the two indicators in Table 9) is positive, even though large capital investments must be financed.

Comparing the three scenarios on a global level, TPES and TFC increase over the time horizon considered in the Hard ROCK scenario. Despite the fact that the share of fossil fuels in TPES decreases and the share of electricity in the TFC increases, Hard ROCK is found to have similar environmental and human health impacts of CO_2, TA, FE, PMF, POF and HT in 2060 compared to

2010. The Unfinished SYMPHONY scenario is characterised by constant TPES and TFC from the middle of the time horizon. Combined with the decrease in the share of fossil fuels in TPES and the share of electricity from renewable energies in the TFC, environmental and human health impacts such as fossil resources, CO_2, GWP, TA, FE, PMF, HT, POF and mortality in severe accidents improve by 2060. The Modern JAZZ scenario usually lies in between the two other scenarios and – despite the increase in TPES and TFC by 2060 – CO_2, TA, FE and mortality in severe accidents improve. Compared to Hard ROCK, Modern JAZZ and Unfinished SYMPHONY have particular strengths related to access to clean energy, GDP per capita and TPES per GDP.

Important technologies ("hotspots") regarding the set of bottom-up indicators are related to coal (mining, heating, process heat, power), industrial diesel motors, oil imports, oil-based transport technologies, residential appliances, biomass (heating and process heat) and nuclear power generation.

4.4.2. Validation of the LCA-based indicators

The LCA-based indicators selected for the case study cannot be validated as these impact categories are not represented in statistics. The only impact category which can be compared with statistics in the base year is the GWP which is represented by the GHG emissions. These emissions are reported on a yearly basis by the IPCC [89]. The IPCC reports global GHG emissions of 49 Gt CO_2eq for 2010 (Figure 48). Of this amount, 45% or 22 Gt CO_2eq can be directly attributed to the energy system as represented by the GMM model (marked with *). The residual GHG emissions, i.e. 55% or 27 Gt CO_2eq are marked with **(*)** and expected to be either partially or not reflected by the LCA-based indicators calculated with the GMM model. The modelling results in this chapter show 28 Gt CO_2eq in annual emissions for the 2010 time period, which is consistent with the expected values based on the IPCC report.

The results that are calculated with the GMM model and the LCA framework are further validated for specific air pollutant emissions in Chapter 5.

4.4.3. Data quality and limitations

In addition to the generic uncertainties and limitations of bottom-up ex-post multi-criteria analysis on the supply and end-use technology levels listed in Section 2.4.2.2, the following specific issues were observed in the case study.

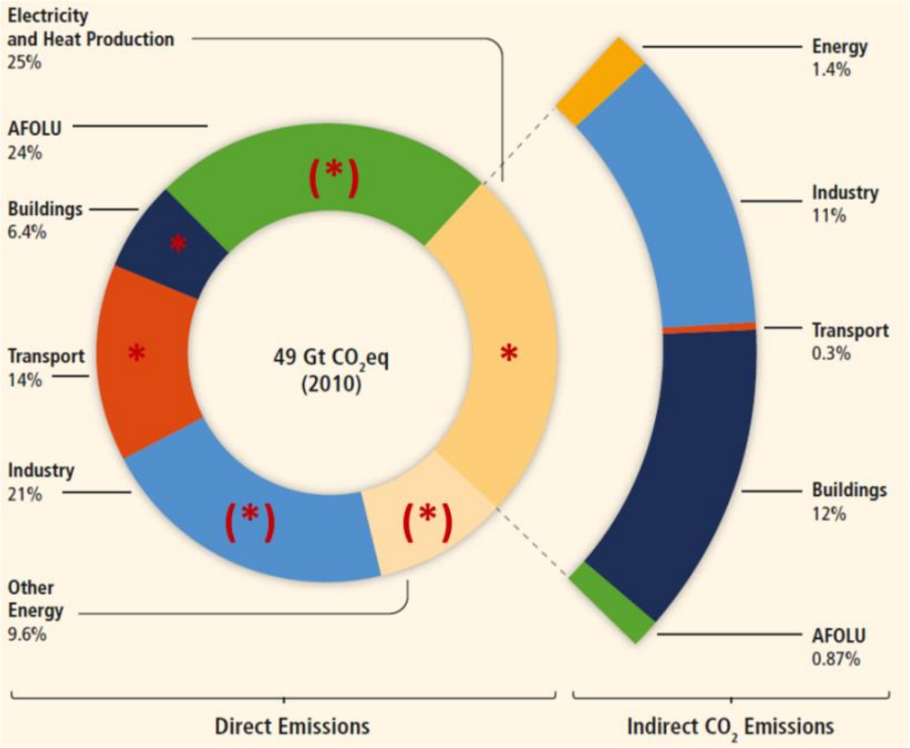


Figure 48: Total anthropogenic GHG emissions (Gt CO$_2$eq/y) by economic sectors [42]. AFOLU = Agriculture, Forestry and Other Land Use

The case study is limited to commercial energy provision and use and their related impacts. Non-commercial biomass is only considered as an indicator for quality of life. The ecoinvent database mostly provides European data, i.e. the other world regions are represented, but mostly on a rougher level. This introduces uncertainties for the quantification of impacts in non-European regions. The ecoinvent database is not complete in its sectoral coverage, i.e. the results are limited to the coverage of the database. Due to the focus on current technologies, the ecoinvent database is not complete regarding (new) energy system technologies, particularly in the hydrogen and biofuel sectors. Therefore, proxies or other (non-reviewed) data sources were used for this case study, for example in the freight transport sector, which can lead to uncertainties in the modelling of technologies. Nevertheless, datasets for advanced technologies were used whenever available (e.g. electricity generation, hydrogen generation and passenger car transport). Due to the differences in the data sources, the modelling of future technologies is less consistent than, for example, the modelling of future electricity generation technologies in the European NEEDS project, which put an emphasis on the consistent modelling of future technologies.

Further uncertainties are introduced due to the expert judgement required during the update process from ecoinvent v2 to v3. The background processes including their market shares, i.e. all processes except the ones in the energy system, remain unchanged in the future. In the European NEEDS project, efforts were made to predict the future development of a set of background processes including electricity mixes, natural gas imports from Middle East, leakage rates of long-distance natural gas pipelines, metal production and lorry transport emissions, which were deployed in the case study in Chapter 3 according to Section 3.2.3. While in this case study the above-mentioned future changes in the electricity, natural gas transport and road transport sectors are endogenously modelled, potential changes of the metal production and other background processes could not be considered due to time constraints and the large scope of the model. This is suggested for further research in Section 7.2. On the level of the quantification of environmental and human health impacts, the analysis is limited by the lack of regionalised LCIA methods.

The two indicators related to the risk of severe accidents in the energy sector are quantified based on historic data, due to the difficulty in estimating future fatality rates and maximum consequences of severe accidents. This implies that the generic characteristics of the energy chains and technologies remain unchanged and are only improved by increases in efficiency. The two indicators related to severe accidents are based on reported accidents which were included in the ENSAD. Due to the possibility of underreporting or omission in data collection, the historic fatality rates and consequences of severe accidents are uncertain. Furthermore, the severe accident data provided in Burgherr and Hirschberg [79] is not geographically complete. Therefore data collected for specific regions is applied to other world regions in this case study, which leads to imprecision in the indicator values. Further, the severe accident data is not complete for all the technologies: in the biofuel sector only accidents for CHP plants are reported. In order to avoid imbalance between the biofuel technologies, no accident indicators for biofuel technologies are included (Appendix, Table 39 and Table 40).

As opposed to the comparison of scenario *variants*, i.e. the comparison the same energy service demands with different technology and/or policy assumptions as discussed in Chapter 3, full MCDA is not possible for the comparison of scenarios presented in this chapter. The reason is that the comparison is based on three different scenarios, i.e. three different energy service demands. The energy service demands can be interpreted as the functional unit of the comparison. As this unit is not the same, no full MCDA could be carried out for this case study.

4.5. Summarising remarks and intermediate conclusions

In this case study, bottom-up ex-post multi-criteria analysis on the technology level is applied to analyse of the three World Energy Scenarios using a set of 22 sustainability indicators. The goal of this case study is to provide a multi-criteria sustainability analysis of the World Energy Scenarios that can comprehensively inform policy-makers and decision-makers about the sustainability of future energy system configurations and the hotspots regarding sustainability impacts. The combined method allows for a detailed analysis of energy system pathways from the level of single technologies to the aggregated system level and in specific cases also based on subjective preferences. This case study does not include a full MCDA, which is not possible as three different scenarios are considered (see Section 4.4.3). The proposed method allows for quantification of the bottom-up sustainability indicators on a LCA basis without double-counting and – due to the global coverage of the energy system model – all energy chains are endogenously modelled.

Bottom-up multi-criteria assessment of energy system scenarios can be applied for scenario studies that are needed to inform decision-makers and policy-makers regarding all sustainability dimensions. The broad perspective allows them to consider a variety of consequences of energy system pathways. Depending on the type and number of bottom-up indicators and the spatial scope of the model, lack of data introduces uncertainties due to the required projection of data. The uncertainties must be weighed against the additional insights gained.

Addressing the complete set of technologies within the global energy system model means that there will be a lack of data for the future time periods addressed within the scenarios, as well as for certain regions under consideration. Together with the inconsistency of the data sources for the different sustainability indicators uncertainties are introduced. Therefore, case studies would profit from improved technology databases. First, indicator values are more abundant for developed regions than for the other world regions. Particularly multi-regional and global models could profit from more and improved regionalised data. Second, the indicator values usually represent historic or current state of development. Consistent projections of the values to the future would therefore be valuable (such as the ones by Roth et al. [24] for severe accident risk indicators). This not only concerns databases such as ENSAD with historic accident data but also comprehensive LCI background databases such as ecoinvent. Third, there is no consistent LCI data for (future) technologies, particularly in the biofuel and hydrogen sectors, which are not represented in ecoinvent.

The case study in the next chapter is therefore limited to a small set of indicators, namely local and global air pollutant emissions. These physical flows are monetised in order to gain insights on the magnitude of economic damage they cause relative to energy system costs and GDP, and to inform decision-makers about the externalities due to different energy system pathways.

Acknowledgments

The case study presented in this chapter was carried out in collaboration with Dr. Christopher Mutel. He provided the LCA calculation framework based on his flexible open source LCA framework *Brightway2*. I would like to thank Dr. Peter Burgherr for the discussions about the accident risk indicators for the case study and Dr. Matteo Spada for extracting the accident risk data required for the case study from the ENSAD. I would also like to thank Christian Bauer for guiding me to the relevant internal LCI data on fuel cells and information for hybridised passenger car technologies. Finally, I would like to thank Brian Cox for providing four LCI datasets for the freight transport sector.

5. External Costs from Human Health Damages due to Air Pollution in the World Energy Scenarios

The so-called “Grand Transition” of the global energy system has been initiated [19] and is expected to have impacts on all three dimensions of sustainability as described in Chapter 4. Among these impacts, local air pollutant (LAP) emissions have particularly attracted attention apart from GHG emissions because they are the source of considerable human health damages, e.g. in China [90]. The human health damages due to LAP emissions from the energy system cause external costs related to the treatment of diseases such as lung cancer and chronic bronchitis as well as welfare losses due to premature deaths and suffering. Additionally, the World Bank found local air pollution to be a drag on development: the quality of life and productive labour is reduced by illness and deaths, and polluted cities lose competitiveness as talented workers avoid living there [91]. Besides LAP, heavy metals and GHG are relevant damaging substances [92]. With the transformation of the energy systems during the “Grand Transition” in the next decades, these emissions and thus the external costs are expected to change.

The goal of this case study is to estimate the external costs from health damages caused by 15 types of LAP and from damages caused by three GHG in the three World Energy Scenarios from 2010 to 2060. This bottom-up ex-post external cost assessment complements the quantification of the sustainability indicators in the previous chapter by allowing for comparisons of sustainability impacts with monetary quantities such as energy system costs (internal costs) and GDP.

5.1. Literature review

Bottom-up ex-post external cost analysis of energy system scenarios has been applied before (Appendix, Table 26). This case study is based on the combination of a full-scale energy system model, the analysis of the whole energy system, the consistent bottom-up quantification of the LAP and GHG emissions for all energy system technologies, world regions and time periods, the analysis of the World Energy Scenarios as well as consistent assumptions for the temporal and regions projection of the specific external costs and for the scenario quantification, thus complementing the existing literature.

5.2. Method and data

5.2.1. Scenario description and quantification

This case study analyses the WEC scenarios Modern JAZZ, Unfinished SYMPHONY and Hard ROCK. The three scenarios are described in more detail in Section 4.2 as well as in the full report [19]. The scenarios and the external cost are quantified with the GMM model, which is described in Sections 2.1.2 and 4.2.2. The emissions are implemented in the GMM model using its existing features for the quantification of environmental indicators (Section 2.1).

5.2.2. Emission and external cost definition and quantification

In total, 15 LAP are selected for the case study, all of which cause human health damages. The first group of LAP is called “classical pollutants”, which includes SO_2, NO_x, particulate matter with diameter <2.5 μm (PM2.5), particulate matter with diameter <10 μm (PM10), Ammonia

(NH_3) and non-methane volatile organic compounds (NMVOC), and was analysed in detail in the NEEDS project by Preiss et al. [92]. The main processes and sources of these six LAP are summarised in Table 14. The second group of LAP contains two organic substances (Formaldehyde and Dioxin) and seven heavy metals (Arsenic, Cadmium, Chromium, Chromium VI, Lead, Mercury, Nickel).

Table 14: Main processes and sources of the six LAP according to Hofer [93]

Pollutant	Processes	Main sources
Ammonia (NH_3)	Biological degradation	Agriculture, waste water treatment facilities
Non-methane volatile organic compounds (NMVOC)	Incomplete combustion evaporation of solvents	Industry and commercial sector, households, furnaces, transport
Nitrogen oxides (NO_x)	Thermal processes	Transport, furnaces, gas turbines, cement and ceramics industry
Particulate matter with diameter <2.5 µm (PM2.5)	Thermal processes	Transport, power generation, industry, agriculture, fires
Particulate matter with diameter <10 µm (PM10)	Thermal processes	Transport, power generation, industry, agriculture, fires
Sulphur dioxide (SO_2)	Combustion of S-containing fuels	Residential and industrial furnaces

In the context of the NEEDS project, Preiss et al. estimated the specific external costs of the above-mentioned LAP for 39 European and non-European countries and five sea regions. They also provided emission-weighted European averages, which can be used for analysis of emissions located in the EU27 [92]. For this case study, the emission weighted European average values are assumed to represent the GMM model region EU31 in 2010. For the external cost analysis of the three World Energy Scenarios with the GMM model, these values are transferred to the other 14 GMM model regions, and also projected to the future time periods represented in the GMM model.

The quantification of external costs is its own field of research and requires location specific investigation of the polluting processes, transmission and immission [93]. The specific external costs of an emission depend on various factors such as the willingness-to-pay for clean air, population density in the immission region, time of day and season, climate, background concentrations, efficiency of the polluting process, sulphur content of the fuel, end-of-pipe technologies and discount rate. Table 15 lists factors, which can influence the external costs and comments on the way they are considered for the projection to the different world regions and time periods in the case study.

Table 15: Factors influencing the external costs

Factor	Representation in the external cost calculations in this case study
Time of the day	not represented due to the aggregated time periods in the GMM model
Climate	not represented due to the highly aggregated regions in the GMM model
Background concentration	not represented due to the lack of information on the development of the global background concentration of pollutants
Discount rate	not represented as only undiscounted costs are compared
Technology specifications	represented by the specific emissions of the technologies in the GMM model
Process efficiency	represented by the specific emissions of the technologies in the GMM model
Sulphur content	represented by the specific emissions of the technologies in the GMM model
End-of-pipe technologies	represented by the specific emissions of the technologies in the GMM model
Willingness-to-pay for clean air	represented by the GDP per capita as proxy
Population affected by the emission	represented with the urban population share as proxy

According to Table 15, the regionalisation and projection of the specific external costs of EU31 ($e_{LAP,EU31,2010}$) from Preiss et al. are based on the willingness-to-pay (WTP) for clean air on the one hand and the population affected by the emissions on the other hand. The concept of the regionalisation and projection is schematically illustrated in Figure 49 and described in detail in the following paragraphs. The symbols used in the equations are explained in Box 3.

In order to define the specific external costs for the other 14 regions (regionalisation), the values for EU31 are adjusted based on unit value transfer (a_r) and population density factors (b_r) (Figure 49).

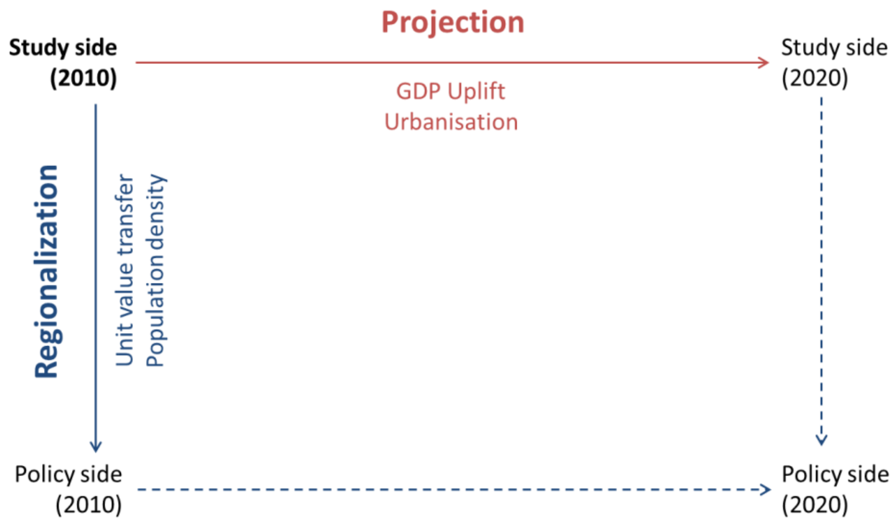


Figure 49: Illustration of the method for temporal and spatial adjustment of specific external cost factors, adopted from [94]

Box 3: List of symbols for the external cost assessment

α	WTP income elasticity
β	GDP per capita growth elasticity
a	unit value transfer factor
b	population density factor
c	GDP uplift factor
d	urbanisation factor
$e_{LAP,EU31,2010}$	specific external costs for EU31 in 2010
f	adjustment factor
g	GDP per capita
p	population density of the densely populated areas
pop	total population
r	region
s	specific external costs
t	time period
u	urbanisation rate
upop	urban population

The unit value transfer income adjustment is based on WTP and income levels, and was developed by Navrud within the NEEDS project [95]. The income level is approximated by the GDP per capita for this case study. The GDP per capita values for the three World Energy Scenarios by WEC [19] are given in Market Exchange Rate (MER) and converted into Purchase Power Parity (PPP) for the above calculations using the PPR/MER rate from IIASA Global Energy Assessment (GEA) [96]. Regions with per capita GDP of US$$_{2010}$ 16000 (PPP) and higher are considered as developed, while regions with lower per capita GDP are considered as developing (Table 16). This arbitrary threshold is tested in the sensitivity analysis in Section 5.3.4.

The income elasticity of WTP (α) was estimated based on surveys in the NEEDS project and found to be between 0.38 and 0.69 for the selected model and country group by Desaigues et al. [97]. The most relevant model for this case study however is Model 1 reported in Desaigues et al. [98], which considers the WTP of all respondents in the survey and their individual income. The model estimated $\alpha = 0.080$ for EU16 countries and $\alpha = 0.527$ for New Member Countries (NMC). Accordingly, $\alpha = 0.080$ and $\alpha = 0.527$ are applied for developed and developing regions in the GMM model, respectively, to calculate the unit value transfer factor (a_r):

$$a_r = \frac{WTP_{r,2010}}{WTP_{EU31,2010}} = \left(\frac{g_{r,2010}}{g_{EU31,2010}}\right)^{\alpha}$$

The calculation of the population density factor is based on the fundamental assumptions that the LAP emissions occur where people are and that the higher the population density is, the more people are affected by the pollution and the more social costs are incurred. To estimate the people affected by the LAP emissions and the associated external costs for each GMM model region, the population densities of the densely populated areas are considered instead of average population densities, which take into account non-habitable land areas. In accordance with the minimum urban density definition of DEMOGRAPHIA [99], a threshold of 400 people per km^2 is used to distinguish densely populated areas from less densely populated areas. The population density data stems from SEDAC [100] and the median population density values are selected and presented in Table 16.

Table 16: Characterisation of the GMM model regions according to GDP per capita, development status and median population density of the densely populated areas

	GDP/cap for 2010, in 1000 US$_{2010}$/cap (PPP)	Classification	Median population density of areas with population densities >400 people/km^2
ASIAPAC	6	developing	735
AUSNZL	46	developed	816
BRAZIL	21	developed	709
CANMEX	17	developed	761
CENASIA	3	developing	728
CHINAREG	15	developing	756
EEUR	11	developing	885
EU31	31	developed	763
INDIA	6	developing	696
JPKRTW	27	developed	922
LAC	12	developing	696
MENA	15	developing	742
RUSSIA	26	developed	610
SSAFRICA	4	developing	713
USA	47	developed	950

The population density threshold is subject to a sensitivity analysis in Section 5.3.4. The calculation of the population density factor (b_r) is shown below:

$$b_r = \frac{p_{r,2010}}{p_{EU31,2010}}$$

In order to quantify the external costs of the LAP emissions for future time periods (projection), i.e. from 2020 onwards, two factors are considered for each GMM model region: the development of the GDP uplift ($c_{r,t}$) and the urbanisation ($d_{r,t}$) as shown in Figure 49.

The GDP uplift factor ($c_{r,t}$), which represents the development of the WTP in the GMM model regions, is approximated with the GDP per capita growth:

$$c_{r,t} = \frac{WTP_{r,t}}{WTP_{r,t-1}} = 1 + \frac{g_{r,t} - g_{r,t-1}}{g_{r,t-1}} * \beta$$

In Bickel et al. [101], the elasticity factor β is reported to lie between 0.7 and 1.0, with 1.0 to be used as a default and 0.7 when air pollution costs prove to contribute an important part of the benefits quantified in an assessment. For the present study, the factor used by Preiss et al. in the NEEDS project, i.e. $\beta = 0.85$, was adopted [92]. The assumption is tested in the sensitivity analysis in Section 5.3.4.

To project the population densities to the future, i.e. to estimate the people affected by the LAP emissions and the social cost incurred in future time periods, the growth of the urbanisation rate is used. It is assumed that the urbanisation growth represents the growth in population density and thus the increase in the external costs. The urbanisation rates ($u_{r,t}$) are calculated based on projections from UN [102]:

$$u_{r,t} = \frac{upop_{r,t}}{pop_{r,t}}$$

The calculation of the urbanisation factor ($d_{r,t}$) is based on the urbanisation rates ($u_{r,t}$):

$$d_{r,t} = 1 + \frac{u_{r,t} - u_{r,t-1}}{u_{r,t-1}}$$

The four adjustment factors calculated above, i.e. unit value transfer a_r, population density b_r, GDP uplift $c_{r,t}$ and urbanisation $d_{r,t}$, are used to calculate the total adjustment factors ($f_{r,t}$). For the base year 2010, the total adjustment factor is calculated as follows:

$$f_{r,2010} = a_r * b_r$$

For the time periods from 2020 onwards, it is defined as:

$$f_{r,t} = f_{r,2010} * \prod_{2020}^{t} (c_{r,t} * d_{r,t})$$

The total adjustment factors ($f_{r,t}$) for the regions and time periods in the WEC scenarios are displayed in Figure 50. As all three scenarios are based on the same population development and the same urbanisation over time, the differences between the scenarios stem from the GDP related adjustments, i.e. the unit value transfer in 2010 and the GDP uplift for 2020 to 2060. The graphs are split to separately represent developed and developing regions according to Table 16.

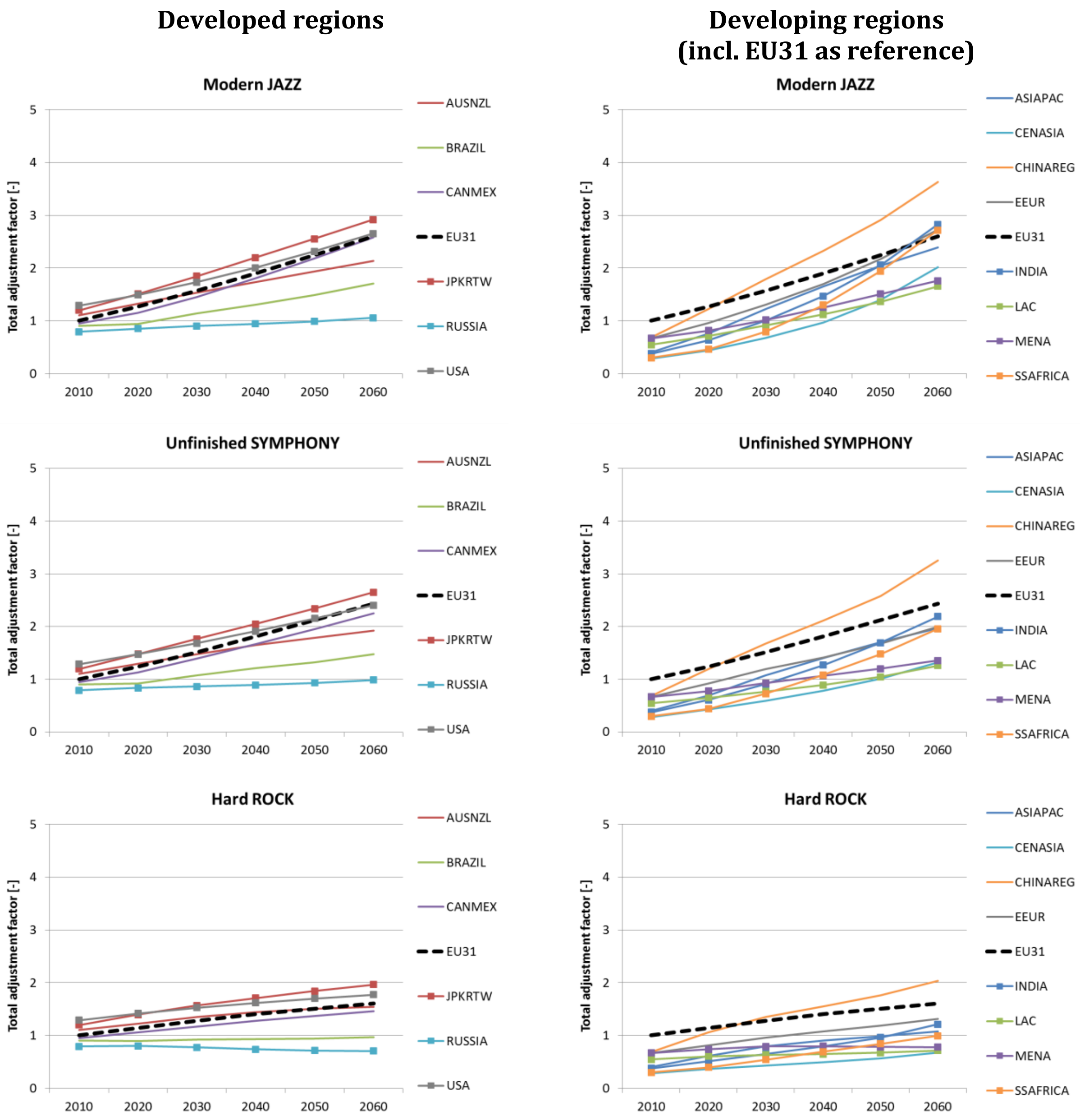


Figure 50: Total adjustment factors $f_{r,t}$ for the three WEC scenarios.

In general, the total adjustment factors increase over time in all scenarios for both developed and developing regions. They grow particularly strongly for the Modern JAZZ scenario, which has the highest GDP growth rate among the three scenarios. The highest adjustment factor and thus the highest specific external costs are found for CHINAREG. Its urban population is expected to grow further from 50% in 2010 to 79% in 2060, leading to more people affected by the emissions in the urban, industrialised areas. At the same time, the per capita GDP increases strongly, leading to increased WTP for cleaner air.

Among the developed regions, the total adjustment factors, and thus the specific external costs of LAP emissions in AUSNZL, CANMEX, EU31, JPKRTW and USA, start on a similar and high GDP level, which increases over time. BRAZIL and RUSSIA have similar population density growth to the other developed regions, but lower increases in GDP per capita and therefore lower increases in the specific external costs. The developing regions start from a lower value than EU31, mainly due to the unit value transfer of the GDP. ASIAPAC, CENASIA, CHINAREG, INDIA and SSAFRICA have particularly high population growth, and – at the same time – their GDP per capita also increases significantly. This leads to strongly increasing total adjustment factors and specific external costs of LAP emissions in these regions over the time horizon considered. EEUR, LAC and MENA experience lower GDP per capita growth than the other developing regions and thus lower growth of specific external costs.

The specific external costs for Western Europe ($e_{LAP,EU31,2010}$) estimated by Preiss et al. are displayed in Table 17. They are multiplied with the total adjustment factors ($f_{r,t}$) to calculate the specific external costs ($s_{LAP,r,t}$) for the LAP emissions for each region r and period t of GMM model:

$$s_{LAP,r,t} = f_{r,t} * e_{LAP,EU31,2010}$$

Apart from the external costs related to the emission of LAP, damages due to the emissions of GHG and subsequent climate change were also analysed. The estimates of these social damages vary strongly between different studies due to differences in the underlying models and in key assumptions [103]. For the comparison of the external costs of GHG emissions and the external costs related to human health damages due to LAP emissions external cost estimates for CO_2, methane (CH_4) and nitrogen oxide (N_2O) are quantified. The estimates are taken from Preiss et al. [92] and not adjusted according to the method described in Section 5.2 as they are global and not local pollutants. The damages factors applied are reported in Table 18 and assumed to be the same for all world regions.

Table 17: Specific external cost data $e_{LAP,EU31,2010}$ for LAP emissions from Preiss et al. [92]. Formaldehyde is considered separate from the other NMVOC due to its high toxicity.

Pollutant	**US$$_{2010}$/t in EU31 (PPP)**
NH_3	10000
NMVOC	616
NO_X	5900
PM>2.5<10	1400
PM2.5	25800
SO_2	6410
Arsenic	559000
Cadmium	88400
Chromium	14000
Chromium VI	69900
Dioxin	391000000
Formaldehyde	211
Lead	294000
Mercury	8450000
Nickel	2430

The emissions of the LAP and GHG under consideration are calculated for each technology in the GMM model using the methodology presented for LCA-based indicators in Section 4.2.2. For this case study, only the direct emissions of the energy system technologies are considered due to the practical complexity related to the quantification of the regional life-cycle emissions described in Section 2.5.2.2.

Table 18: Specific external costs of three GHG emissions [92]

US$$_{2010}$/t	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
CH_4	336	415	551	682	859	1110
CO_2	9	12	14	16	22	26
N_2O	14300	18000	22600	28600	38600	46800

5.3. Results

The results section is subdivided according to the three scenarios Modern JAZZ (Section 5.3.1), Unfinished SYMPHONY (Section 5.3.2) and Hard ROCK (Section 5.3.3). The external cost estimates are presented per region and per pollutant for each scenario and supplemented with comparisons to the total energy system cost and GDP. This set of results is followed by a sensitivity analysis on key parameters in Section 5.3.4.

5.3.1. Results for Modern JAZZ

The external costs induced by 15 major air pollutants increase over the considered time horizon in Modern JAZZ (Figure 51). Particularly, CHINAREG, but also INDIA and USA contribute significantly to the external costs of $\text{US\$}_{2010}$ 1.57 trillion per year in 2060. The costs are clearly dominated by three pollutants, namely NO_x, PM2.5 and SO_2, while the other pollutants play a minor role.

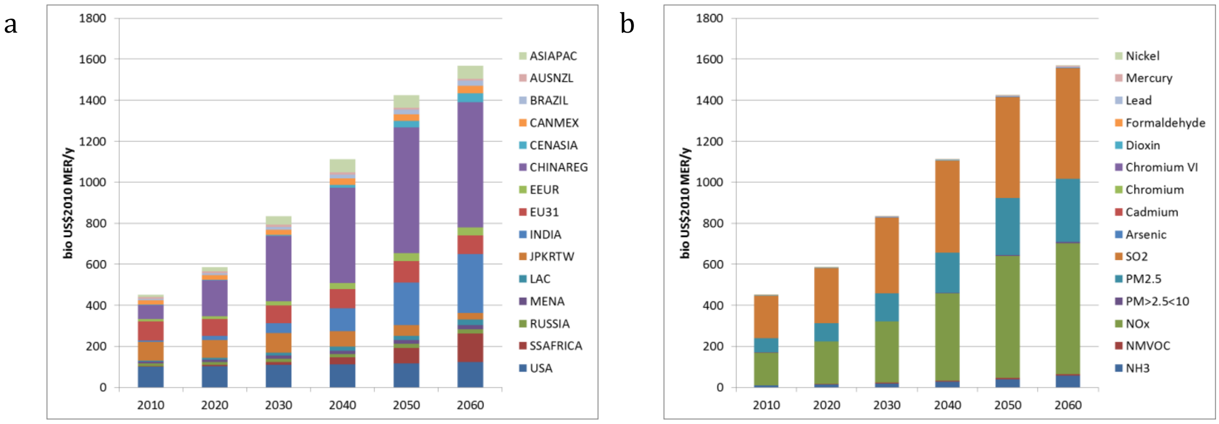


Figure 51: External costs of 15 major air pollutants in Modern JAZZ by region (a) and by pollutant (b)

The NO_x and PM2.5 emissions mainly stem from CHINAREG and INDIA (Appendix, Table 46). The major sources of the NO_x and PM2.5 emissions in the 2010 time period are coal power generation, coal heat generation, coal industrial furnaces, diesel motors and oil-based freight transport. At the end of the time horizon, biomass technologies become the major source of NO_x and PM2.5 emissions. The SO_2 emissions mainly stem from CHINAREG and INDIA and decrease over time after peaking in 2020 (Appendix, Table 46). This results in slower growth in the related external costs than for the other two pollutants. The direct SO_2 emissions of the energy system mainly occur in coal industrial furnaces, coal mines (blasting) and coal heat and power generation, in 2060 also in oil-fired industrial furnaces.

The external costs for the three analysed GHG reach US$$_{2010}$ 752 billion in 2060 after peaking in 2050 (Figure 52). CHINAREG and INDIA are the major contributors to the external costs, which are dominated by the contribution of the CO_2 emissions.

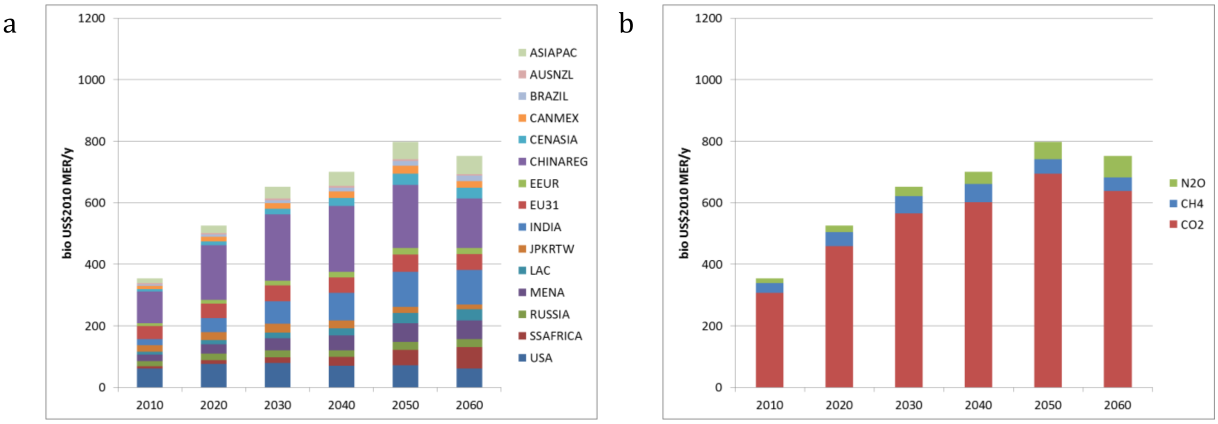


Figure 52: External costs of three major GHG in Modern JAZZ by region (a) and by GHG (b)

To complete the ex-post assessment, the total energy system costs are calculated: The external costs induced by the 15 LAP and the three GHG are added to the internal costs, i.e. the energy system costs (Figure 53). The total energy system cost reaches US$$_{2010}$ 20100 billion in 2060. The external costs amount to 11-13% of the total energy system costs depending on the time period. The external costs of the GHG are lower than the costs of the LAP in all time periods.

The external costs are contrasted with the GDP of the respective time period (Figure 54). The LAP and the GHG trajectories have a decreasing tendency from 2010 to 2060. The decreasing total trajectory to 0.7% indicates that the GDP growth outperforms the increase in emission costs in the Modern JAZZ scenario.

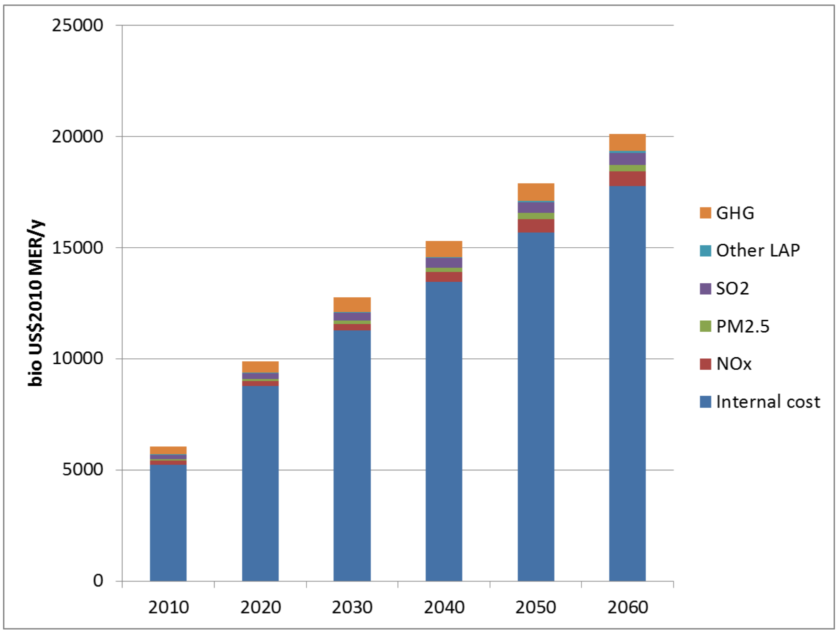


Figure 53: Undiscounted total energy system costs in Modern JAZZ

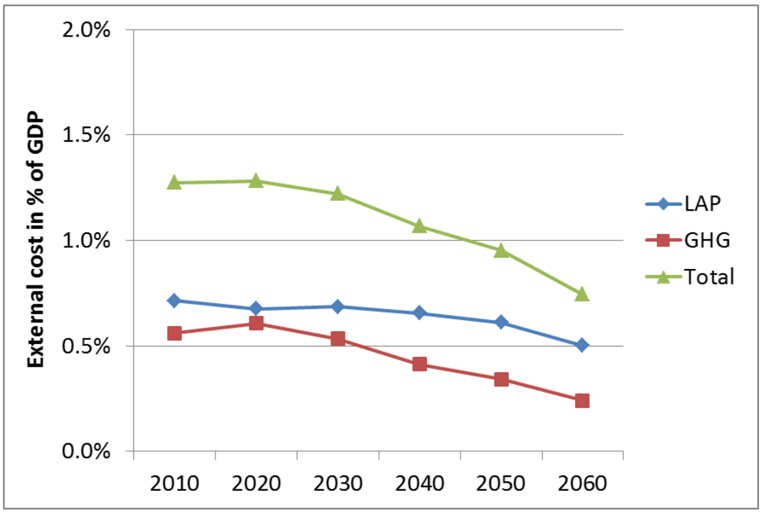


Figure 54: External costs in % of GDP in Modern JAZZ

5.3.2. Results for Unfinished SYMPHONY

The external costs of the 15 LAP reach US$$_{2010}$ 816 billion in 2060 compared to US$$_{2010}$ 1570 billion in Modern JAZZ. The lower costs are related to a peak in CHINAREG and SO_2 emissions in

2040 (Figure 55). Again, NO_x, SO_2 and PM2.5 drive the level and development of the external costs from LAP.

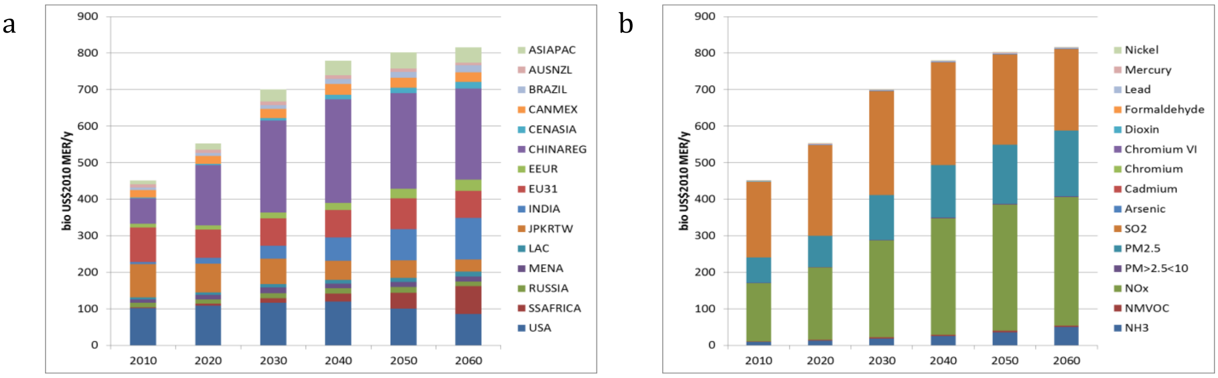


Figure 55: External costs of 15 major air pollutants in Unfinished SYMPHONY by region (a) and by pollutant (b)

NO_x and PM2.5 peak earlier and on a lower level than in Modern JAZZ, and SO_2 emissions reach a lower level in 2060 (Appendix, Table 47). Major sources of NO_x emissions are CHINAREG, INDIA and USA with coal industrial furnaces, coal power generation and diesel motors in 2010. Towards 2060, biomass technologies and aviation start to contribute substantially to the NO_x emissions. CHINAREG, INDIA and SSAFRICA are the major emitters of PM2.5. In 2060, biomass technologies are more important sources of PM2.5 emissions than coal power generation and coal industrial furnaces. SO_2 emissions are significantly lower in 2060 than in 2010 (Appendix, Table 47). The remaining emissions mainly stem from coal industrial furnaces, coal mining, oil industrial furnaces and coal heating plants in CHINAREG and INDIA.

The external costs due to GHG emissions reach US$_{2010}$ 447 billion in 2060 after peaking at US$_{2010}$ 566 billion in 2030 (Figure 56). This is lower than the corresponding values in the Modern JAZZ scenario. Apart from the major contribution from CHINAREG, EU31, INDIA and USA, SSAFRICA has large and increasing contributions. The external costs are dominated by the CO_2 emissions.

The total energy system cost reaches US$_{2010}$ 17400 billion in 2060 in Unfinished SYMPHONY and is displayed in Figure 57. The external costs due to GHG and LAP emissions reach 7-13% of the total energy system costs depending on the time period.

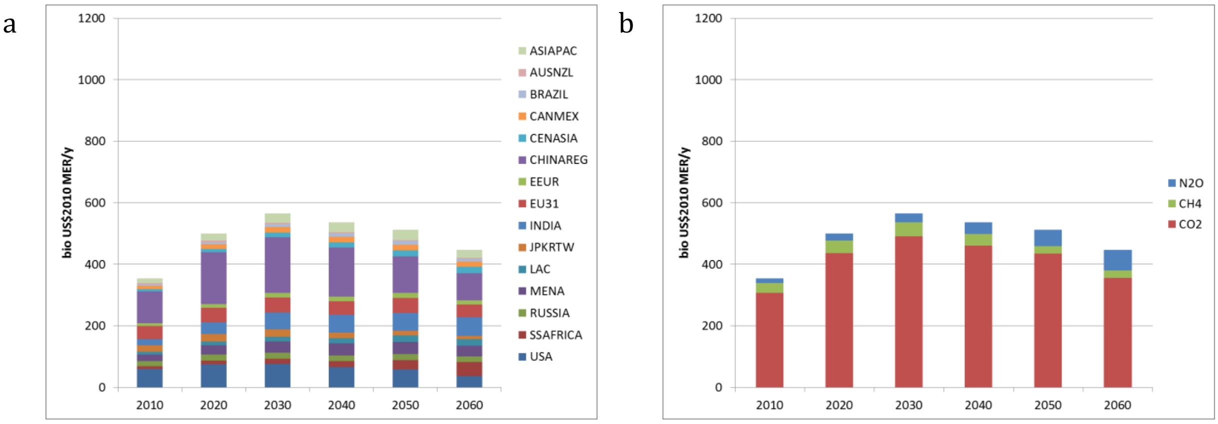


Figure 56: External costs of three major GHG in Unfinished SYMPHONY by region (a) and by GHG (b)

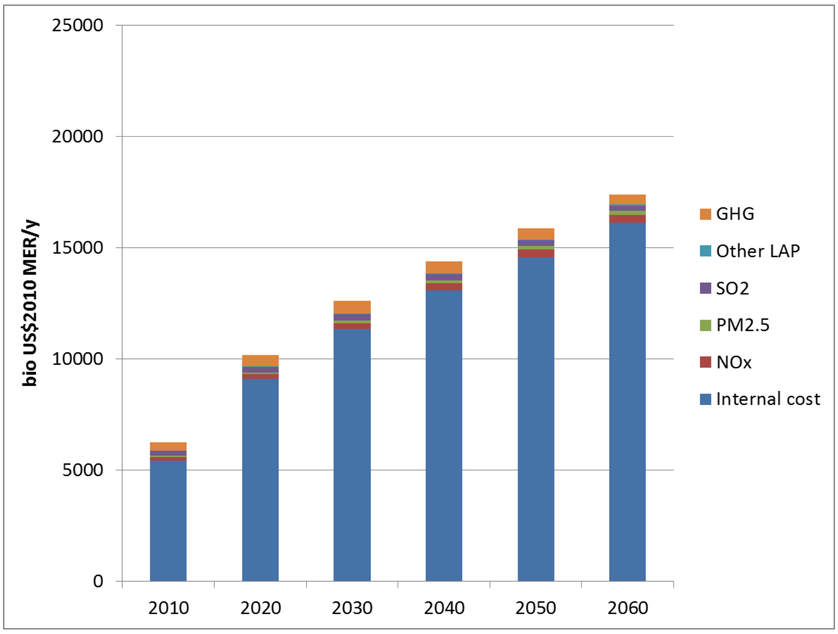


Figure 57: Undiscounted total energy system cost in Unfinished SYMPHONY

The share of external costs due to LAP emissions decreases over time from 0.7% to 0.3% of the corresponding GDP (Figure 58). Also the share of external costs due to GHG emissions decreases by 2060. This can be explained by the strong GDP increases in MER terms and – at the same time – moderate emission cost increases.

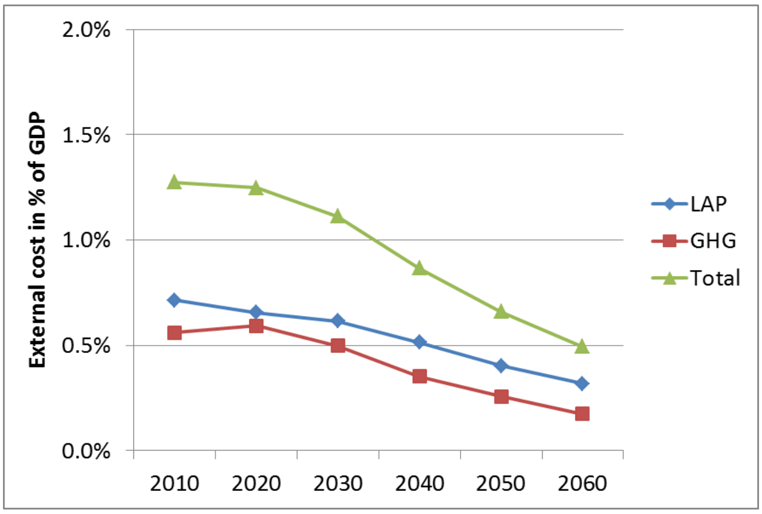


Figure 58: External costs in % of GDP in Unfinished SYMPHONY

5.3.3. Results for Hard ROCK

External costs of $US\$_{2010}$ 1010 billion due to LAP emissions are estimated for the Hard ROCK scenario in 2060 and displayed in Figure 59. CHINAREG is the major contributor, followed by EU31, INDIA, JPKRTW and USA. The external costs are dominated by the emissions of NO_x, PM2.5 and SO_2 emissions. The 2060 cost estimate lies between Modern JAZZ (1570 billion) and Unfinished SYMPHONY (816 billion). Despite the higher pollutant emissions, Hard ROCK faces lower external costs than Modern JAZZ due to the moderate GDP growth rates observed in all regions over the time horizon.

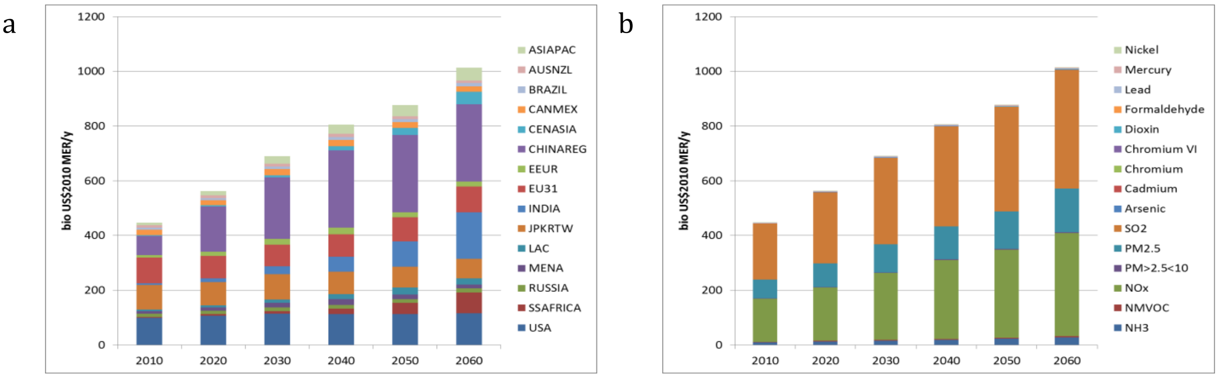


Figure 59: External costs of 15 major air pollutants in Hard ROCK by region (a) and by pollutant (b)

The NO_x emissions mainly stem from CHINAREG, INDIA and SSAFRICA (Appendix, Table 48). The majority of the emissions stem from coal industrial furnaces, diesel motors and aviation in 2060. The PM2.5 emissions have the same regions as major contributors as the NO_x emissions. Towards 2060, the contribution of biomass technologies to the global PM2.5 emissions gains importance. The NO_x and PM2.5 emissions follow similar trajectories as in Modern JAZZ, but SO_2 emissions decrease only slightly after peaking in 2020 (Appendix, Table 48). While CHINAREG lowers its contribution, INDIA significantly increases its share in the SO_2 emission towards 2060. The main reasons for the SO_2 emissions are coal industrial furnaces and coal mining (blasting).

The damage estimate for the GHG emissions is US$$_{2010}$ 1120 billion, which is high compared to the estimates for Modern JAZZ (752 billion) and Unfinished SYMPHONY (447 billion), respectively (Figure 60). CO_2 emissions are the largest contribution, and mostly stem from CHINAREG and INDIA.

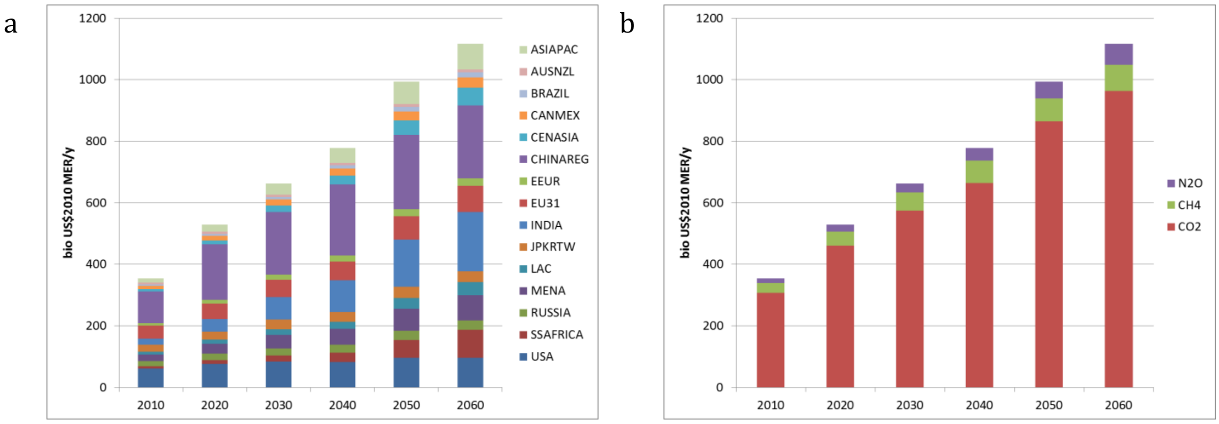


Figure 60: External costs of three major GHG in Hard ROCK by region (a) and by GHG (b)

The total energy system costs of the Hard ROCK scenario reach US$$_{2010}$ 20200 billion in 2060 (Figure 61). The external cost amounts to 10-13 % of the total energy system cost depending on the time period.

The shares of external costs due to LAP and GHG emissions in GDP are each stable around 0.7% in the period 2010 to 2060 (Figure 62). The total emission damage costs slightly increase over the time horizon. While the emission costs increase over time, the GDP only grows slowly in Hard ROCK leading to stable trajectories.

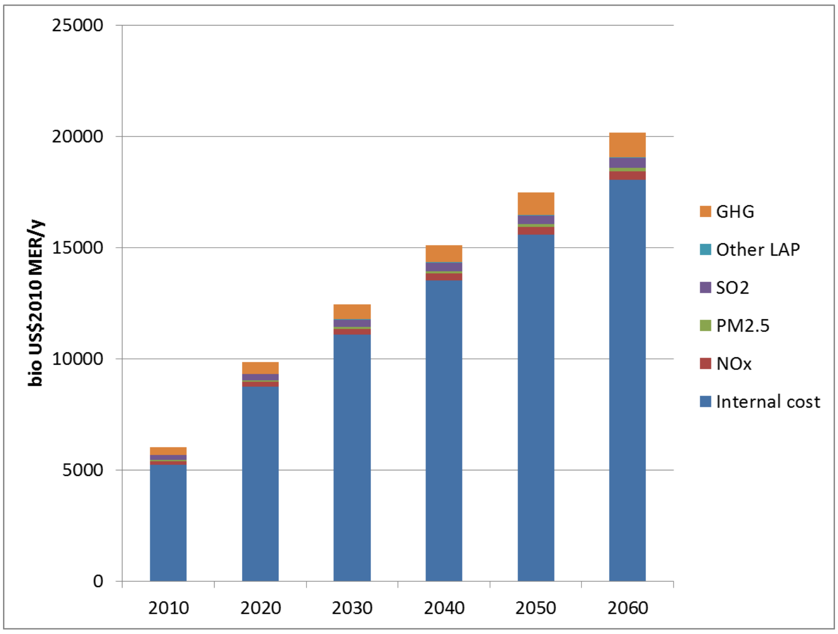


Figure 61: Undiscounted total energy system costs in Hard ROCK

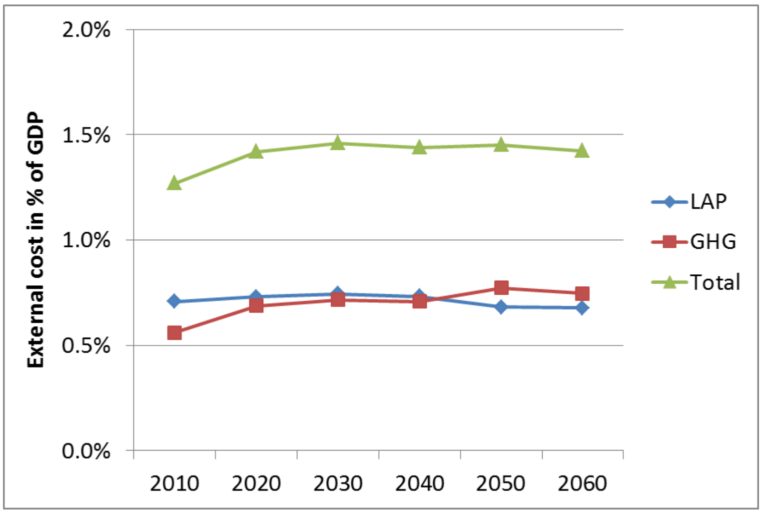


Figure 62: External costs in % of GDP in Hard ROCK

5.3.4. Sensitivity analysis

The method for regionalising and projecting the external costs of LAP as described in Section 5.2 includes some key assumptions. Their impact on the results is tested in a sensitivity analysis.

Sensitivity cases are developed based on three major assumptions as described in Table 19 for all three scenarios. The results of the sensitivity analysis are presented in Table 20 for the time period 2060.

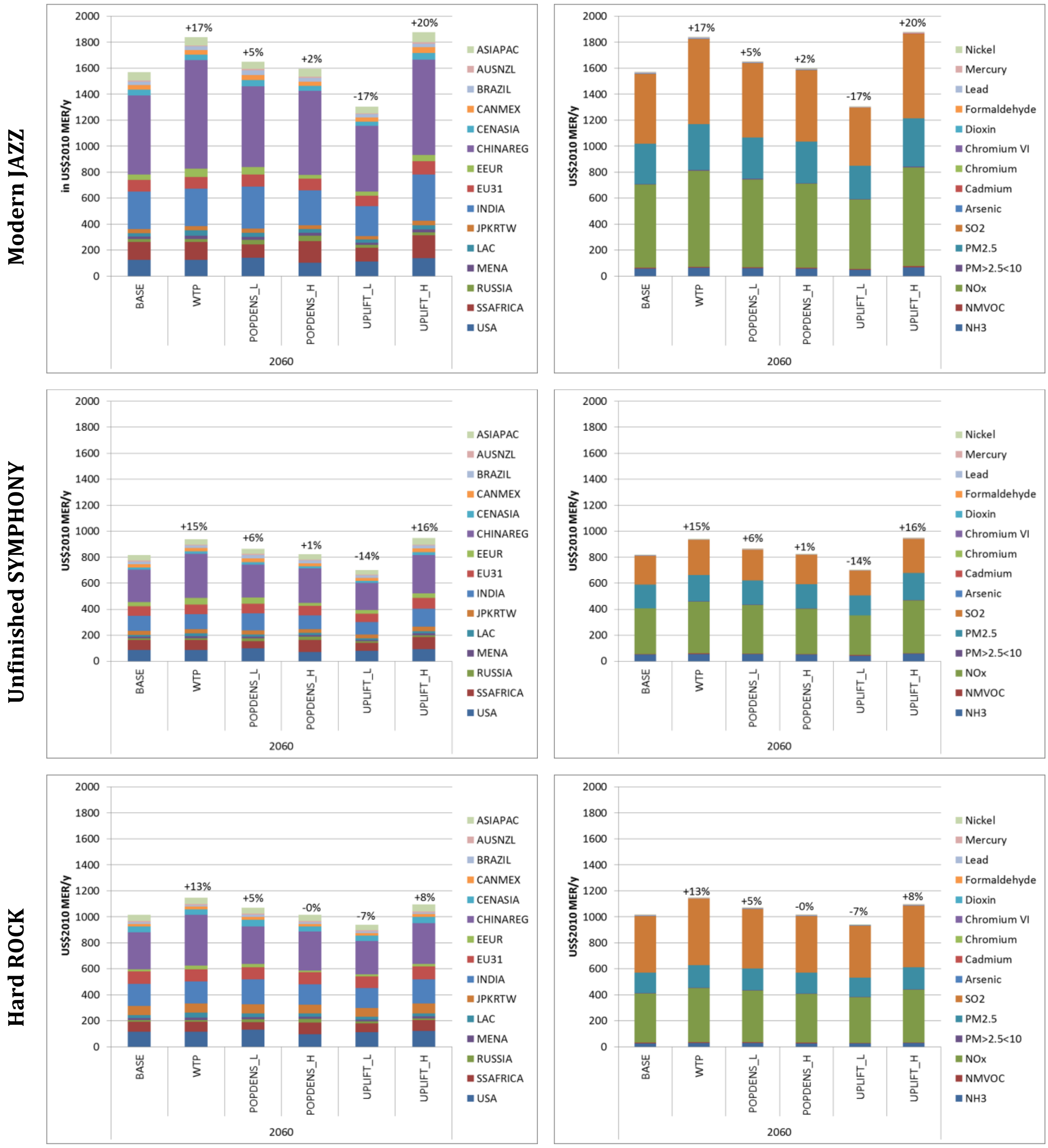
Table 19: Description of the sensitivity cases

Case	Description
WTP	The threshold for classifying regions as being either developed or developing is changed from a per capita GDP of US$$_{2010}$ 16000 to 10000 (PPP). In this case, only ASIAPAC, CENASIA, INDIA and SSAFRICA remain in the developing category.
POPDENS_L	The threshold of classifying a region as being densely populated is set to 100 people/km^2 instead of 400 people/km^2.
POPDENS_H	The threshold of classifying a region as being densely populated is set to 1000 people/km^2 instead of 400 people/km^2.
UPLIFT_L	The inter-temporal elasticity for the GDP per capita growth is set to 0.7 instead of 0.85.
UPLIFT_H	The inter-temporal elasticity for the GDP per capita growth is set to 1.0 instead of 0.85.

Classifying CHINAREG, EEUR, LAC and MENA as being developed (WTP case), i.e. applying an income elasticity of WTP α of 0.08 for these regions, results in higher external costs due to LAP emissions for all three scenarios: +17%, +15% and +13% for Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively. The regions listed above have lower GDP per capita values than EU31. Thus using $\alpha = 0.08$ in the exponent of the ratio of the respective GDP per capita and the GDP per capita of EU31 leads to higher unit value transfer values than in the BASE case, to higher starting values for the adjustment factors and – ceteris paribus – to higher external costs. The major contributor to the external costs is CHINAREG. As this sensitivity case changes the income elasticity of CHINAREG, the region also changes most regarding the external costs.

The change of the population density threshold to 100 (POPDENS_L) and 1000 people/km^2 (POPDENS_H) for the calculation of the population density factor has low influence on the external costs due to LAP emissions, i.e. the external costs of LAP emissions stay almost the same. One reason is that this factor only differs between 0.70 and 1.76, 0.80 and 1.24, and 0.83 and 1.52 for the 100, 400 and 1000 people/km^2 threshold (Appendix, Figure 86). The second reason is that the population density factor is only applied to the first period, i.e. it only changes the starting values but not the further developments.

Table 20: Sensitivity of the results for the 15 major LAP emissions regarding key assumptions in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK by region and by pollutant in 2060



The change in the inter-temporal elasticity for the GDP per capita growth β has a strong impact on the external costs of LAP emissions. When applying the two elasticities recommended by Bickel et al. [101], i.e. 0.7 (UPLIFT_L) and 1.0 (UPLIFT_H) instead of the NEEDS recommendation of 0.85, the contributions of all regions shrink and grow, respectively.

5.4. Discussion

5.4.1. Insights from the case study

The annual external costs due to LAP emissions are substantial for all three scenarios: They amount to US$$_{2010}$ 1.57, 0.816 and 1.01 trillion in 2060 in Modern JAZZ, Unfinished Symphony and Hard ROCK, respectively, which corresponds to 0.5%, 0.3% and 0.7% of the GDP in the corresponding scenario and time period. The annual external costs due to GHG emissions are estimated to be equivalent to an additional 0.2%, 0.2% and 0.7% of the respective GDP in the three scenarios in 2060. The favourable performance of Unfinished SYMPHONY regarding LAP and GHG emissions reported in Chapter 4 (represented by CO_2, GWP, TA, FE, PMF, and POF indicators) is confirmed by the external cost assessment. Despite the increase in global GDP by a factor of four by 2060 and the corresponding increase in the specific external costs of the various pollutants, the total external costs are lower than in the other two scenarios. The Hard ROCK scenario however is found to have higher LAP and GHG emissions but lower total external costs than Modern JAZZ. This seemingly contradictory result is mainly driven by the difference in global GDP growth from 2010 to 2060, which amounts to 136% in Hard ROCK compared to 394% in Modern JAZZ.

Among the analysed LAP, NO_x, PM2.5 and SO_2 are found to be the most important contributors to the external costs with 95%, 92% and 96% of the external costs related to LAP in 2060 in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively. For the GHG emissions, CO_2 makes the most important contribution with 85%, 80% and 86% of the external costs related to GHG emissions in the three scenarios in 2060.

The application of the proposed approach for regionalisation and projection of external costs of LAP results in particularly strong external cost increases for developing regions such as ASIAPAC, CENASIA, CHINAREG, INDIA and SSAFRICA over the time horizon considered. These regions not only face large increases in their GDP per capita and in their urbanisation rate, but also significantly emit LAP. This leads to the result that these regions bear large shares of the external costs, namely 73%, 61% and 61% of the global external costs related to LAP emissions in 2060 in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively. The developed regions, AUSNZL, BRAZIL, CANMEX, EU31, JPKRTW, RUSSIA and USA, bear smaller shares of the global external costs, namely they decrease from 75% of the global external costs related to LAP emissions in 2010 to 26%, 29% and 28% in Modern JAZZ, Unfinished SYMPHONY and Hard ROCK, respectively.

Overall, the progress of developing world regions in terms of GDP and urbanisation not only results in increased energy demand and related pollutant emissions by the energy system processes, but also in increased specific external costs. CHINAREG seems to be the only one of the developing regions able to break the trend of increasing external costs by peaking in total primary energy demand and by phasing out coal and associated LAP emissions. Overall, an Unfinished SYMPHONY type of world not only allows for economic development in terms of GDP per capita, but it is also favourable regarding external costs from LAP and GHG emissions.

5.4.2. Validation of the emission and external cost estimates

The calculations of the direct air pollutant emissions are based on the methodology described in Section 4.2.2. As the scenarios expand to the unknown future, the estimates can only be validated for the base year 2010 using information from emission databases. Only few databases cover all world regions and all pollutants and often the focus lies on developed regions and GHG emissions. For the validation, three comprehensive data sources are used: EDGAR from the Joint Research Centre of the European Commission [104], IPCC [89] and a database from the US EPA [105]. Figure 63 displays the comparison of the GMM model calculations with statistical data.

The direct CO_2 emissions modelled with the GMM model match well with the statistics. The estimated CH_4 emissions lie below those from other statistics. This is related to the fact that there are substantial CH_4 emissions which are not related to the energy system such as the ones from biogenic decomposition. The N_2O emissions calculated by the GMM model are much lower than those from the statistics. Again, this is related to the fact that the major sources of global N_2O emissions are denitrification and mineral fertilisation, which are not part of the energy system and thus not represented by the presented estimates of the GMM model. The same holds true for NH_3 emissions which are mainly caused by biological degradation.

The estimates of the GMM model for NO_x and SO_2 are lower than the values in the EDGAR database. There are two explanations for the deviation: First, the EDGAR estimates were calculated based on the energy balances of IEA, i.e. in a top-down approach, which requires simplification and aggregation of technologies for the derivation of the emission factors and emissions. In contrast, the emissions calculated by the GMM model are built on specific processes, i.e. the bottom-up matching of GMM model processes with LCI datasets. Second, the values are reported for different years: EDGAR reports data for 2008, while the GMM model values are based on the average of 2005-2015.

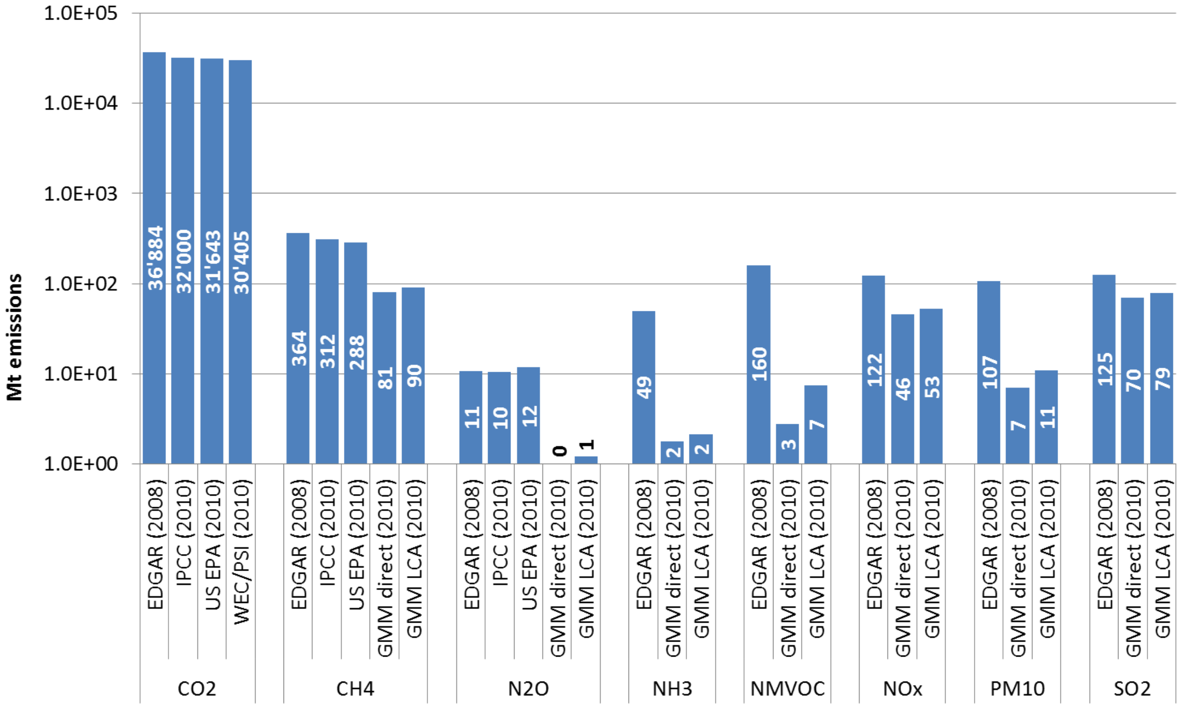


Figure 63: Comparison of the GMM model-based estimates with statistical sources for 2010. The year in the brackets indicates the year for which the data is reported, not the year of the study.

The PM10 emissions quantified by the GMM model are lower than the ones reported in EDGAR. In addition to the two reasons mentioned for NO_x and SO_2, there are other significant sources of PM emissions such as mechanical processes, agriculture and fires, which are not captured by the GMM model. Overall, the bottom-up calculations of the LAP and GHG emissions are comparable with the estimates of other emission data sources.

The external cost estimates are compared with other studies, which cover all world regions (Table 21). Hirschberg and Burgherr [106] analysed the external costs of the whole energy sector for some IPCC scenarios, while Rafaj [15] focusses on scenarios for the electricity sector.

Table 21: Comparison of the external cost estimates for GHG and LAP to literature values

	GHG emissions	**LAP emission**
Hirschberg and Burgherr (2003) [106]	CO_2 A1F1: US\$$_{2000}$ 8–1400 billion in 2050 A1T: US\$$_{2000}$ 5 –700 billion in 2050 B1: US\$$_{2000}$ 4–700 billion in 2050 A1F1: US\$$_{2000}$ 0.8–130 trillion cumulative for 1990-2100 A1T: US\$$_{2000}$ 0.4–65 trillion cumulative for 1990-2100 B1: US\$$_{2000}$ 0.4–60 trillion cumulative for 1990-2100	SO_2, NO_x, PM10 A1F1: US\$$_{2000}$ 8700 billion in 2050 A1T: US\$$_{2000}$620 billion in 2050 B1: US\$$_{2000}$ 3000 billion in 2050 A1F1: US\$$_{2000}$ 1140 trillion cumulative for 1990-2100 A1T: US\$$_{2000}$ 600 trillion cumulative for 1990-2100 B1: US\$$_{2000}$ 250 trillion cumulative for 1990-2100
Rafaj (2005) [15]	CO_2 Baseline: US\$ 55-93 trillion in 2010-2050	SO_2, NO_x, PM Baseline: US\$ 16-20 trillion in 2010-2050
This study	CO_2 JAZZ: US\$$_{2010}$ 0.69 trillion in 2050 SYMPHONY: US\$$_{2010}$ 0.43 trillion in 2050 HARD ROCK: US\$$_{2010}$ 0.86 trillion in 2050 JAZZ: US\$$_{2010}$ 2.63 trillion in 2010-2050 SYMPHONY: US\$$_{2010}$2.13 trillion in 2010-2050 HARD ROCK: US\$$_{2010}$ 2.87 trillion in 2010-2050	SO_2, NO_x, PM10 JAZZ: US\$$_{2010}$ 1.37 trillion in 2050 SYMPHONY: US\$$_{2010}$ 0.757 trillion in 2050 HARD ROCK: US\$$_{2010}$ 0.844 trillion in 2050 JAZZ: US\$$_{2010}$ 42.5 trillion in 2010-2050 SYMPHONY: US\$$_{2010}$ 31.5 trillion in 2010-2050 HARD ROCK: US\$$_{2010}$ 32.6 trillion in 2010-2050

The total external cost estimates of this case study are found to be lower than those presented by Hirschberg and Burgherr (2003). While the ranges of the total emissions of the key pollutants are found to be similar, the damage factors are found to be lower for this case study. Comparing specifically the damage factors of the region CHINAREG of this study with the detailed bottom-up study in the China Energy Technology Program (CETP) [78], the damage factors are at the lower end, which leads to lower total external costs for this region. In the bottom-up modelling of the CETP, specific local conditions such as the location of coal power plants in the vicinity of cities were taken into account. Furthermore, the location-specific chemical transformations of SO_x and NO_x to secondary particles, the damages to materials, crops and other ecosystems were considered and the damages due to morbidity were estimated very comprehensively, i.e. including loss of workforce for the economy, costs of hospitalisation, etc. Regarding the estimation of GHG emissions, the damage factors are disputed [103], and the factors used for this case study only represent one possible estimate.

Overall, the described deviations in the total external cost estimates can be mainly explained by the simplified approach applied in this case study to regionalise and project the European values to the other world regions and future time periods, respectively, and the uncertainty in the damages due to GHG emissions. Therefore, the presented values should be interpreted and used in consideration of these reservations and – if required – be refined with more detailed analysis and estimations.

5.4.3. Data quality and limitations

The case study presented in this chapter combines data from different sources and includes some key assumptions such as the ones addressed in the sensitivity analysis in Section 5.3.4. Furthermore, the following specific limitations and uncertainties could be discerned: Due to the lack of surveys on the willingness-to-pay for clean air in the 15 world regions, the GDP per capita is used as a proxy what induces uncertainty in the analysis. The analysis focuses on commercial energy technologies and carriers. Thus, human health damages due to the use of non-commercial biomass and associated indoor air pollution are not considered. The focus of the case study lies on human health damages related to air pollutant emissions. The human health damages related to emissions to water and soil and the damages related to other impacts of the energy system such as noise and traffic accidents are not considered. Other human health risks from energy systems, such as the failure of dams or nuclear power plants, are also not included.

5.5. Summarising remarks and intermediate conclusions

In this case study, a bottom-up ex-post external cost analysis of the World Energy Scenarios is carried out. The goal of the investigation is the quantification of the external costs related to human health damages from 15 LAP and related to three GHG emissions. The estimates are compared to the energy system costs and the GDP of the analysed time periods and regions. The external cost analysis allows monetisation of multiple impacts on society, which are not reflected by the prices of energy goods paid on markets. Results of external cost assessments can be communicated well as the monetisation of impacts allows abstract metrics to be made more comprehensible.

Cost minimising energy system modelling frameworks further offer the opportunity for ex-ante analysis, i.e. the comparison of energy system pathways that minimise (internal) energy system cost and total cost. Such analysis gives an indication of the location and size of damage mitigation potentials (hot spots).

As external cost data is developed for specific sites and time periods, it is rather scarce from a global perspective and influenced by many factors such as willingness-to-pay for clean air, population affected by the immission and fuel composition. External cost analyses for the global energy system thus require projection of existing data. The implementation of external cost data in energy system models further needs aggregation of data from single processes to generic technologies and from local areas to modelling regions. This introduces uncertainties in addition to the ones related to the value choices required for monetising the impacts.

Further research could include the calculation of specific external costs for regions with scarce data such as developing regions. From an energy system modelling perspective, it would be of interest to have global set of external cost data. The data would ideally be based on a flexible methodology, which allows for consistently quantifying external cost data based on the relevant characteristics of the regions and time periods of the case study and aligning it with the respective socio-economic energy system scenario assumptions. As a starting point, the data could be limited to a set of key pollutants such as NO_x, PM2.5, SO_2 and CO_2.

Overall, the gain in insights on the damages caused by the impacts must be traded off against the increased uncertainty introduced by the monetisation step.

In order to avoid the uncertainty induced by the monetisation of indicators that are not cost-based, indicators can also be endogenised in the PE energy system model, i.e. introduced in its objective function. A case study for such an approach is presented in the next chapter.

Acknowledgements and references

The method for temporal and spatial adjustment of specific external cost factors presented in this chapter was applied in the TIAM model in the ETSAP-Project on "*Introducing external costs for Local Atmospheric Pollution in TIAM-MACRO to study synergies and co-benefits of climate change mitigation*" which is docu-

mented in Kypreos et al. [107]. I would like to thank Michael Hegglin for the contribution he made to the development of the temporal and spatial adjustments of specific external cost factors with his Bachelor thesis [94]. I would like to thank Dr. Evangelos Panos for discussing about the methodology and Dr. Christopher Mutel for calculating the current population densities for the 15 regions.

6. Optimisation of Multiple Objectives for the Global Energy System

The transformation of the energy systems is expected to impact all dimensions of sustainability as shown in the case studies in Chapters 3 to 5. The IPCC has also identified the energy transformation for climate change mitigation as a multi-objective problem [89]. Therefore, the case study presented in this chapter aims at the optimisation of multiple objectives for the global energy system. In particular, three global energy system scenarios are first quantified based on the optimisation of three single objectives. These scenarios represent expected developments when focussing on one single policy objective. Second, the global energy system scenarios are further optimised based on the other two objectives to find Pareto optimal solutions.

6.1. Method and data

6.1.1. Scenario description

For this analysis, a new scenario variant of Modern JAZZ (Section 4.2) is introduced, which is named Free JAZZ. It builds upon the main features such as the energy service demands of Modern JAZZ, however some of the original policy assumptions are modified or deleted since new and partly more stringent policy goals are implemented through the new optimisation criteria:

- All the techno-economic assumptions of the Modern JAZZ scenario are retained.
- Potentials of renewable energies, costs of unconventional resources, annual capacity expansion as well as short-term developments such as planned investments are taken into account.
- Further, the dispatch of thermal power plants is assumed to follow economic criteria to avoid unrealistic results such as investing in many plants with very low full load hours instead of fewer plants with higher full load hours.
- The policy-related assumptions of Modern JAZZ such as nuclear energy deployment and the development of CCS technologies instead, are removed to allow for diverse pathways regarding these technologies within the techno-economic boundary conditions specified in the previous points.

6.1.2. Indicator definition and description

This case study captures an illustrative set of three objectives which are described in Table 22. They are namely direct CO_2 emissions, total discounted energy system costs, and energy carrier imports, and reflect all three dimensions of sustainability and represent different policy goals ranging from climate change protection to a least-cost strategy and improved security of supply.

The energy system costs are defined according the standard formulation of the MARKAL framework and include annualised investment costs, fixed and variable O&M costs, distribution costs, mining costs, trade costs, import and export prices and taxes on emissions. The CO_2 emissions indicator represents the direct emissions from energy conversion. The energy carrier imports are defined as the sum of coal, crude oil, diesel, gasoline, natural gas, LNG and biofuels imports and expressed in energy units. In this context, only exchanges between the 15 GMM model regions are considered in the calculation of the imports, but not the exchanges within the 15 regions.

Table 22: Objectives considered for the optimisation

Dimension	Objective	Optimal	Unit	Description
ECONOMY	Total discounted energy system costs (COST)	min	M$	Sum of discounted annual investment, O&M, fuel and CO_2 emission costs
ENVIRONMENT	CO_2 emissions (CO_2)	min	Mt CO_2	Direct CO_2 emissions related to energy conversion
SOCIETY and SECURITY OF SUPPLY	Energy carrier imports (IMP)	min	EJ	Imports of fossil fuels and biofuels

6.1.3. Scenario quantification

The scenario is quantified with the GMM model presented in Section 2.1.2 with the adjustments described in Section 4.2.2. The objective function of the MARKAL modelling framework is adjusted according to Section 6.1.3.1 and 6.1.3.2, respectively.

6.1.3.1. Single-objective optimisation

The single-objective optimisation optimised each objective separately. The default objective function in the MARKAL framework is to minimise the sum over all regions of the discounted present values of the annual costs incurred in each year over the time horizon [9]. For the optimisation of the first objective, the total discounted energy system costs, this standard formulation of the objective function is used. For the optimisation of the CO_2 emissions, the formulation is adjusted so that the sum of all CO_2 emissions over all regions and time periods is minimised without discounting. Analogously, the sum of all energy carrier imports is minimised over the considered regions and time horizon. The two expressions are shown below (r = regions, t = time period).

$$\min \sum_{r,t} CO_2 emissions_{r,t}$$

$$\min \sum_{r,t} Energy\ carrier\ imports_{r,t}$$

6.1.3.2. Lexicographic optimisation of multiple objectives

The single-objective optimisation shown above gives an optimal result for each particular objective. But this solution is not necessarily optimal for the other objectives as the Linear Programming (LP) solver may stop searching before finding a Pareto optimal solution. To reach a Pareto optimal non-dominated solution, lexicographic optimisation according to Mavrotas [108] can be applied. This method is based on the optimisation of objectives in a predefined order, and allows for finding Pareto optimal (non-dominated) solutions by incorporating all objectives in the optimisation procedure.

For the three objectives in this case study, lexicographic optimisation requires the following steps [108], in which f_1, f_2 and f_3 are objective functions and z_1^*, z_2^* and z_3^* are the optimal solutions:

1) The first objective is optimised (minimised) and min $f_1 = z_1^*$ is obtained.
2) The second objective is optimised (minimised) subject to $f_1 = z_1^*$. Thereby, min $f_2 = z_2^*$ is obtained.
3) The third objective is optimised (minimised) subject to $f_1 = z_1^*$ and $f_2 = z_2^*$. Thereby, min $f_3 = z_3^*$ is obtained.

z_1^*, z_2^* and z_3^* form a Pareto optimal solution. This approach requires the definition of priority among the objectives since the order of the implementation of the different optimisations has an impact on the optimal solutions.

6.2. Results and discussion

The results and discussion for the three single-objective optimisation pathways are presented in Section 6.2.1. The results and discussion of the lexicographic optimisation are described in Section 6.2.2.

6.2.1. Global results for the single-objective optimisation

An overview of the objective values of the three energy system transformation pathways is presented in Table 23, which displays the performance of the three energy system pathways regarding the three objectives in the period 2010-2060. Compared to the cost minimal pathway, the cumulative undiscounted energy system costs from 2010 to 2060 of the CO_2 and energy carrier import minimal pathways are 16% and 7% higher, respectively. Compared to the CO_2 minimal pathway, the cumulative CO_2 emissions are 30% and 31% higher for the cost and energy carrier minimal pathways, respectively. Compared to the minimisation of total energy carrier imports, the cumulative energy carrier imports are 160% and 238% higher than the pathways with minimal costs and minimal CO_2 emissions, respectively. The energy system pathways represented by these three single-objective optimisations are described in detail in Section 6.2.1.1 to 6.2.1.3.

Table 23: Overview of the cumulative results (2010-2060) for the three single-objective runs. Values in italics describe the optimal (minimal) observed values.

Cumulative results for 2010-2060	**Unit**	**min(COST)**	**min(CO_2)**	**min(IMP)**
Total undiscounted energy system costs	M$	*5.77E+05*	6.70E+05	6.16E+05
CO_2 emissions	Gt	1.70E+03	*1.30E+03*	1.71E+03
Energy carrier imports	EJ	9.96E+03	1.30E+04	*3.84E+03*

6.2.1.1. Minimising total discounted system costs

The TPES increases from 522 EJ in 2010 to 698 EJ in 2060, while its share of fossil fuels decreases from over 80% to 58% in 2060 (Figure 64). Major growing regions include INDIA and SSAFRICA. CHINAREG's TPES first increases and then stabilises, while the contributions of EU31 and USA decrease over the time horizon. The global TFC increases from 377 EJ to 527 EJ in 2060 and the share of electricity in TFC increases to 27% over the same time (Figure 65). While the TFC of ASIAPAC, INDIA and SSAFRICA increase over time, they decrease in the EU31 and USA.

Compared to the Modern JAZZ scenario presented in Section 4.3.1, the Free JAZZ scenario – which has the same energy service demands – uses more primary energy. The general development of the use of the different energy resources is the same in both scenarios, but overall Free JAZZ has more renewable and nuclear energy as nuclear energy is not blocked by low acceptance and hydro and renewable power develops do not have limited support. There is also more coal use (with and without CCS) in Free JAZZ as CCS is not blocked by low acceptance. Free JAZZ is characterised by less oil and natural gas use as the markets for unconventional resources are not opened.

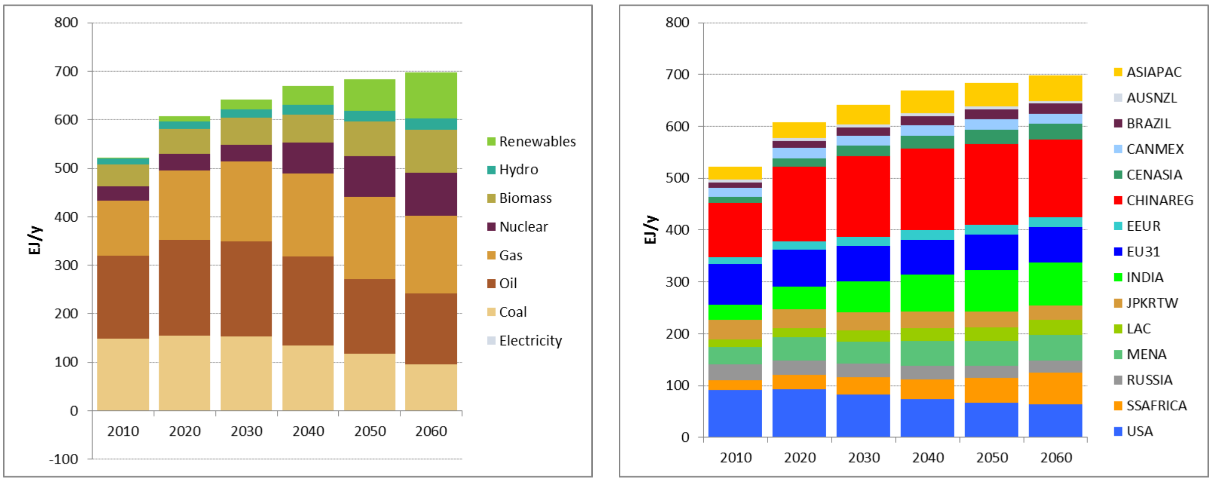


Figure 64: Total primary per energy resource and region for the cost minimal pathway

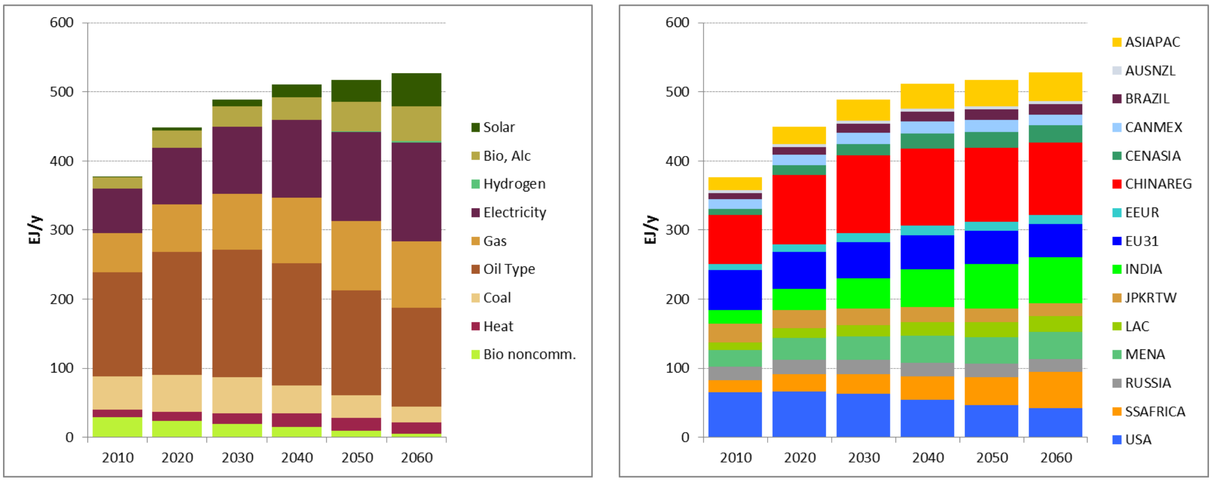


Figure 65: Total final consumption per fuel and region for the cost minimal pathway

In the power sector, the installed capacity and electricity production double over the time horizon (Figure 66). The contribution of renewable energies and nuclear power increases, while fossil fuel-based power generation decreases towards 2060 and is increasingly equipped with CCS technologies. Renewable electricity generation corresponds to 47% of the total global electricity production in 2060.

The electricity generation in Free JAZZ is based on more nuclear and coal generation and less on natural gas and biomass generation compared to Modern JAZZ. This is related to the policy assumptions in Modern JAZZ which include low acceptance for nuclear power and CCS technologies. The total amounts of electricity generated are the same in both scenarios, but the electric capacity is lower in Free JAZZ than in Modern JAZZ due to larger share of base load power plants such as coal and nuclear power plants.

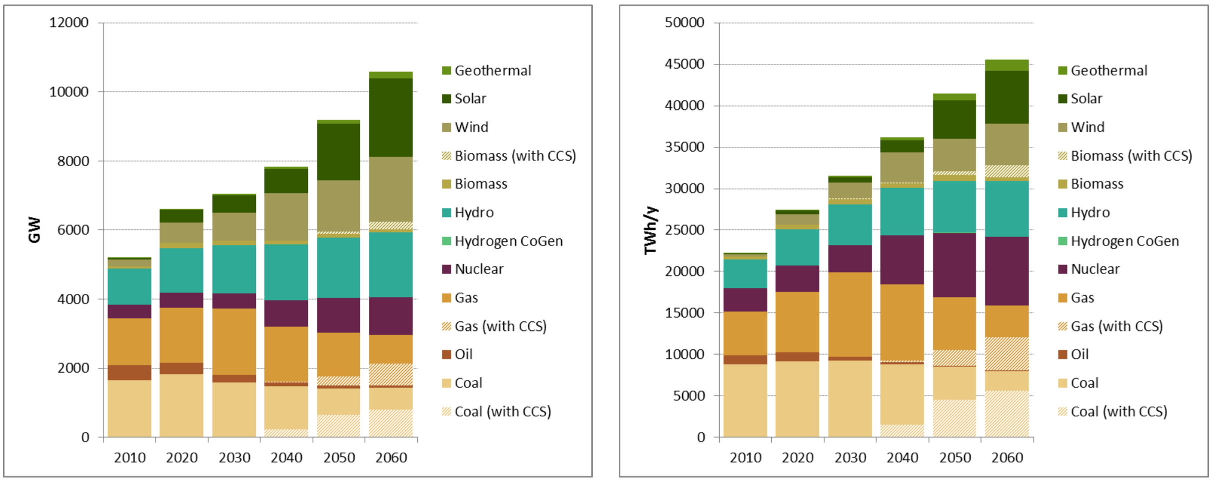


Figure 66: Electric capacity and electricity generation per fuel and region for the cost minimal pathway

The CO_2 emissions peak in 2030 and decrease to 16.5 Gt in 2060, which is almost 50% lower than in 2010 (Figure 67). CHINAREG is and remains the dominant region for emissions, while the USA as the second largest emitter can decrease its emissions by 2060. There is a strong growth of CCS technologies after 2040 when the technology has matured (Figure 68). CHINAREG captures 3.0 Gt CO_2 out of the global total of 7.8 Gt CO_2 in 2060. In the longer term (after 2060; not shown in Figure 68), the annually captured CO_2 emissions stagnate at around 9 Gt CO_2.

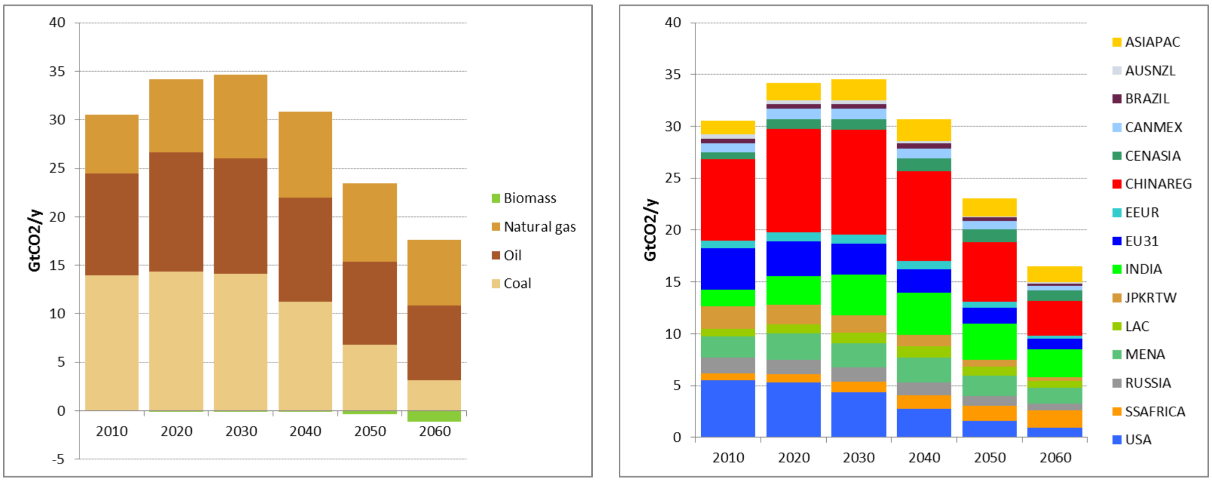


Figure 67: CO_2 emissions per fuel and region for the cost minimal pathway

The amounts of CO_2 captured are more than doubled in Free JAZZ compared to Modern JAZZ, particularly in coal and biomass power generation. As opposed to the Free JAZZ scenario, CCS faces low acceptance in the Modern JAZZ scenario. This leads to lower CO_2 emissions in 2060 in Free JAZZ than in Modern JAZZ, even though CO_2 emissions peak in 2030 in both scenarios in reaction to the same increasing CO_2 prices.

The share of alternative transport fuels (hydrogen, electricity, biofuels) stays low and reaches around 9% in 2060 (Figure 68). Energy carrier imports are part of the cost minimal solution in both Modern JAZZ and Free JAZZ, and occur on a constant level, which is around 130 EJ/y in and 150 EJ/y, respectively. The energy carrier imports are dominated by crude oil and oil products; biofuels play a minor role (Figure 69). ASIAPAC, CHINAREG, EU31, INDIA, JPKRTW and USA are the major importing countries by 2060.

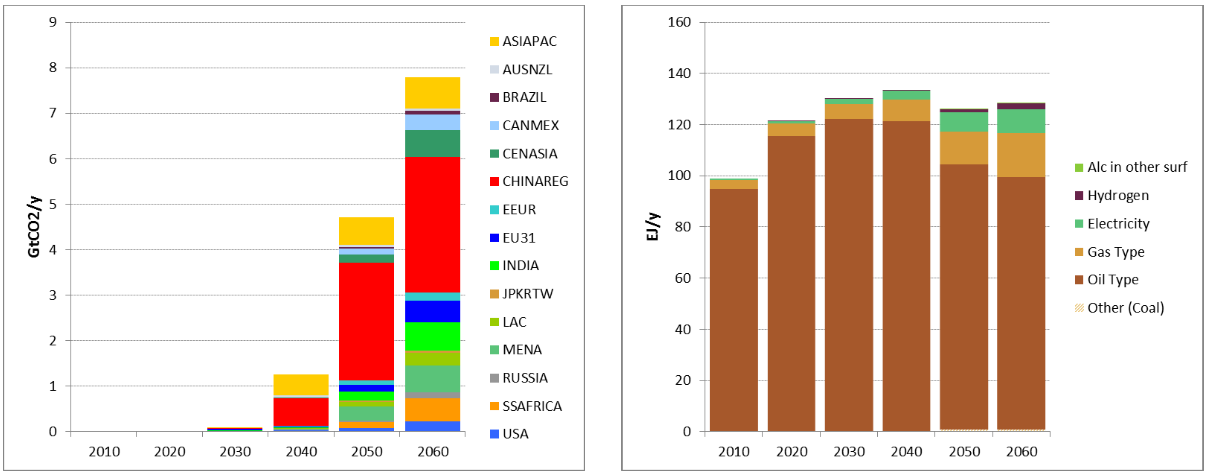


Figure 68: CO_2 captured per region and fuel consumption in transport for the cost minimal pathway. Alc in other surf = Alcohols (methanol, ethanol) in freight transport.

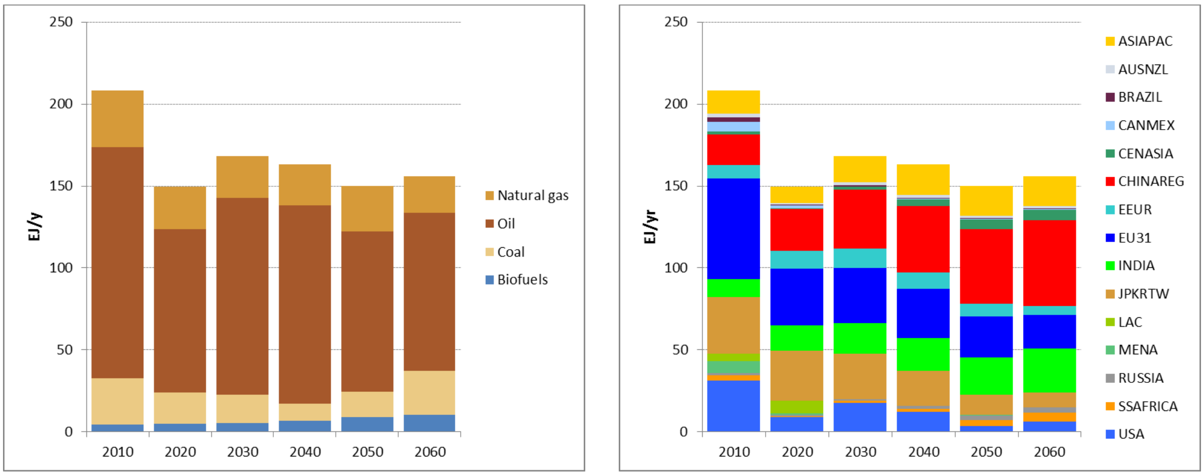


Figure 69: Energy carrier imports per energy carrier and region for the cost minimal pathway

6.2.1.2. Minimising total CO_2 emissions

In the CO_2 minimal energy system pathway, the TPES increases to 677 EJ in 2060 (Figure 70), which is less than in the cost minimal pathway and indicates higher conversion efficiencies and more renewable energies in the energy system. The share of low-carbon resources in TPES, particularly biomass, wind and solar energy, increases to 59% in 2060 compared to 42% in the cost minimal pathway. The global TFC increases from less than 400 EJ in 2010 to 518 EJ in 2060 (Figure 71). The shares of electricity and hydrogen in TFC increase towards 2060 at the expense of CO_2 emitting oil and gas fuels.

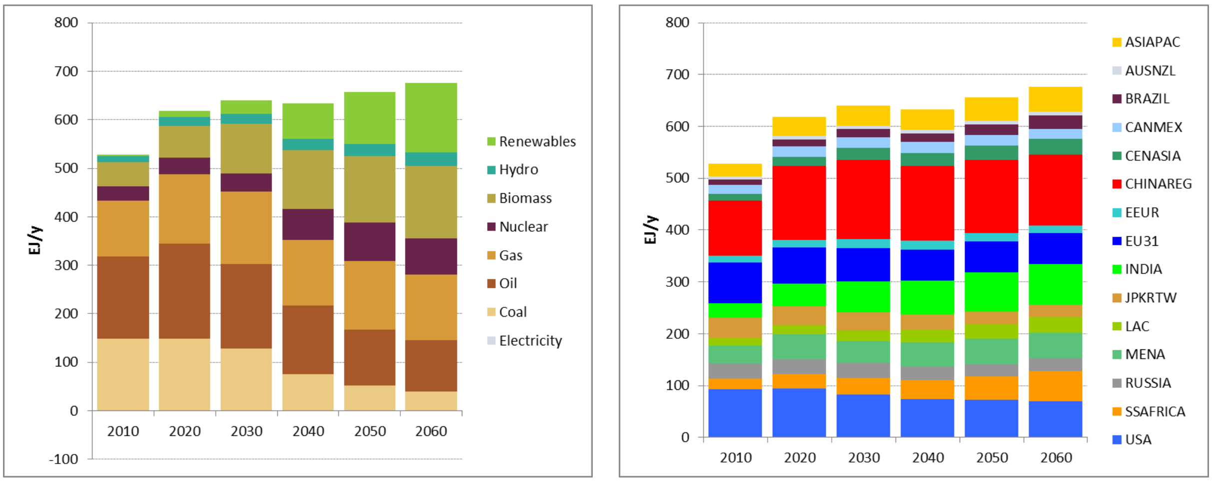


Figure 70: Total primary energy supply per energy resource and region for the CO_2 minimal pathway

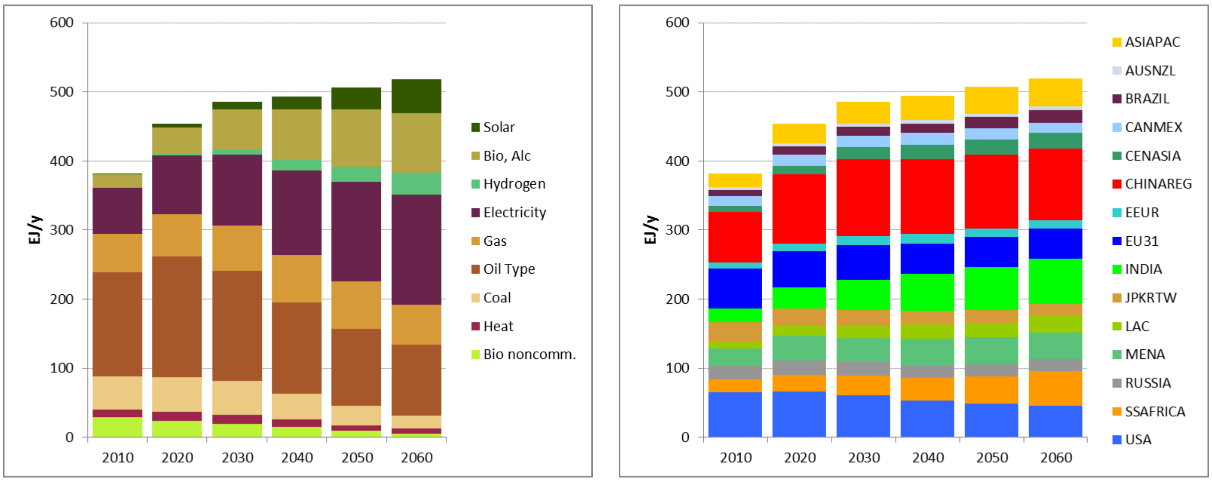


Figure 71: Total final consumption per fuel and region for the CO_2 minimal pathway

The electric capacity triples and electricity production more than doubles from 2010 to 2060 (Figure 72). There is more electricity capacity and production than the cost minimal pathway, particularly solar and wind power. The increase in electricity production mainly stems from the expansion of renewable energies, but also from more low-carbon nuclear and hydro power generation. Accordingly, the share of renewable electricity generation increases to 70% in 2060 compared to 47% in the cost minimal pathway.

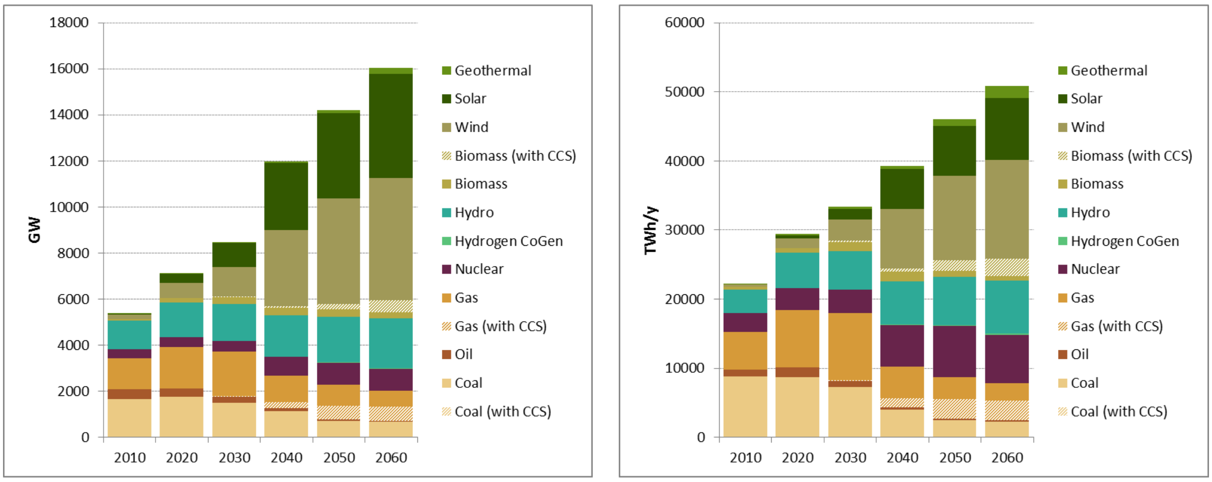


Figure 72: Electric capacity and electricity generation by fuel and region for the CO_2 minimal pathway

In 2060, the CO_2 emissions drop to one quarter compared to the emissions in 2010 (Figure 73). By then, CO_2 emissions from coal are strongly reduced and biomass power generation with CCS contributes with negative emissions. Less coal power generation with and without CCS is deployed, so that the amounts of CO_2 captured are lower than in the cost minimal pathway in the first half of this century (Figure 74). CO_2 capture mainly takes place in ASIAPAC, CHINAREG, MENA and SSAFRICA. Towards 2100 (not shown in Figure 73), the amounts of CO_2 captured increase strongly to around 30 Gt CO_2/y with increasing amounts captured in MENA and RUSSIA, which both have large CO_2 storage potentials [20].

The share of alternative transport fuels, mainly electricity and hydrogen, increases to 39% in 2060 (Figure 74) compared to 9% in the cost minimal pathway. Particularly, the deployment of hydrogen technologies increases compared to the cost minimal pathway, where they are only marginally present due to their high costs. Electric transport technologies are mainly applied in the passenger car sector, while hydrogen is also applied in the freight transport sector. However, the transport sector remains dependent on oil products by the mid-century.

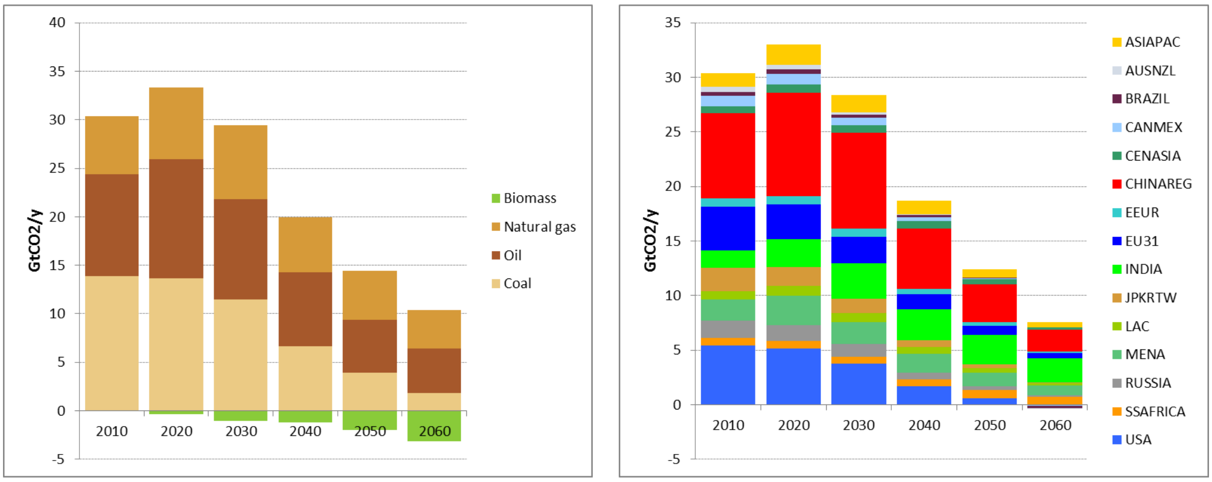


Figure 73: CO$_2$ emissions per fuel and region for the CO$_2$ minimal pathway

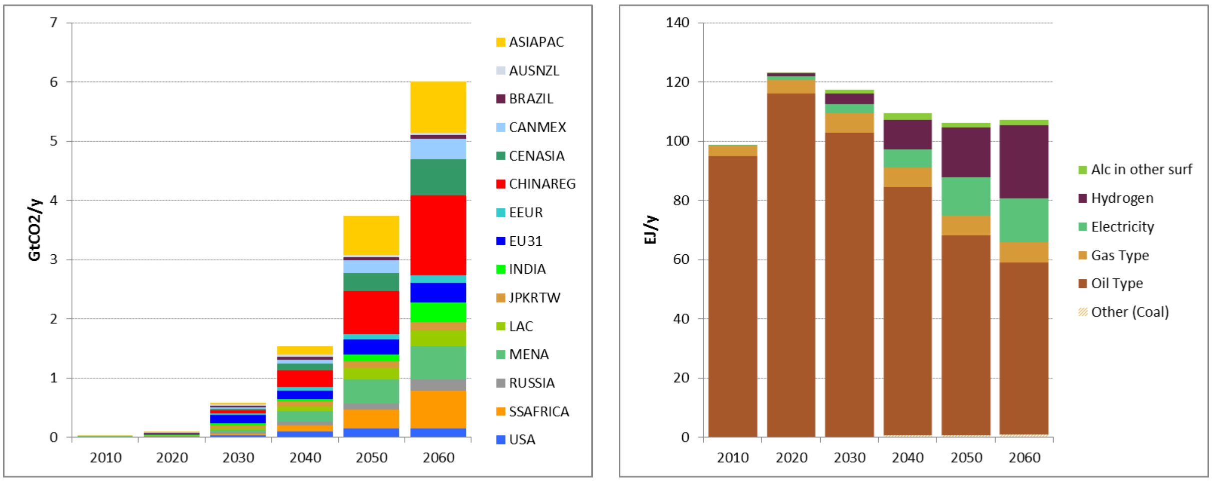


Figure 74: CO$_2$ captured per region and fuel consumption in transport for the CO$_2$ minimal pathway. Alc in other surf = Alcohols (methanol, ethanol) in freight transport.

The energy carrier imports are dominated by crude oil and oil products (Figure 75). The total imports of coal decrease by 2060, while the imports of natural gas increase. Compared to the cost minimal pathway, the trade level is higher. Particularly EU31, JPKRTW and USA trade more oil and natural gas products if the costs of trade are not taken into account.

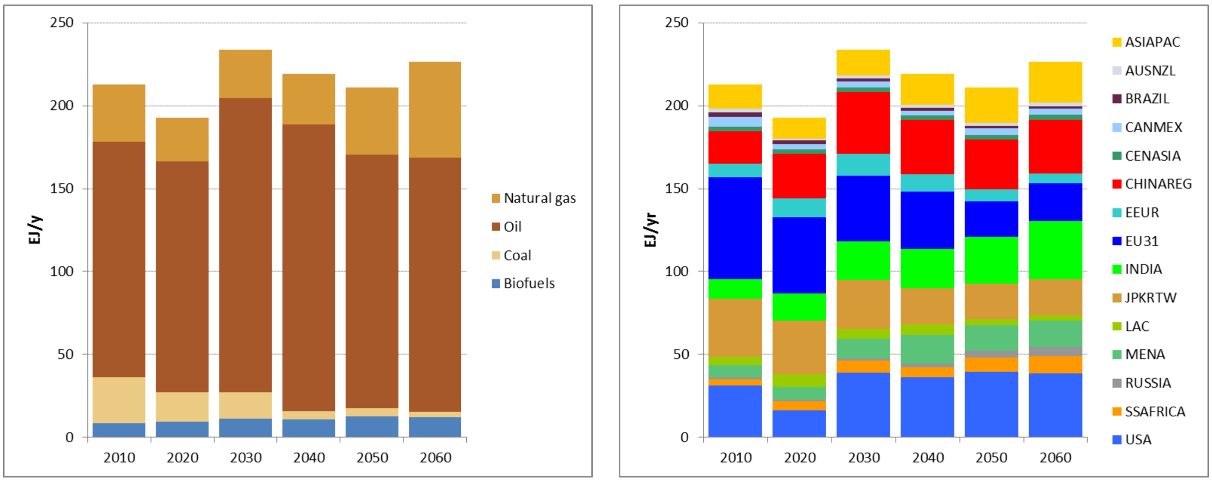


Figure 75: Energy carrier imports per energy carrier and region for the CO_2 minimal pathway

6.2.1.3. Minimising total energy carrier imports

When minimising the energy carrier imports, the TPES increases from over 500 EJ in 2010 to 689 EJ in 2060 (Figure 76). The share of fossil fuels decreases from over 80% to 57% over the time horizon, which is about the same level as in the cost optimal pathway. The contribution of renewable energies, nuclear energy, natural gas and coal increases. While nuclear fuel is not accounted for in the energy imports, renewable energies, natural gas and coal are domestically available in many world regions. Therefore, their share increases if energy carrier imports are minimised. The contribution of oil to the TPES instead decreases because oil resources are not spread evenly around the world and many regions must import the fuel to satisfy their demands.

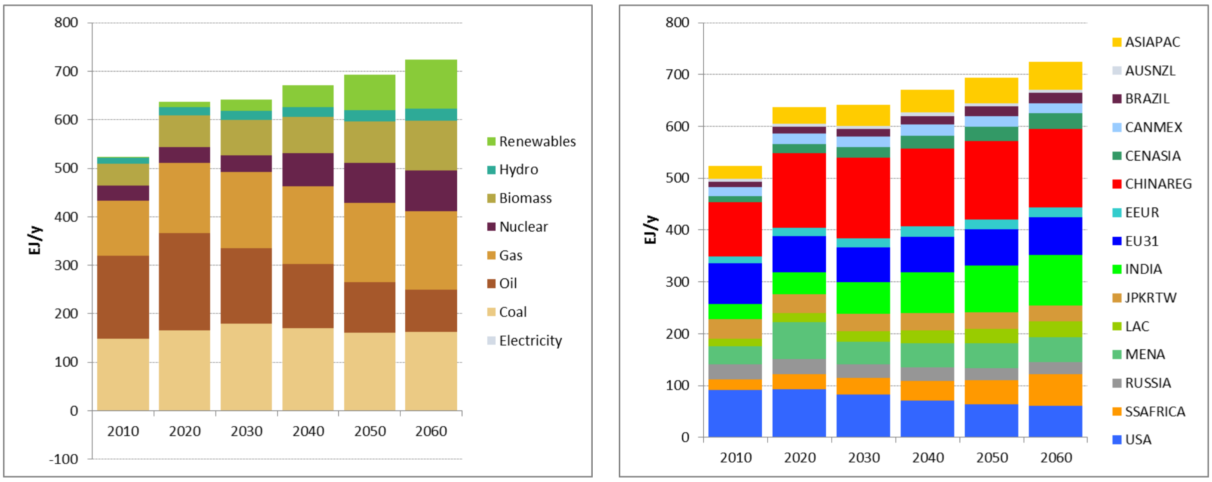


Figure 76: TPES per energy resource and region for the energy carrier import minimal pathway

The global TFC increases to 529 EJ by 2060 (Figure 77) and has decreasing contributions of oil products as described above, but increasing domestic contributions from renewable fuels, natural gas, district heat and electricity. The share of electricity in the TFC reaches 28% in 2060, what is similar to the share in the cost minimal pathway.

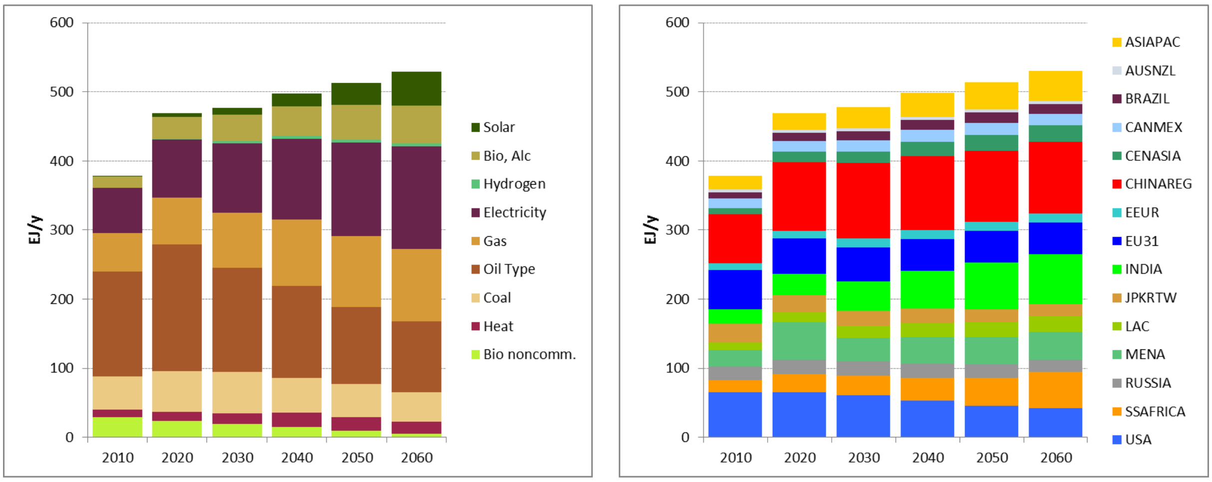


Figure 77: TFC per fuel and region for the energy carrier import minimal pathway

The electric capacities more than double from 2010 to 2060 (Figure 78). At the same time, the electricity production also more than doubles and the renewable energies contribute almost 50% to the total electricity mix. The electricity mix is similar to the one in the cost minimal pathway, but it has a higher share of domestic renewable energies (about 1000 TWh more wind generation in 2060).

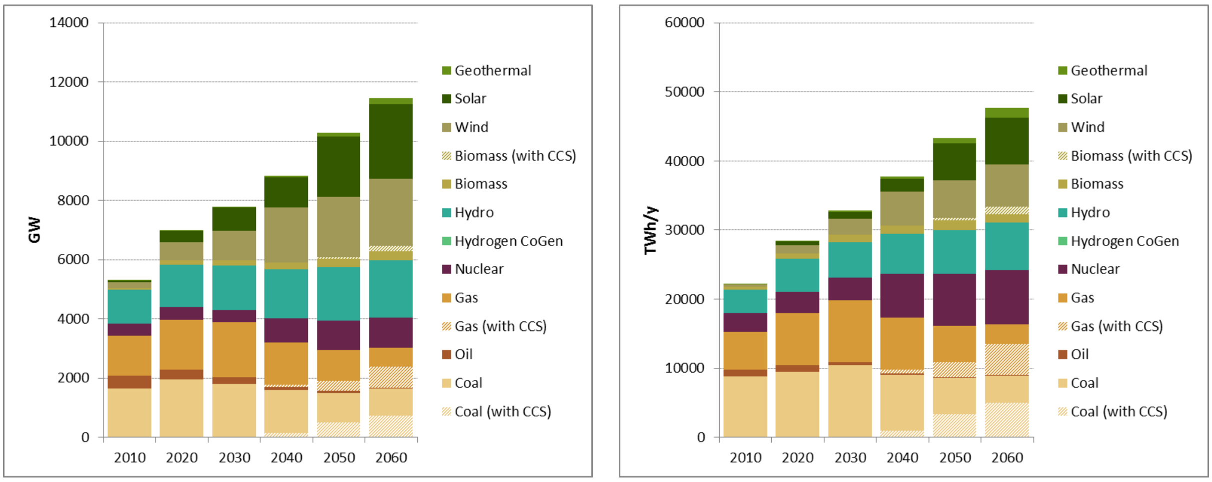


Figure 78: Electric capacity and electricity generation per fuel and region for the energy carrier import minimal pathway

The CO_2 emissions peak in 2020 and decrease to 19 Gt by 2060 (Figure 79). The annual CO_2 emissions from oil decrease from 10.6 Gt/y to one third from 2010 to 2060 due to the reduced oil product imports. The CO_2 emissions from coal instead increase by 2030 and decrease to 9.6 Gt in 2060 in line with the use of coal up to 2030 and the subsequent application of CCS in coal power plants. The captured CO_2 reaches 7.5 Gt in 2060 and mainly takes place in CHINAREG (Figure 80). The CO_2 capture rate stabilises around 9 Gt CO_2 in the second half of this century (not shown in Figure 80), what is similar to the cost minimal trajectory.

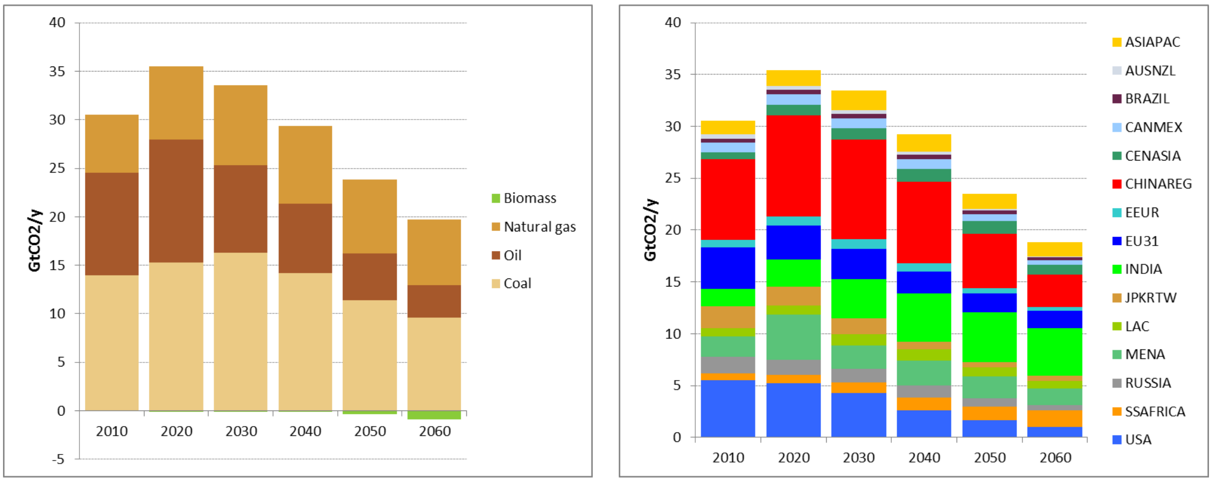


Figure 79: CO_2 emissions per fuel and region for the energy carrier import minimal pathway

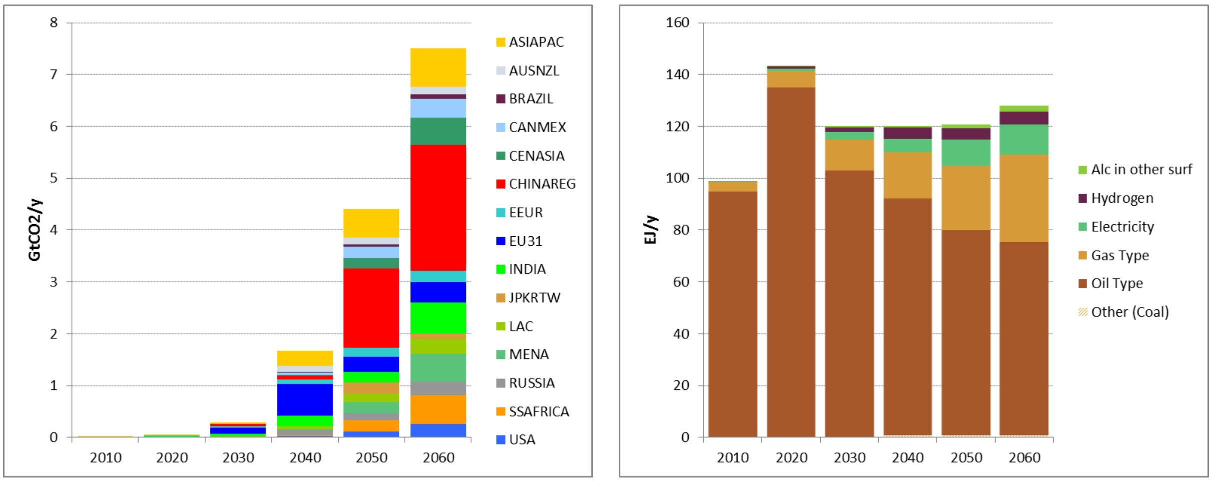


Figure 80: CO_2 captured per region and fuel consumption in transport for the energy carrier import minimal pathway. Alc in other surf = Alcohols (methanol, ethanol) in freight transport.

Despite the minimisation of energy carrier imports, the transport sector remains dominated by oil and gas fuels. Alternative transport fuels, mainly electricity, but also hydrogen and alcohols, only reach a share of 15% in 2060 (Figure 80). Among the fossil fuels, gas is used more than in the cost minimal pathway as less oil is imported. Compared to the cost minimal pathway, the alternative transport fuels are also expanded because they can be produced from domestic resources.

The energy carrier import minimal pathway reaches very low levels of energy carrier imports in 2060 (Figure 81): Coal imports stop after 2030 and natural gas imports reduce to zero by 2060. Biofuel imports slightly increase over the time horizon, but remain on a very low level. The major energy carrier imports, i.e. the oil imports, are significantly reduced by 2060, when they reach 5.3 EJ. In that time period, ASIAPAC, INDIA, JPKRTW and USA are the main importers. The imports of JPKRTW and INDIA are reduced towards the last time period, while some imports to ASIAPAC and USA remain also in the last considered period.

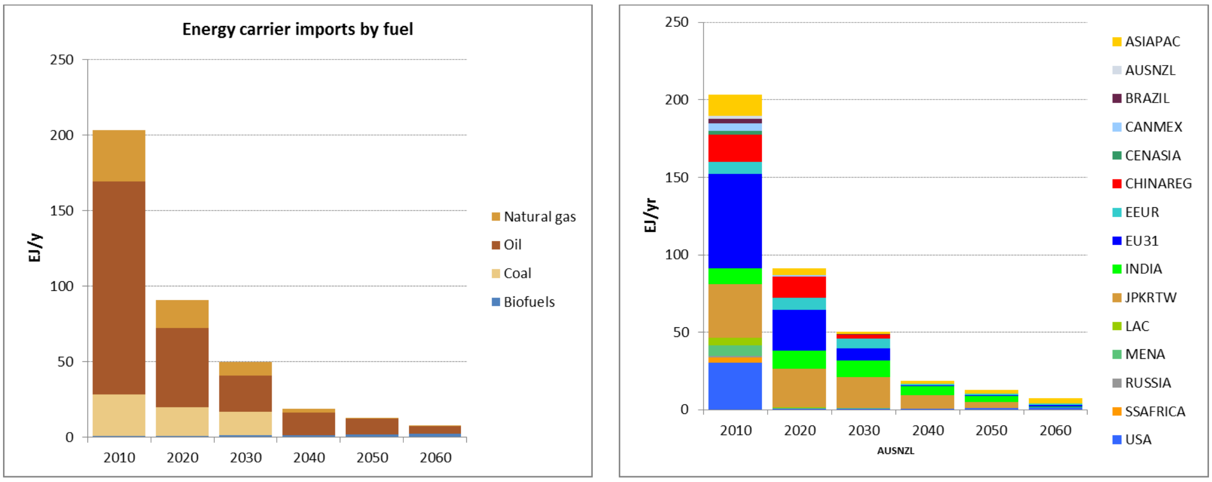


Figure 81: Energy carrier imports per energy carrier and region for the energy carrier import minimal pathway

6.2.2. Results and discussion of the lexicographic optimisation

The lexicographic optimisation is carried out for all three objectives. The priority order is arbitrarily set to be first COST, then CO_2 and IMP. For the first objective, the cost, the single-objective run is performed and the minimum possible costs are obtained (COST-1). Second, the minimal cost is set as equality constraint and CO_2 is minimised (COST-2). Third, the obtained minimal CO_2 emissions are set as second equality constraint and the energy carrier imports are minimised (COST-3). The procedure for the other two objectives is analogous (CO2-1 to CO2-3 and IMP-1 to IMP-3, respectively). The results of the lexicographic optimisation runs are presented in Figure 82.

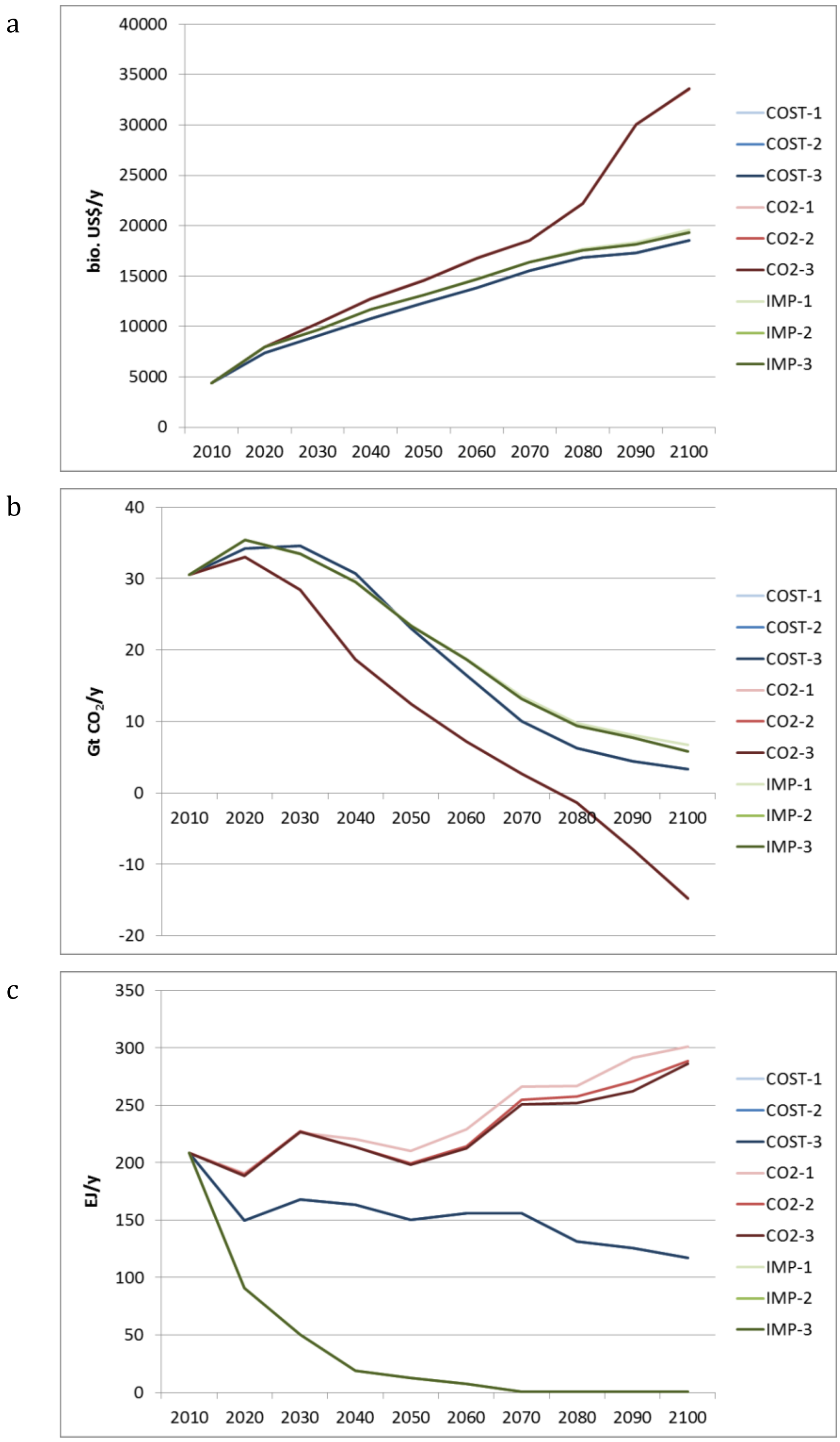


Figure 82: Costs (a), CO_2 emissions (b) and energy carrier imports (c) of the lexicographic optimisation pathways

The results show that for the optimisation which starts from the cost minimal solution, the other two objectives can only be marginally improved, i.e. the cost minimal solution without constraints is already close to the Pareto optimal solution. For the optimisation starting from the CO_2 minimal solution, the other two objectives can be improved by 0.7% (COST) and 7% (IMP). For the optimisation starting from the energy carrier import minimal solution, the other two objectives can be improved by 0.3% (COST) and 1.9% (CO_2), respectively. The cost (a), CO_2 emission (b) and energy carrier import (c) trajectories of the lexicographic optimisation runs are presented in Figure 82. The lowest curve in each graph represents the optimal pathway, i.e. the pathway, which leads to the minimal respective objective value.

6.3.Summarising remarks and intermediate conclusions

The three single-objective optimisation pathways presented in Section 6.2.1 represent different views on the development of the energy system: While cost optimisation is selected for the scenario quantification in PE energy system models to approximate how decisions are made in reality, CO_2 and energy carrier import optimisations allow for insights on what pathways would be possible if neither costs nor other (policy) objectives were considered. So they frame the set of feasible pathways in consideration of the modelling constraints.

The results discussed above, which are based on the optimisation of a single objective, are only slightly altered when the other objectives are introduced in the optimisation (Section 6.2.2). This indicates that the solver produces almost Pareto optimal (non-dominated) solutions for the optimisation of the single policy objectives. The Pareto optimal solutions define the pathways for minimal costs, CO_2 emissions and energy carrier imports, respectively, and the minimal cumulative objective values for the period 2010 to 2110, which amount to \$191 trillion for cost, 706 Gt CO_2 emissions and 3.85 ZJ for energy carrier imports for the period 2010-2110.

All three single-objective pathways face trade-offs related to the three objectives under consideration (Table 23). According to the results derived from the applied modelling framework and the assumptions in the Free JAZZ scenario, it is possible to become import independent for all regions except JPKRTW by the mid-century. On the one hand, this comes at the expense of higher CO_2 emissions due to the constantly high use of domestic coal resources and on the other hand the higher cost as benefits of trade cannot be gained and more expensive domestic energy supply chains are implemented. A CO_2 minimal pathway instead leads to increased energy system costs as well as higher levels of energy carrier imports and thus lower security of supply compared to the cost minimal pathway.

With the current version of the modelling framework and the selected scenario, it is possible to achieve cumulative emissions with the CO_2 minimal pathway which are approximately consistent with reaching the 2°C target for the end of this century with 66% probability according to Rogelj et al. [109]: The cumulative CO_2 emissions from 2010 to 2100 are 1090 Gt. Contrarily, the total cumulative energy system CO_2 emissions from 2010 to 2100 are 1940 Gt and 2090 Gt in the cost minimal and energy carrier import minimal pathways, respectively. The CO_2 minimal trajectory with negative energy system emissions in the second half of this century is consistent with the results from other models which aim to limit GHG emissions for climate change mitigation [110, 111].

Acknowledgments

I would like to thank Dr. Martin Densing and Dr. Evangelos Panos for their support regarding the MARKAL code. I would like acknowledge the two of them as well as Dr. Tom Kober for discussions on the methodology.

7. Conclusions and Outlook

7.1. Conclusions

7.1.1. Conclusions on the methods

The long-term development of energy technologies and systems can be analysed with scenarios quantified with energy system models. Partial equilibrium energy system models allow the investigation of the long-term development of the energy system, taking into account technology details. The sustainability impacts however, i.e. the impacts regarding the three dimensions of sustainability, are often not equally covered. Other methods, such as multi-criteria decision analysis (MCDA), allow for the comprehensive and balanced consideration of all sustainability aspects as well as subjective preferences. Thus, the two methods, partial equilibrium energy system models and MCDA, can complement each other.

As partial equilibrium energy system models are and MCDA can be technology-based, their combination is facilitated. In this thesis, four such combinations for technology-based long-term multi-criteria sustainability analysis of energy systems are described, analysed and applied: bottom-up ex-post multi-criteria analysis of energy systems on the end-use technology level, bottom-up ex-post multi-criteria analysis of energy systems on the supply and end-use technology levels, bottom-up ex-post external cost analysis of energy systems, and endogenisation of sustainability indicators in energy system models. The four combined methods represent progressive integration steps of the two methods from the ex-post quantification of sustainability indicators on the end-use level to their endogenisation in the objective function of the energy system model. The combined methods could be applied in full-scale energy system models and provided credible results. The three ex-post combined methods can be applied within existing modelling frameworks and scenarios. The optimisation of endogenous objectives instead requires changes to the modelling code and leads to new energy system transformation pathways. The three ex-post combined methods are based on least-cost optimisation and considered as realistic pathways and can thus be used as basis for decision-making. The fourth combined method instead leads to extreme energy system pathways, which are more of academic interest, but can be illustrative as limiting cases defining the possible scope of future developments.

The combined methods applied require the following approaches in data processing and changes to existing approaches. In case of incomplete data, the quantification of sustainability indicators for energy system scenarios requires approaches for temporal and geographical projection of existing indicator values, particularly for global models. In this context, a trade-off between regional coverage and uncertainty was found: global energy system models allow for endogenous modelling of the energy chains across regions and for different time periods which facilitates the quantification of sustainability indicators. The wider regional scope however often introduces more uncertainty in the indicator values because they must often be geographically and temporarily projected due to the lack of data. The quantification of life-cycle assessment (LCA)-based indicators for energy systems needs approaches to avoid double-counting the energy system's impacts and allowing dedicated allocation of impacts to the modelling regions. The endogenisation of sustainability objectives in partial equilibrium energy system models requires adjustments to the standard energy system modelling code, i.e. to the objective function and other model equations. Overall, the combined methods described for technology-based long-term multi-criteria sustainability analysis of energy systems require interdisciplinary work in energy system modelling and technology assessment (including for example LCA, risk assessment and external cost assessment).

Further approaches were proposed but could not be implemented consistently in full-scale energy system models. The calculation of the external costs for LCA-based indicators was described. Such an approach requires consistency of the regions in the energy system model and background life-cycle inventory database, or the complex aggregation and disaggregation of the regional contributions. An LCA-based approach for the endogenisation of the energy system's own energy use in partial equilibrium energy system models was proposed. In the way the approach was set up, it influenced the interactions between conversion technologies, end-use technologies and energy service demands of existing energy system models and thus the modelling results. MCDA with weighted sum approach was successfully applied for bottom-up ex-post multi-criteria sustainability analysis of energy systems. The weighting was implemented *after* the optimisation on the level of total indicator values and provided ranked scenarios – analogous to the MCDA of energy technologies. For the optimisation of multiple endogenous objectives in partial equilibrium energy system models with the weighted sum approach instead, the weighting was implemented *concurrent* to the optimisation, i.e. in the objective function. Together with the scaling of the objectives, which is usually required, no robust results could be found.

In summary, this thesis consistently describes four combined methods for long-term multi-criteria sustainability analysis of energy systems on progressive levels of integration including the set-up, the benefits and drawbacks, and the respective quantification of energy chain- and LCA-based indicators. In this context, an approach that avoids double-counting the energy system's impacts for LCA-based indicators, has been developed and applied. The practicality of the combined methods is demonstrated by implementing them in full-scale models of the whole energy system with full MCDA (if applicable). Further approaches are theoretically described for the disaggregation of LCA-based indicators into direct and indirect impacts, the quantification of external costs of LCA-based impacts and the quantification of energy flows for the endogenisation of the energy system's own energy use, but could not be implemented consistently in existing full-scale energy system models. This thesis can serve as a basis for future long-term multi-criteria sustainability analysis of energy systems and assist with the selection of the appropriate combined method and the quantification of energy chain- and LCA-based indicators for the respective case study.

7.1.2. Conclusions on the case studies

The first case study addresses three scenario variants for Switzerland in 2035. The variants differ in their assumptions on the Swiss climate policy and the availability of carbon capture and storage technology. It is found that the implementation of a greenhouse gas reduction target leads to co-benefits such as the reduction in the use of fossil resources (-34%), better overall public acceptance of the energy system technologies, higher resource autonomy and fewer fatalities from accidents in the energy chains (-13%) compared to the reference case without climate policy. Carbon capture and storage technologies allow the achievement of greenhouse gas emission reduction goals at lower cost (-7% investment cost) at the expense of more societal conflicts due to the storage of the Carbon Dioxide (CO_2) in the ground. The MCDA results show clearly different scores for the three variants for high weights on relevant criteria for fossil energy and for carbon capture and storage technology, respectively. With a more balanced weighting profile, i.e. with the presented interpretation of the multiple goals of the Swiss government from all dimensions of sustainability, the climate scenario variant performs best, but the MCDA scores lie much closer to each other.

This case study can inform the Swiss government about the consequences of the implementation of a climate policy on sustainable development. It shows not only the co-benefits such as more resource autonomy, but also the drawbacks, which point out possible fields of (political) action or research. In this case, for example the higher energy technology costs, the additional waste and the higher variability of energy supply are potential fields for complementary policies. For energy companies, these fields can indicate business opportunities. In the case where carbon capture and storage technologies are allowed, the public opposition (which caused the nuclear phase-out in Switzerland) is a key field for (political) action, for example with participative decision-making processes.

The second and third case studies are multi-criteria sustainability and external cost analyses of the three World Energy Scenarios for 2010 to 2060. The second case study is based on a comprehensive set of bottom-up and top-down sustainability indicators, while the third case study is limited to a set of local air pollutant and greenhouse gas emissions.

On the global level, it is found that the external costs related to local air pollutant and greenhouse gas emissions range from 0.3 to 0.7% and from 0.2 to 0.7% of gross domestic product (GDP), respectively, in the three scenarios in 2060. Among the analysed emissions, CO_2, Nitrogen Oxides, Particulate Matter with a diameter of <2.5 μm and Sulphur Dioxide contribute most to the external costs. Developing regions, which are characterised by strongly increasing GDP, urbanisation, and greenhouse gas and local air pollutant emissions, are expected to bear 61 to 73% of the external cost burdens due to local air pollutant emissions in the three scenarios in 2060. The climate change mitigation scenario Unfinished SYMPHONY leads to co-benefits related to environment, human health and risks for severe accidents in the energy chains. Such a pathway also allows for economic development without increasing external costs. The Hard ROCK scenario instead, which is characterised by low GDP growth, increasing energy demand and high shares of fossil energies, is expected to face increasing external costs relative to its GDP. The Modern JAZZ scenario, which has the highest GDP growth of the three addressed scenarios, not only improves outcomes with regard to access to clean energy, GDP per capita and the energy intensity of the economy, but also regarding CO_2, terrestrial acidification, freshwater eutrophication and mortality in severe accidents.

On the regional level, the two global case studies show that China, Macau and Mongolia remains an important region regarding the global energy consumption, but its sustainability indicators are found to improve, namely environmental and human health damages and socio-economic indicators. The region can break the trend of increasing external costs by reducing the coal use and associated impacts and by peaking in total primary energy supply. The European Union plus Liechtenstein, Norway and Switzerland as a developed region has a reduced share in the global energy consumption over the time horizon considered. At the same time, the region is expected to improve regarding most of the sustainability indicators, while the external costs are stable or moderately increasing. The developing region sub-Saharan Africa is instead found to undergo large changes in its energy system and most of its human health and environmental damages and risk indicators, as well as external costs worsen by 2060. In contrast, the development of the economic indicators is positive.

These cases studies can inform national governments about the progress of their region regarding the Sustainable Development Goals in the field of energy. Possible negative developments ("hotspots") can be identified based on a comprehensive set of indicators and external costs, respectively, and targeted with possible (political) interventions. The case studies show that an Unfinished SYMPHONY type of climate change mitigation pathway has co-benefits regarding various other indicators. This can help the government to start engaging in climate negotiations and to justify investments in greenhouse gas emission reductions. Energy companies can benchmark and possibly adjust their portfolios according to sustainable pathways.

The fourth case study quantifies global energy system scenarios by endogenising the sustainability objectives in the energy system model. Three policy objectives are optimised: total discounted system costs, CO_2 emissions and energy carrier imports. The CO_2 minimal pathway is characterised by efficient energy use, more low-carbon and less fossil resources and more alternative transport fuels than in the cost minimal pathway. It has decreasing (by 2070) and even negative (from 2080) CO_2 emissions from the energy system and is thus compliant with the 2°C target. The achievements must be traded off against the 16% cumulative cost increase from 2010 to 2060 compared to the cost minimal pathway. The minimisation of energy carrier imports for increasing security of supply is characterised by more domestic coal and less imported oil use than in the cost minimal pathway, and more gas and alternative fuels in the transport sector. This pathway reaches very low energy imports from 2070, but it has increased cumulative cost (+7% compared to the cost minimal pathway) and CO_2 emissions (+31% compared to the CO_2 minimal pathway) from 2010 to 2060 as trade-offs.

This illustrative case study shows that strong security of supply policies, such as the ones in the Hard ROCK scenario, are associated with additional costs and increased CO_2 emissions. It also indicates that scenarios with high GDP growth, such as the Free JAZZ scenario, can reach a 2°C pathway but only with dedicated efforts in all regions and sectors, and with additional costs.

Overall – due to the large diversity in the regional energy systems – there is no homogenous development in the world regions, and regional solutions, which address the individual challenges of the regions, are required for reaching the SDG in the field of energy. Long-term multi-criteria sustainability analysis of energy systems can contribute to finding such solutions and defining sound strategies and energy policies that lead to sustainable development.

7.2. Outlook for future research

Further research could complement the work presented in thesis. The possible fields for further work can be allocated to the energy system model, the LCA indicator quantification, the indicator databases, and the larger context.

Regarding the energy system model used, some energy technologies in the Global Multi-regional MARKAL (GMM) model could be disaggregated or added in order to better represent the impacts of the energy system. In the freight transport sector of the GMM model, the end-use technologies are aggregated based on the fuel used. For example, gas-based freight transport could be disaggregated to transport by pipeline, on the road and by water. Coal power plants could be disaggregated into lignite and hard coal power plants, and the application of carbon capture and storage and carbon capture and utilisation technologies in different industries could be modelled.

Regarding the LCA indicator quantification, the modelling of the direct and indirect impacts of the energy technologies could be more accurate as indicated in Section 2.4.2. The existing modelling framework for the quantification of LCA indicators for the GMM model can be improved: Some energy technologies of the GMM model are matched with proxy life-cycle datasets (Appendix, Table 42), which could be replaced newly developed ones. Some GMM energy technologies are matched with internal life-cycle inventory datasets (Section 4.2.2), which could be replaced by peer-reviewed ones. The application of regionalised life-cycle impact assessment methods would allow more accurate quantification of LCA-based indicators. A theoretical approach for the calculation of regionalised LCA indicators was proposed by Mutel and Hellweg [112]. The generic approach described for the calculation of the external costs for LCA-based indicators could be adapted so that it becomes practically implementable. The quantification of the energy inputs for each energy system technology using an LCA-based approach in combination with a future background life-cycle inventory database would improve the representation of the energy system’s own energy use, particularly for the optimisation of endogenous sustainability indicators. The development or application of further MCDA methods (e.g. the Pairwise Outperformance Algorithm [113]) could enrich the results and conclusions. Additional combined methods for the optimisation of endogenous objectives in energy system models could be explored, for example the implementation of methods from process engineering such as multi-objective optimisation (e.g. epsilon-constraint method and goal-attainment method [114]).

Regarding the indicator databases used in the case studies for the indicator quantification, future research could aim at the development of future versions of indicator databases such as ecoinvent, e.g. by extending the work performed in the European project NEEDS [67]. A future version of ecoinvent could include estimations of expected changes in the different modelled sectors and improve the quantification of LCA-based indicators for future time periods. One example is the treatment of metals: consistently closed material balances and estimates of future recycling rates could improve the indicator quantification (Sections 3.4.4 and 4.2.2). In this context, it would be possible to model key material flows in the partial equilibrium energy system model (e.g. Pietrapertosa et al. [48]). Specifically for ecoinvent, the regional data could be improved to better represent non-European regions. Fuels, i.e. the energy carriers represented in the GMM model, could be labelled according to their IEA classification [87] to ease their identification. Similarly, the main input, i.e. the upstream contribution, of each dataset could be labelled to distinguish it from other fuel inputs (energy system's own energy use). The severe accident risk indicator data from ENSAD could be extended by the development of methods for the quantification of risk indicators for further energy chains on the one hand and for future time periods and missing world regions on the other hand (e.g. Roth et al. [24]). Similarly, consistent specific external cost estimates for the different world regions and future time periods considering all important influencing factors (Section 5.2.2) could improve the analysis. Such an approach should allow for consistency of scenario and external cost assumptions.

Regarding the larger context, the quantified environmental flows could be analysed in terms of their compliance with the planetary boundaries [115, 116]. The performance of the energy systems related to the respective Sustainable Development Goals could be compared with the region's performance with respect to other Sustainable Development Goals to gain a more comprehensive picture.

The work presented in this thesis and further research in this field can contribute to the identify trends, quantify the performance and define strategies with regard to the sustainability of long-term transformation pathways of energy systems.

8. Appendix

Table 24: Literature review of ex-post multi-criteria analysis of energy system scenarios. LCI = life-cycle inventory, MCDA = Multi-criteria Decision Analysis.

Study	Scope	Energy system model	Scenarios	Indicators	LCI database	MCDA method
Atilgan and Azapagic, 2016 [117]	Electricity Turkey 2010	no model	current system	11 environment 3 economy 6 societal	ecoinvent v2.2 Flury and Frischknecht Kouloumpis et al. PE International	MAVT
Rahman, Paatero et al., 2016 [118]	Electricity Bangladesh 2010-2040	LEAP	4 scenarios	24 indicators	-	SMAA
Shmelev and van den Bergh, 2016 [119]	Electricity UK 2050	MARKAL	7 scenarios	8 indicators	indicator values from literature	APIS
Brand and Missaoui, 2014 [120]	Electricity Tunesia 2030	Own electricity market model	5 scenarios	4 cost 4 technology 5 emission 4 society and security of supply	-	TOPSIS
Santoyo-Castelazo and Azapagic, 2014 [121]	Electricity Mexico 2050	no model (made up scenarios)	11 scenarios	17 indicators	Dones et al. (2007) Jungbluth et al., (2007) Bauer et al. (2008) SENER (2006) GEMIS (Oko Institute (2005) Lecointe et al. (2007) Sørensen and Naef (2008) Viebahn et al. (2007) Frankl et al. (2005) DONG Energy (2008)	MAVT

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Hong, Bradshaw et al., 2013 [122]	Electricity South Korea 2010-50	no model	4 scenarios	12 indicators total cost assessment	-	ranking orders
Ribeiro, Ferreira et al., 2013 [123]	Electricity Portugal 2020	Own MILP	5 scenarios	13 indicators	-	value measurement methods
Streimikiene and Balezentis, 2013 [31]	Energy Lithuania 2012/2020	MESSAGE	7 scenarios	12 indicators	-	MULTIMOORA
Sheinbaum-Pardo, Ruiz-Mendoza et al., 2012 [32]	Energy Mexico 1990/2008	no model	historic years	8 indicators	-	-
Eckle, Burgherr et al., 2011 [33]	Energy 47 regions today-2050	POLES	14 scenarios	2 environment 2 economy 4 society 5 security of supply	-	Weighted Sum Approach (WSA)
Browne, O'Regan et al., 2010 [124]	domestic heating and electricity city-region in Ireland 2010	no model (current system)	6 scenarios	4 environment 1 security of supply 2 economy	-	NAIADE
Jovanović, Afgan et al., 2009 [34]	Energy Belgrade 2015	MEAD simulation model	15 scenarios	4 environment 4 economy 4 societal	-	-
Eliasson and Lee, 2003 [78]	Electricity China 2000-2025	EGEAS (Electric Generation Expansion Analysis System)	12 scenarios	3 economy 8 environment 1 society 1 technology	LCI data from various Chinese institutions	ELECTRE III

Table 25: Literature review of energy system scenario analysis with life-cycle assessment-based indicators. LCI = Life-cycle inventory, LCIA = Life-cycle Impact Assessment

Study	Scope	System model & Scenarios	LCI database	Prospective approach	LCIA	Double-counting
Berrill et al., 2016 [125]	Electricity Europe 2050	THEMIS Input-Output model 44 scenarios from REMix	ecoinvent EXIOBASE	electricity mixes aluminium, copper, nickel, iron, steel, silicon, flat glass, zinc and clinker fugitive NG emissions	climate change freshwater eutrophication freshwater ecotoxicity particulate matter formation metal depletion land occupation	not mentioned
Portugal Pereira et al., 2016 [126]	Electricity Brazil 2010-50	MESSAGE-Brazil 3 scenarios	ecoinvent literature	not mentioned	GHG emissions	not mentioned
Sokka et al., 2016 [127]	Renewable Energy Finland 2020	no model (national targets)	literature review expert interviews	not mentioned	14 impact categories 6 further categories	not mentioned
Garcia-Gusano et al., 2016 [36]	Electricity Norway (5 regions) 2014-2050	TIMES-Norway BAU scenario	ecoinvent	electricity mixes	IMPACT 2002+ CC IMPACT 2002+ EQ IMPACT 2002+ HH	explicitly mentioned and shortly discussed
Hertwich et al., 2015 [128]	Electricity World (9 regions) 2010-2050	THEMIS Input-Output model IEA BLUE MAP IEA BAU	ecoinvent EXIOBASE	electricity mixes aluminium, copper, nickel, iron, steel, silicon, flat glass, zinc and clinker fugitive NG emissions	ReCiPe GHG ReCiPe eutrophication ReCiPe PM formation ReCiPe aquatic ecotox. aluminium, iron, copper, cement non-renewable energy land	not mentioned
Kouloumpis et al., 2015 [129]	Electricity UK 2010-70	ETLCA model 4 scenarios	NEEDS ecoinvent Kouloumpis et al. (2012)	electricity mixes	12 impacts (based on CML methodology)	not mentioned

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Laurent and Espinosa, 2015 [130]	Electricity 199 countries or territories 1980-2011	no model, historic data	ecoinvent	none (historic assessment)	ILCD recommended midpoints: climate change human toxicity freshwater ecotoxicity eutrophication respiratory inorganics ionising radiation land use non-renewable resource depletion	not mentioned
Vazquez-Rowe et al., 2015 [131]	Electricity Spain, Peru 1989-2013	no model, historic data	ecoinvent	none (historic assessment)	ReCiPe midpoints ReCiPe endpoints	not mentioned
Messagie et al., 2014 [132]	Electricity	no model, historic data	ecoinvent	none (historic assessment)	GWP	not mentioned
Portugal Pereira et al., 2014 [126]	Electricity Japan 2030	no model 4 scenarios	GEMIS database		NRE consumption GHG SO_2e PM10e	not mentioned
Hammond et al., 2013 [133]	Electricity UK 1990-2050	no model 3 scenarios	not mentioned (use SimaPro)	not mentioned	EcoIndicator 99 single-score indicator	not mentioned
Brand et al., 2012 [35]	Transport UK 2010-50	UK Transport Carbon Model	LCEIM (life-cycle inventory and environmental impacts assessment model); hybrid approach of process-chain analysis and input–output analysis	electricity mixes fuel consumption	25 emissions categories CO_2 nitrous oxide land use conversion from undeveloped to cultivated crude oil	Double-counting within the hybrid life-cycle inventory was avoided as much as possible following Strømman et al.(2009).

Table 26: Literature review for external cost analysis of energy system scenarios

Study	Scope	System model	Scenarios	Indicators	Modelling of emissions	Source of external costs
Streimikiene, 2017 [42]	Baltic States Electricity sector 2004-2014	Context-mechanism-outcome" (CMO) model	1 scenario	6 pollutants (6 LAP)	Direct emissions	Data from Streimikiene and Alisauskaite-Seskiene 2014
Tokimatsu et al., 2016 [43]	China Electricity sector 2006-26	Power generation planning model LIME	2 scenarios	3 pollutants (2 LAP, 1 GHG)	Life-cycle assessment	Data from LIME
Rentizelas and Georgakellos, 2014 [44]	Greece Electricity sector 2012-2050	Own linear programming model	2 scenarios	6 pollutants (5 LAP, 1 GHG)	Life cycle assessment	Data from NEEDS 2009
Shih and Tseng, 2014 [45]	Taiwan Electricity sector 2010-2030	System dynamics model	2 scenarios	6 pollutants (5 LAP, 1 GHG)	Life cycle assessment	Data from Shih et al. 2012
Brown et al., 2013 [46]	USA Electricity sector 2015-2055	MARKAL	4 scenarios	5 pollutants (4 LAP, 1 GHG)	Upstream and operation pollutant emissions	Data from NRC2010
Pietrapertosa et al., 2010 [47]	Italy Energy sector 2000-2050	TIMES	6 scenarios	8 pollutants (5 LAP, 3 GHG)	Direct emissions per sector	Data from ExternE
Kosugi et al., 2009 [41]	Japan Economy 2000-2100	LIME GRAPE	2 simulations	3 pollutants (1 LAP, 1 GHG, 1 Land use)	Life cycle assessment	Data from LIME
Kypreos et al., 2009 [40]	EU25 plus Iceland, Norway Romania and Switzerland Energy sector 2000-2050	Pan-EU-TIMES	4 scenarios	11 pollutants (7 LAP, 4 GHG)	Life-cycle assessment	Data from other NEEDS research streams
Pietrapertosa et al., 2009 [48]	Southern Italy Energy sector 1996-2023	MARKAL GEMIS	3 scenarios	6 pollutants in 3 categories (4 LAP, 2 GHG)	Life cycle assessment	Data from ExternE
Rafaj, 2005 [15]	World Electricity sector 2000-2050	MARKAL	5 scenarios	4 pollutants (3 LAP, 1 GHG)	Direct emissions per technology	Data from ExternE Adjustments for PPP, population density and sulphur content of the fuel
Roeder, 2001 [49]	OECD Europe Passenger car sector 2000-50	MARKAL	4 scenarios	5 pollutants (4 LAP, 1 GHG)	Life-cycle assessment	Data from Infras/ Econcept/ Prognos

Table 27: Energy service demands, end-use energy demands and end-use technologies per sector (residential, commercial) and corresponding end-use technology LCI datasets. LCI = life-cycle inventory, CH = Switzerland, CHP = combined heat and power

End-use sector	Energy service demand	End-use energy demand	End-use technology	End-use technology LCI dataset[a]
Residential	Hot water, cooking	**Biomass**[b]	Wood log heater	Heat, mixed logs, at wood heater 6kW/CH U
			Wood pellet furnace	Heat, wood pellets, at furnace 15kW/CH U
	Space heating	**Light oil**	Light fuel oil boiler	Heat, light fuel oil, at boiler 10kW condensing, non-modulating/CH U
	Electricity	**Electricity**	-	Electricity, low voltage, at grid/CH U[c]
	Space heating	**District heat**[b]	Natural gas CHP plant	Heat, at cogen 1MWe lean burn, allocation exergy/CH U
			Waste incineration plant	Heat from waste, at municipal waste incineration plant/CH U
			Wood CHP plant	Heat, at cogen 6400kWth, wood, allocation exergy/CH U
	Space heating, hot water, cooking	**Natural gas**	Natural gas boiler	Heat, natural gas, at boiler atm. low-NO_x condensing non-modulating <100kW/CH U
	Space heating	**Wood pellets**	Wood pellet furnace	Heat, wood pellets, at furnace 15kW/CH U
	Hot water, cooking	**Solar energy**[b]	Combined solar system	Heat, at flat plate collector, one-family house, for combined system/CH U
			Solar hot water system	Heat, at flat plate collector, one-family house, for hot water/CH U
	-	**Energy savings**	Wall and window insulation	see Table 31
Commercial	Heating	**Biomass**[b]	Wood log furnace	Heat, mixed logs, at furnace 30kW/CH U
			Wood pellet furnace	Heat, wood pellets, at furnace 50kW/CH U
	Hot water	**Light oil**	Light fuel oil boiler	Heat, light fuel oil, at boiler 100kW condensing, non-modulating/CH U
	Electricity	**Electricity**	-	Electricity, low voltage, at grid/CH U[c]
	Space heating	**District heat**[b]	Natural gas CHP plant	Heat, at cogen 1MWe lean burn, allocation exergy/CH U
			Waste incineration plant	Heat from waste, at municipal waste incineration plant/CH U
			Wood CHP plant	Heat, at cogen 6400kWth, wood, allocation exergy/CH U
	Heating	**Heavy fuel oil**	Heavy fuel oil furnace	Heat, heavy fuel oil, at industrial furnace 1MW/CH U
	Heating, other, cooking, cooling, hot water	**Natural gas**[b]	Natural gas boiler	Heat, natural gas, at boiler condensing modulating >100kW/CH U
			Natural gas cooler	Cooling energy, natural gas, at cogen unit with absorption chiller 100 kW/CH U
	Hot water	**Solar energy**	Solar hot water system	Heat, at flat plate collector, multiple dwelling, for hot water/CH U

[a] ecoinvent v2.2 dataset [57] unless otherwise stated.

[b] The allocation of the end-use energy demands to the corresponding end-use technologies is 1/3 : 1/3 : 1/3 for district heat and 1/2 : 1/2 for the others.

[c] The electricity mix is adjusted according to the scenario variant as reported in Table 29.

Table 28: Energy service demands, end-use energy demands and end-use technologies per sector (industrial, transport) and corresponding end-use technology LCI datasets. LCI = life-cycle inventory, CH = Switzerland, CHP = combined heat and power, SBB = Schweizerische Bundesbahnen

End-use sector	**Energy service demand**	**End-use energy demand**	**End-use technology**	**End-use technology LCI dataset**[a]
Industry	Heat use (process heat, steam production, machine drive)	**Coal**	Hard coal furnace	Heat, at hard coal industrial furnace 1-10MW/CH U
	Heat use (process heat, steam production, machine drive)	**Oil products**	Heavy fuel oil furnace	Heat, heavy fuel oil, at industrial furnace 1MW/CH U
	Heat use (process heat, steam production, machine drive)	**Natural gas**	Natural gas furnace	Heat, natural gas, at industrial furnace low-NO_x >100kW/CH U
	Electricity	**Electricity**	-	Electricity, medium voltage, at grid/CH U[b]
	Heat use (process heat, steam production, machine drive)	**Renewables / waste**	Waste incineration plant	Heat, biowaste, at waste incineration plant, allocation price/CH U
	Space heating	**District heat**[b]	Natural gas CHP plant Waste incineration plant Wood CHP plant	Heat, at cogen 1MWe lean burn, allocation exergy/CH U Heat from waste, at municipal waste incineration plant/CH U Heat, at cogen 6400kWth, wood, allocation exergy/CH U
Transport[d]	International air transport, domestic air transport	**Jet kerosene**	Passenger aircraft	Transport, aircraft, passenger/CH U
	Passenger cars Trucks Rail Busses International navigation, domestic navigation	**Diesel**	Diesel passenger car Diesel truck Diesel freight train Diesel bus Diesel barge tanker	Transport, passenger car, diesel, fleet average/CH U Transport, lorry 3.5-20t, fleet average/CH U Transport, freight, rail, diesel, with particle filter/CH U Transport, regular bus/CH U Transport, barge tanker/CH U
	Rail Passenger cars	**Electricity**	Electric passenger train Battery electric passenger car	Transport, average train, SBB mix/CH U Transport, passenger car, electric, LiMn2O4/CH U[b]
	Passenger cars Two wheelers	**Gasoline**	Gasoline passenger car Gasoline two wheeler	Transport, passenger car, petrol, fleet average/CH U Transport, scooter/CH U
	Passenger cars	**Natural gas**	Natural gas passenger car	Transport, passenger car, natural gas/CH U
	Passenger cars	**Hydrogen**	Hydrogen fuel cell passenger car	[134]

[a] ecoinvent v2.2 dataset [57] unless otherwise stated.

[b] The electricity mix is adjusted according to the scenario variant as reported in Table 29.

[c] The allocation of the end-use energy demand to the corresponding end-use technologies is 1/3 : 1/3 : 1/3.

[d] Due to the lack of appropriate LCI datasets, the following allocations had to be made in the transport sector: the aviation gasoline demand is included in the kerosene demand. The gasoline truck and bus transport is included in the passenger car gasoline demand. Natural gas truck and bus transport is included in the passenger car natural gas demand.

Table 29: Swiss electricity supply mix in 2035 in the three scenario variants by technology, in %. LCI = life-cycle inventory, CHP = combined heat and power, CH = Switzerland, CCS = carbon capture and storage, FR = France

Power generation technology	LCI dataset[a]	Ref	Clim	Clim+CCS
Biomass CHP	Electricity, at cogen 6400kWth, wood, allocation exergy/CH U	0.0	6.3	4.3
Waste incineration	Electricity from waste, at municipal waste incineration plant/CH U	1.9	2.2	2.1
Natural gas combined cycle	[59]	45.7	8.9	2.7
Natural gas CHP	Electricity, at cogen 1MWe lean burn, allocation exergy/CH U	1.9	1.6	1.2
Natural gas combined cycle with CCS	[59]	0.0	0.0	12.9
Reservoir and run-of-river hydro	Electricity, hydropower, at power plant/CH U	33.5	38.6	36.5
Pumped hydro	Electricity, hydropower, at pumped storage power plant/CH U	6.0	6.9	6.5
Nuclear	Electricity, nuclear, at power plant boiling water reactor/CH U	3.2	3.7	3.5
Solar PV	[24]	0.1	17.9	16.9
Wind	[24]	0.0	5.2	4.9
Import of French nuclear power[b]	Electricity, nuclear, at power plant pressure water reactor/FR U	3.0	3.4	3.2
Import of power from Europe[b]	see Table 30	4.8	5.5	5.2

[a] ecoinvent v2.2 dataset [57] unless otherwise stated.

[b] The established long-term purchase rights of French nuclear power will amount to 2.6 TWh_e in 2035 (SFOE 2011c). The residual imports are assumed to amount to 4.23 TWh_e which is the average import of the months with net imports in Switzerland from 2010 to 2012.

Table 30: European electricity mix in 2025 and 2050 by technology, in %. The European mix is based on the so-called realistic-optimistic UCTE electricity mixes reported in [63]. The 2035 values are calculated from linear interpolation of the 2025 and 2050 values. CCS = carbon capture and storage, UCTE = Union for Coordination of the Transmission of Electricity, GLO = global, CHP = combined heat and power, RER = Europe, CH = Switzerland, PV = photovoltaics

Power generation technology	LCI dataset [a]	2025	2050
Hard coal	[59]	4.3	0.0
Hard coal with post-combustion CO_2 capture (CCS)	[59]	0.5	0.0
Hard coal with oxy-fuel combustion (CCS)	[59]	0.5	0.0
Integrated gasification combined cycle with hard coal	[59]	0.2	0.0
Integrated gasification combined cycle with hard coal and pre-combustion CO_2 capture (CCS)	[59]	1.3	5.8
Lignite	[59]	3.0	0.0
Lignite with post-combustion CO_2 capture (CCS)	[59]	0.0	0.0
Lignite with oxy-fuel combustion (CCS)	[59]	0.0	0.0
Integrated gasification combined cycle with lignite	[59]	0.1	0.0
Integrated gasification combined cycle with lignite and pre-combustion CO_2 capture (CCS)	[59]	0.1	0.0
Oil	Electricity, oil, at power plant/UCTE U	0.7	0.2
Natural gas	Electricity, natural gas, at power plant/UCTE U	0.2	0.0
Natural gas combined cycle	[59]	29.5	3.1
Natural gas turbine	Electricity, natural gas, at turbine, 10MW/GLO U	1.0	0.0
Natural gas combined cycle with post-combustion CO_2 capture (CCS)	[59]	0.9	38.3
Natural gas CHP	[58]	9.0	0.1
Natural gas solid oxide fuel cell	[58]	0.0	0.1
Nuclear European pressurized reactor	[58]	21.6	24.4
Synthetic natural gas from wood CHP	[58]	3.8	3.3
Run-of-river hydro	Electricity, hydropower, at run-of-river power plant/RER U	6.7	4.4
Reservoir hydro	Electricity, hydropower, at reservoir power plant, alpine region/RER U	10.8	10.2
Pumped hydro	Electricity, hydropower, at pumped storage power plant/CH U	0.8	0.5
Wind onshore	[58]	3.8	3.4
Wind offshore	[58]	0.9	3.6
Solar PV	[58]	0.3	0.4
Geothermal	[58]	0.1	2.2

[a] ecoinvent v2.2 dataset [57] unless otherwise stated.

Table 31: Energy savings per scenario variant and corresponding material inputs. LCI = life-cycle inventory

		Unit	Ref	Clim	Clim+CCS	LCI dataset[a]
Energy savings (as quantified with the SMM)	Level 2	PJ	6.55	9.53	7.84	-
	Level 3	PJ	6.06	12.18	7.53	-
	Level 4	PJ	8.66	12.77	9.66	-
	Level 5	PJ	6.26	12.33	8.49	-
	Total	PJ	27.53	46.81	33.52	-
Material used to achieve the energy savings (calculated)	Rock wool	kg	7.62E+07	1.37E+08	9.60E+07	Rock wool, packed, at plant/CH U
	Glass wool	kg	4.93E+07	8.85E+07	6.22E+07	Glass wool mat, at plant/CH U
	Cellulose fiber	kg	4.17E+07	7.48E+07	5.25E+07	Cellulose fibre, inclusive blowing in, at plant/CH U
	Urea formaldehyde foam	kg	5.61E+06	1.01E+07	7.08E+06	Urea formaldehyde foam slab, hard, at plant/CH U
	Polystyrene extruded	kg	3.17E+06	5.68E+06	3.99E+06	Polystyrene, extruded (XPS), at plant/RER U
	Polystyrene foam	kg	8.55E+06	1.53E+07	1.08E+07	Polystyrene foam slab, at plant/RER U
	Foam glass	kg	7.16E+05	1.23E+06	8.73E+05	Foam glass, at regional storage/CH U
	Windows	m^2	2.06E+06	3.73E+06	2.61E+06	Difference of Glazing, double (2-IV), U<1.1 W/m2K, at plant/RER U and Glazing, triple (3-IV), U<0.5 W/m2K, at plant/RER U

Table 32: Specific indicator values for the residential sector

				Biomass		Light oil	Electricity	District heat			Natural gas	Wood pellets	Solar energy		Energy efficiency[a]
				Wood log heater	**Wood furnace**	**Boiler**	**-**	**Natural gas CHP plant**	**Waste incineration plant**	**Wood CHP plant**	**Boiler**	**Wood pellet furnace**	**Combined solar system**	**Hot water system**	**Wall and window insulation**
Environment	**Metal depletion**	kg Fe-eq/MJ	Ref	8.44E-04	1.21E-03	1.71E-03	6.58E-03	5.10E-04	0.00E+00	5.93E-05	8.71E-04	1.21E-03	9.34E-03	1.15E-02	4.30E+07
			Clim	8.46E-04	1.23E-03	1.74E-03	8.00E-03	5.11E-04	0.00E+00	5.95E-05	8.95E-04	1.23E-03	9.38E-03	1.16E-02	7.85E+07
			Clim+CCS	8.46E-04	1.23E-03	1.73E-03	7.92E-03	5.11E-04	0.00E+00	5.95E-05	8.93E-04	1.23E-03	9.38E-03	1.16E-02	5.50E+07
	Fossil energy depletion	MJ/MJ	Ref	3.36E-02	1.19E-01	1.28E+00	1.28E+00	1.27E+00	0.00E+00	8.85E-03	1.28E+00	1.19E-01	1.09E-01	1.57E-01	5.26E+09
			Clim	3.20E-02	1.04E-01	1.27E+00	4.10E-01	1.27E+00	0.00E+00	8.72E-03	1.27E+00	1.04E-01	8.28E-02	1.09E-01	8.72E+09
			Clim+CCS	3.24E-02	1.07E-01	1.27E+00	5.92E-01	1.27E+00	0.00E+00	8.75E-03	1.27E+00	1.07E-01	8.83E-02	1.19E-01	6.23E+09
	Ecosystem damages	species*y/MJ	Ref	7.65E-10	3.72E-10	5.92E-11	3.44E-11	2.18E-11	0.00E+00	8.48E-11	2.22E-11	3.72E-10	1.46E-11	1.62E-11	6.93E-01
			Clim	7.65E-10	3.73E-10	5.99E-11	7.88E-11	2.19E-11	0.00E+00	8.48E-11	2.28E-11	3.73E-10	1.59E-11	1.87E-11	1.28E+00
			Clim+CCS	7.65E-10	3.72E-10	5.96E-11	6.30E-11	2.18E-11	0.00E+00	8.48E-11	2.26E-11	3.72E-10	1.54E-11	1.78E-11	8.90E-01
	Greenhouse gas emissions	kg CO_2-eq/MJ	Ref	7.29E-04	7.89E-03	8.82E-02	7.26E-02	7.73E-02	0.00E+00	7.65E-04	7.47E-02	7.89E-03	6.89E-03	9.54E-03	2.92E+08
			Clim	6.23E-04	7.06E-03	8.75E-02	2.44E-02	7.72E-02	0.00E+00	7.58E-04	7.41E-02	7.06E-03	5.42E-03	6.84E-03	4.84E+08
			Clim+CCS	6.41E-04	6.98E-03	8.75E-02	2.01E-02	7.72E-02	0.00E+00	7.57E-04	7.40E-02	6.98E-03	5.29E-03	6.60E-03	3.37E+08
Society	**Conflict potential**	Ordinal scale	all	2	2	4	7	4	1	4	3	2	1	1	1
	Human health damages	DALY/MJ	Ref	6.88E-08	2.95E-08	1.59E-08	2.35E-08	8.63E-09	0.00E+00	1.33E-08	6.38E-09	2.95E-08	1.40E-08	1.62E-08	2.84E+02
			Clim	6.88E-08	2.97E-08	1.60E-08	3.25E-08	8.64E-09	0.00E+00	1.33E-08	6.52E-09	2.97E-08	1.42E-08	1.67E-08	5.18E+02
			Clim+CCS												
	Expected mortality in severe accidents	fatalities/ (TJ_{final}*y)	all	1.40E-03	1.40E-03	9.63E-03	9.56E-03	4.20E-03	1.40E-03	2.42E-03	4.20E-03	1.40E-03	0.00E+00	0.00E+00	0.00E+00
	Chemical waste	m^3/y	Ref	1.75E-10	4.00E-10	3.25E-10	9.74E-10	8.10E-10	0.00E+00	7.76E-12	8.84E-10	4.00E-10	3.95E-09	3.19E-09	6.75E+00
			Clim	1.77E-10	4.19E-10	3.40E-10	2.04E-09	8.10E-10	0.00E+00	7.92E-12	9.11E-10	4.19E-10	3.98E-09	3.25E-09	1.31E+01
			Clim+CCS												
Security of supply	**Resource autonomy of the supply chain**	Ordinal scale	all	9	9	2	5	1	9	9	1	9	10	10	9
	Resource variability	Ordinal scale	all	9	9	10	8	10	10	9	10	9	1	1	10

Table 33: Specific indicator values for the commercial sector

				Biomass		Light oil	Electricity	District heat			Heavy fuel oil	Natural gas		Solar
				Wood log heater	**Wood furnace**	**Boiler**	**-**	**Natural gas CHP plant**	**Waste incineration plant**	**Wood CHP plant**	**Furnace**	**Boiler**	**Cooler**	**Hot water system**
Environment	**Metal depletion**	kg Fe-eq/MJ	Ref	8.14E-04	6.76E-04	9.09E-04	6.58E-03	5.10E-04	0.00E+00	5.93E-05	3.35E-04	3.16E-04	7.01E-03	4.07E-03
			Clim	8.30E-04	7.01E-04	9.20E-04	8.00E-03	5.11E-04	0.00E+00	5.95E-05	3.42E-04	3.21E-04	7.16E-03	4.08E-03
			Clim+CCS	8.30E-04	6.99E-04	9.19E-04	7.92E-03	5.11E-04	0.00E+00	5.95E-05	3.42E-04	3.21E-04	7.15E-03	4.08E-03
	Fossil energy depletion	MJ/MJ	Ref	4.50E-02	1.14E-01	1.27E+00	1.28E+00	1.27E+00	0.00E+00	8.85E-03	1.31E+00	1.25E+00	1.45E+00	3.57E-02
			Clim	3.51E-02	9.90E-02	1.26E+00	4.10E-01	1.27E+00	0.00E+00	8.72E-03	1.30E+00	1.25E+00	1.36E+00	3.09E-02
			Clim+CCS	3.72E-02	1.02E-01	1.27E+00	5.92E-01	1.27E+00	0.00E+00	8.75E-03	1.30E+00	1.25E+00	1.38E+00	3.19E-02
	Ecosystem damages	species*y/MJ	Ref	7.68E-10	3.73E-10	5.85E-11	3.44E-11	2.18E-11	0.00E+00	8.48E-11	2.95E-11	2.02E-11	3.02E-11	5.13E-12
			Clim	7.69E-10	3.73E-10	5.88E-11	7.88E-11	2.19E-11	0.00E+00	8.48E-11	2.98E-11	2.04E-11	3.49E-11	5.38E-12
			Clim+CCS	7.69E-10	3.73E-10	5.87E-11	6.30E-11	2.18E-11	0.00E+00	8.48E-11	2.97E-11	2.03E-11	3.32E-11	5.29E-12
	Greenhouse gas emissions	kg CO_2-eq/MJ	Ref	3.37E-03	7.29E-03	8.74E-02	7.26E-02	7.73E-02	0.00E+00	7.65E-04	9.39E-02	7.00E-02	8.58E-02	2.43E-03
			Clim	2.82E-03	6.47E-03	8.71E-02	2.44E-02	7.72E-02	0.00E+00	7.58E-04	9.36E-02	6.99E-02	8.07E-02	2.16E-03
			Clim+CCS	2.77E-03	6.39E-03	8.70E-02	2.01E-02	7.72E-02	0.00E+00	7.57E-04	9.36E-02	6.99E-02	8.03E-02	2.14E-03
Society	**Conflict potential**	Ordinal scale	all	2	2	4	7	4	1	4	5	4	4	1
	Human health damages	DALY/MJ	Ref	4.66E-08	2.74E-08	1.45E-08	2.35E-08	8.63E-09	0.00E+00	1.33E-08	3.95E-08	4.69E-09	2.14E-08	6.47E-09
			Clim	4.67E-08	2.76E-08	1.45E-08	3.25E-08	8.64E-09	0.00E+00	1.33E-08	3.96E-08	4.72E-09	2.23E-08	6.52E-09
			Clim+CCS	4.67E-08	2.75E-08	1.45E-08	2.99E-08	8.64E-09	0.00E+00	1.33E-08	3.95E-08	4.71E-09	2.21E-08	6.50E-09
	Expected mortality in severe accidents	fatalities/ (TJ_{final}*y)	all	1.40E-03	1.40E-03	9.63E-03	9.56E-03	4.20E-03	1.40E-03	2.42E-03	9.63E-03	4.20E-03	4.20E-03	0.00E+00
	Chemical waste	m^3/y	Ref	1.82E-10	2.34E-10	2.43E-10	9.74E-10	8.10E-10	0.00E+00	7.76E-12	7.53E-11	7.76E-10	2.21E-09	2.12E-09
			Clim	1.94E-10	2.52E-10	2.51E-10	2.04E-09	8.10E-10	0.00E+00	7.92E-12	8.09E-11	7.82E-10	2.32E-09	2.12E-09
			Clim+CCS	1.98E-10	2.59E-10	2.54E-10	2.39E-09	8.10E-10	0.00E+00	7.97E-12	8.28E-11	7.83E-10	2.35E-09	2.12E-09
Security of supply	**Resource autonomy of the supply chain**	Ordinal scale	all	9	9	2	5	1	9	9	2	1	1	10
	Resource variability	Ordinal scale	all	9	9	10	8	10	10	9	10	10	10	1

Table 34: Specific indicator values for the industry sector

				Coal	Oil products	Natural gas	Electricity	Renewables / Waste	District heat		
				Furnace	**Furnace**	**Furnace**	**-**	**Waste incineration plant**	**Natural gas CHP plant**	**Waste incineration plant**	**Wood CHP plant**
Environment	**Metal depletion**	kg Fe-eq/MJ	Ref	1.36E-04	3.35E-04	3.90E-04	1.41E-03	6.52E-04	5.10E-04	0.00E+00	5.93E-05
			Clim	1.52E-04	3.42E-04	4.08E-04	2.70E-03	6.55E-04	5.11E-04	0.00E+00	5.95E-05
			Clim+CCS	1.51E-04	3.42E-04	4.07E-04	2.62E-03	6.55E-04	5.11E-04	0.00E+00	5.95E-05
	Fossil energy depletion	MJ/MJ	Ref	1.08E+00	1.31E+00	1.26E+00	1.14E+00	1.54E-01	1.27E+00	0.00E+00	8.85E-03
			Clim	1.07E+00	1.30E+00	1.25E+00	3.61E-01	1.52E-01	1.27E+00	0.00E+00	8.72E-03
			Clim+CCS	1.07E+00	1.30E+00	1.25E+00	5.25E-01	1.52E-01	1.27E+00	0.00E+00	8.75E-03
	Ecosystem damages	species*y/MJ	Ref	5.38E-11	2.95E-11	2.06E-11	2.62E-11	8.66E-12	2.18E-11	0.00E+00	8.48E-11
			Clim	5.42E-11	2.98E-11	2.11E-11	6.64E-11	8.75E-12	2.19E-11	0.00E+00	8.48E-11
			Clim+CCS	5.41E-11	2.97E-11	2.09E-11	5.21E-11	8.72E-12	2.18E-11	0.00E+00	8.48E-11
	Greenhouse gas emissions	kg CO_2-eq/MJ	Ref	1.05E-01	9.39E-02	7.04E-02	6.50E-02	1.25E-02	7.73E-02	0.00E+00	7.65E-04
			Clim	1.05E-01	9.36E-02	7.00E-02	2.13E-02	1.24E-02	7.72E-02	0.00E+00	7.58E-04
			Clim+CCS	1.05E-01	9.36E-02	6.99E-02	1.75E-02	1.24E-02	7.72E-02	0.00E+00	7.57E-04
Society	**Conflict potential**	Ordinal scale	all	6	5	4	7	1	4	1	4
	Human health damages	DALY/MJ	Ref	6.16E-08	3.95E-08	5.55E-09	9.92E-09	2.91E-08	8.63E-09	0.00E+00	1.33E-08
			Clim	6.17E-08	3.96E-08	5.65E-09	1.81E-08	2.91E-08	8.64E-09	0.00E+00	1.33E-08
			Clim+CCS	6.17E-08	3.95E-08	5.62E-09	1.57E-08	2.91E-08	8.64E-09	0.00E+00	1.33E-08
	Expected mortality in severe accidents	fatalities/ (TJ_{final}*y)	all	8.78E-03	9.63E-03	4.20E-03	9.56E-03	1.40E-03	4.20E-03	1.40E-03	2.42E-03
	Chemical waste	m^3/y	Ref	2.99E-11	7.53E-11	7.85E-10	8.48E-10	1.89E-10	8.10E-10	0.00E+00	7.76E-12
			Clim	4.81E-11	8.09E-11	8.05E-10	1.81E-09	1.91E-10	8.10E-10	0.00E+00	7.92E-12
			Clim+CCS	5.07E-11	8.28E-11	8.08E-10	2.13E-09	1.92E-10	8.10E-10	0.00E+00	7.97E-12
Security of supply	**Resource autonomy of the supply chain**	Ordinal scale	all	3	2	1	5	9	1	9	9
	Resource variability	Ordinal scale	all	10	10	10	8	10	10	10	9

Table 35: Specific indicator values for the transport sector

				Jet kerosene	Diesel	Diesel	Diesel	Electricity	Electricity	Gasoline	Gasoline	Natural gas	Natural gas	Hydrogen	Hydrogen
				Passenger aircraft	**Passenger car**	**Truck**	**Freight train**	**Bus**	**Barge tanker**	**Passenger train**	**Battery electric passenger car**	**Passenger car**	**Two wheeler**	**Passenger car**	**Fuel cell hybrid passenger car**
Environment	**Metal depletion**	kg Fe-eq/MJ	Ref	4.00E-04	5.95E-03	3.66E-03	1.05E-02	2.42E-03	4.36E-03	6.23E-03	1.41E-01	5.46E-03	3.25E-03	5.76E-03	3.45E-02
			Clim	4.10E-04	6.05E-03	3.70E-03	1.05E-02	2.46E-03	4.43E-03	6.38E-03	1.43E-01	5.55E-03	3.25E-03	5.89E-03	3.45E-02
			Clim+CCS	4.10E-04	6.05E-03	3.70E-03	1.05E-02	2.46E-03	4.42E-03	6.37E-03	1.42E-01	5.55E-03	3.25E-03	5.88E-03	3.45E-02
	Fossil energy depletion	MJ/MJ	Ref	1.20E+00	1.53E+00	1.51E+00	1.47E+00	1.38E+00	1.39E+00	3.30E-01	2.76E+00	1.55E+00	1.45E+00	1.68E+00	8.80E-01
			Clim	1.20E+00	1.47E+00	1.48E+00	1.43E+00	1.35E+00	1.36E+00	2.41E-01	1.97E+00	1.49E+00	1.45E+00	1.60E+00	8.80E-01
			Clim+CCS	1.20E+00	1.49E+00	1.49E+00	1.44E+00	1.36E+00	1.36E+00	2.60E-01	2.14E+00	1.50E+00	1.45E+00	1.62E+00	8.80E-01
	Ecosystem damages	species*y/MJ	Ref	5.95E-11	1.43E-10	9.62E-11	1.71E-10	7.60E-11	3.10E-10	1.54E-10	5.03E-10	1.40E-10	7.26E-11	1.16E-10	3.10E-10
			Clim	5.99E-11	1.46E-10	9.77E-11	1.73E-10	7.73E-11	3.11E-10	1.59E-10	5.45E-10	1.43E-10	7.27E-11	1.20E-10	3.10E-10
			Clim+CCS	5.97E-11	1.45E-10	9.72E-11	1.72E-10	7.68E-11	3.11E-10	1.57E-10	5.30E-10	1.42E-10	7.26E-11	1.18E-10	3.10E-10
	Greenhouse gas emissions	kg CO_2-eq/MJ	Ref	8.26E-02	9.93E-02	9.50E-02	1.01E-01	9.03E-02	1.04E-01	2.26E-02	1.46E-01	9.93E-02	1.01E-01	9.17E-02	8.23E-02
			Clim	8.23E-02	9.59E-02	9.35E-02	9.85E-02	8.88E-02	1.03E-01	1.77E-02	1.02E-01	9.62E-02	1.01E-01	8.74E-02	8.23E-02
			Clim+CCS	8.22E-02	9.56E-02	9.33E-02	9.83E-02	8.87E-02	1.02E-01	1.72E-02	9.73E-02	9.60E-02	1.01E-01	8.70E-02	8.23E-02
Society	**Conflict potential**	Ordinal scale	all	7	5	6	5	5	5	3	2	5	5	5	5
	Human health damages	DALY/MJ	Ref	2.79E-08	4.38E-08	7.57E-08	1.07E-07	7.14E-08	8.90E-08	3.44E-08	2.37E-07	3.61E-08	3.97E-08	2.58E-08	9.81E-08
			Clim	2.80E-08	4.45E-08	7.60E-08	1.07E-07	7.17E-08	8.94E-08	3.53E-08	2.46E-07	3.67E-08	3.97E-08	2.66E-08	9.81E-08
			Clim+CCS	2.80E-08	4.43E-08	7.59E-08	1.07E-07	7.16E-08	8.93E-08	3.50E-08	2.43E-07	3.65E-08	3.97E-08	2.64E-08	9.81E-08
	Expected mortality in severe accidents	fatalities/ (TJ_{final}*y)	all	9.63E-03	9.63E-03	9.63E-03	9.63E-03	9.63E-03	9.63E-03	9.56E-03	9.56E-03	9.63E-03	9.63E-03	4.20E-03	2.42E-03
	Chemical waste	m^3/y	Ref	2.75E-10	1.49E-09	7.72E-10	1.19E-09	8.82E-10	5.61E-10	1.62E-09	1.85E-08	1.42E-09	2.15E-09	2.09E-09	4.35E-09
			Clim	2.83E-10	1.57E-09	8.06E-10	1.24E-09	9.15E-10	6.37E-10	1.73E-09	2.01E-08	1.48E-09	2.15E-09	2.18E-09	4.35E-09
			Clim+CCS	2.87E-10	1.59E-09	8.17E-10	1.25E-09	9.26E-10	6.50E-10	1.77E-09	2.04E-08	1.51E-09	2.15E-09	2.22E-09	4.35E-09
Security of supply	**Resource autonomy of the supply chain**	Ordinal scale	all	2	2	2	2	2	2	5	5	2	2	1	9
	Resource variability	Ordinal scale	all	10	10	10	10	10	10	8	8	10	10	10	9

Table 36: Specific indicator values for the Swiss electricity mix

Power generation technology	**Expected mortality in severe accidents**	**Conflict potential**	**Resource autonomy of the supply chain**	**Resource variability**
Unit	fatalities/(TJ$_{final}$*y)	Ordinal scale	Ordinal scale	Ordinal scale
Biomass CHP	10	4	9	9
Waste incineration	10	1	9	10
Natural gas combined cycle	27	6	1	10
Natural gas CHP	27	4	1	10
Natural gas combined cycle with CCS	27	9	1	10
Reservoir and run-of-river hydro	151	8	10	5
Pumped hydro	276	8	10	5
Nuclear	48797	10	4	10
Solar PV	5	2	10	1
Wind	5	8	10	1
Import of French nuclear power	48797	10	4	10
Import of power from Europe	11107	6.5	4.3	8.6
Ref	**3620**	**6.9**	**5.1**	**8.0**
Clim	**4154**	**6.3**	**8.2**	**5.5**
Clim+CCS	**3932**	**6.8**	**7.7**	**5.8**

Table 37: Specific indicator values for the European electricity mix

Power generation technology	Expected mortality in severe accidents	Conflict potential	Resource autonomy of the supply chain	Resource variability
Unit	fatalities/(TJ_{final}*y)	Ordinal scale	Ordinal scale	Ordinal scale
Hard coal	65	6	3	10
Hard coal with post-combustion CO_2 capture (CCS)	65	8	3	10
Hard coal with oxy-fuel combustion (CCS)	65	8	3	10
Integrated gasification combined cycle with hard coal	65	6	3	10
Integrated gasification combined cycle with hard coal and pre-combustion CO_2 capture (CCS)	65	8	3	10
Lignite	65	7	3	10
Lignite with post-combustion CO_2 capture (CCS)	65	9	3	10
Lignite with oxy-fuel combustion (CCS)	65	9	3	10
Integrated gasification combined cycle with lignite	65	7	3	10
Integrated gasification combined cycle with lignite and pre-combustion CO_2 capture (CCS)	65	9	3	10
Oil	167	5.5	2	10
Natural gas	27	5	1	10
Natural gas combined cycle	27	5	1	10
Natural gas turbine	27	5	1	10
Natural gas combined cycle with post-combustion CO_2 capture (CCS)	27	7	1	10
Natural gas CHP	27	4	1	10
Natural gas solid oxide fuel cell	27	7	1	10
Nuclear European pressurized reactor	48797	10	4	10
Synthetic natural gas from wood CHP	10	3	9	9
Run-of-river hydro	5	4	10	5
Reservoir hydro	14	6	10	5
Pumped hydro	14	6	10	5
Wind onshore	5	5	10	1
Wind offshore	10	2	10	1
Solar PV	5	1	10	1
Geothermal	7	6	10	10
All scenario variants	**11107**	**6.5**	**4.3**	**8.6**

Table 38: Total indicator values for the three scenario variants. The numbers in the brackets indicate the percentage change of the total indicator values compared to the *Ref* variant. Red/yellow/green colours indicate worst/medium/best performer among the three scenario variants for each indicator.

	Metal depletion	**Fossil energy depletion**	**Eco-system damages**	**GHG emissions**	**Investment cost**	**O&M cost**	**Human health damages**	**Expected mortality**	**Chemical waste**	**Conflict potential**	**Resource autonomy of the supply chain**	**Resource variability**
Unit	kg Fe-eq	MJ	species*y	kg CO_2-eq	M$	M$	DALY	fatalities/ $(TJ_{final}*y)$	m^3	Ordinal scale	Ordinal scale	Ordinal scale
Optimal	min	min	min	min	min	min	min	min	min	min	max	max
Ref	2.71E+09	1.01E+12	54.8	6.00E+10	22742	7519	1.86E+04	6.80E-03	8.06E+02	5.1	3.3	9.3
Clim	3.39E+09 (+25%)	6.69E+11 (-34%)	72.3 (+32%)	4.04E+10 (-33%)	27615 (+21%)	7766 (+3%)	2.04E+04 (+10%)	5.89E-03 (-13%)	1.05E+03 (+30%)	4.7 (-8%)	4.9 (+49%)	8.5 (-9%)
Clim+CCS	3.06E+09 (+13%)	7.40E+11 (-27%)	72.5 (+32%)	4.09E+10 (-32%)	25598 (+13%)	7736 (+3%)	2.00E+04 (+8%)	6.12E-03 (-10%)	1.13E+03 (+40%)	4.9 (-3%)	4.6 (+40%)	8.6 (-8%)

Table 39: Mortality in severe accidents in the energy chain. Ref./Proc. = Refining / Processing.

Primary energy	World region[a]	fatalities / GW$_e$y	Efficiency	Split, in %	
Coal	OECD	1.20E-01	0.35	Extraction	95
				Transport	1
				Ref./Proc.	0
				Heat/Electricity	4
				Waste storage	0
				N/A	0
	EU27	1.35E-01	0.35	Extraction	98
				Transport	0
				Ref./Proc.	0
				Heat/Electricity	2
				Waste storage	0
				N/A	0
	non-OECD	5.75E-01	0.35	Extraction	99
				Transport	1
				Ref./Proc.	0
				Heat/Electricity	0
				Waste storage	0
				N/A	0
	China	3.77E+00	0.35	Extraction	98
				Transport	0
				Ref./Proc.	0
				Heat/Electricity	0
				Waste storage	0
				N/A	1
Oil	OECD	9.55E-02	0.35	Extraction	21
				Transport	68
				Ref./Proc.	8
				Heat/Electricity	1
				Waste storage	0
				N/A	2
	EU27	9.95E-02	0.35	Extraction	19
				Transport	67
				Ref./Proc.	8
				Heat/Electricity	1
				Waste storage	0
				N/A	5
	non-OECD	9.51E-01	0.35	Extraction	4
				Transport	91
				Ref./Proc.	2
				Heat/Electricity	1
				Waste storage	0
				N/A	1

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Natural gas	OECD	7.19E-02	0.35	Extraction Transport Ref./Proc. Heat/Electricity Waste storage N/A	3 83 1 14 0 0
	EU27	6.81E-02	0.35	Extraction Transport Ref./Proc. Heat/Electricity Waste storage N/A	2 62 0 37 0 0
	non-OECD	1.16E-01	0.35	Extraction Transport Ref./Proc. Heat/Electricity Waste storage N/A	21 49 6 23 0 1
Hydro	OECD	2.70E-03	1.00	Heat/Electricity	100
	EU27	8.53E-02	1.00	Heat/Electricity	100
	non-OECD	9.54E-01	1.00	Heat/Electricity	100
	China	1.50E-01	1.00	Heat/Electricity	100
Nuclear Gen II		7.26E-03	0.33	Heat/Electricity	100
Nuclear Gen III		1.07E-05	0.33	Heat/Electricity	100
Photovoltaics (crystalline Silicon)		2.45E-04	1.00	Heat/Electricity	100
Wind onshore		1.78E-03	1.00	Heat/Electricity	100
Wind offshore		8.50E-03	1.00	Heat/Electricity	100
Geothermal EGS		1.86E-03	1.00	Heat/Electricity	100

[a] OECD is applied to AUSNZL, CANMEX, JPKRTW, USA
EU27 is applied to EU31
Non-OECD is applied to ASIAPAC, BRAZIL, CENASIA, EEUR, INDIA, LAC, MENA, RUSSIA, SSAFRICA
CHINA is applied to CHINAREG

Table 40: Maximum credible consequences of severe accidents in the energy sector. CAP = capacity, INV = investment.

Energy chain	World region[a]	fatalities	Reference capacity, in GW	Technology level
Coal	OECD	272	0.5	Extraction, CAP
	EU27	65	0.5	Extraction, CAP
	non-OECD	434	0.5	Extraction, CAP
	China	215	0.5	Extraction, CAP
Oil	OECD	252	0.5	Final energy, CAP
	EU27	167	0.5	Final energy, CAP
	non-OECD	4386	0.5	Final energy, CAP
Natural gas	OECD	109	0.5	Final energy, CAP
	EU27	27	0.5	Final energy, CAP
	non-OECD	243	0.5	Final energy, CAP
Hydro	OECD	14	0.5	Electricity, CAP
	EU27	116	0.5	Electricity, CAP
	non-OECD	2500	0.5	Electricity, CAP
	China	28	0.5	Electricity, CAP
Nuclear Gen II		6596	1.0	Electricity, CAP
Nuclear Gen III		46990	1.5	Electricity, CAP
Photovoltaic		5	0.00057	Electricity, INV
Wind onshore		5	0.005	Electricity, INV
Wind offshore		10	0.02	Electricity, INV
Geothermal EGS		7	0.05	Electricity, INV

[a] OECD is applied to AUSNZL, CANMEX, JPKRTW, USA
EU27 is applied to EU31
Non-OECD is applied to ASIAPAC, BRAZIL, CENASIA, EEUR, INDIA, LAC, MENA, RUSSIA, SSAFRICA
CHINA is applied to CHINAREG

Table 41: CO_2 storage potentials and costs based on the Ecofys study [20]

	CO_2 storage potential, in Mt C	CO_2 storage cost, in US$_{2000}$/t C
ASIAPAC	27100	34.6
AUSNZL	10500	39.7
BRAZIL	8350	18.4
CANMEX	17100	29.0
CENASIA	17000	41.8
CHINAREG	49400	31.1
EEUR	3330	20.4
EU31	21800	27.1
INDIA	7790	32.1
JPKRTW	2860	33.3
LAC	19500	22.5
MENA	139000	30.1
RUSSIA	86500	61.7
SSAFRICA	21500	30.5
USA	21300	39.6

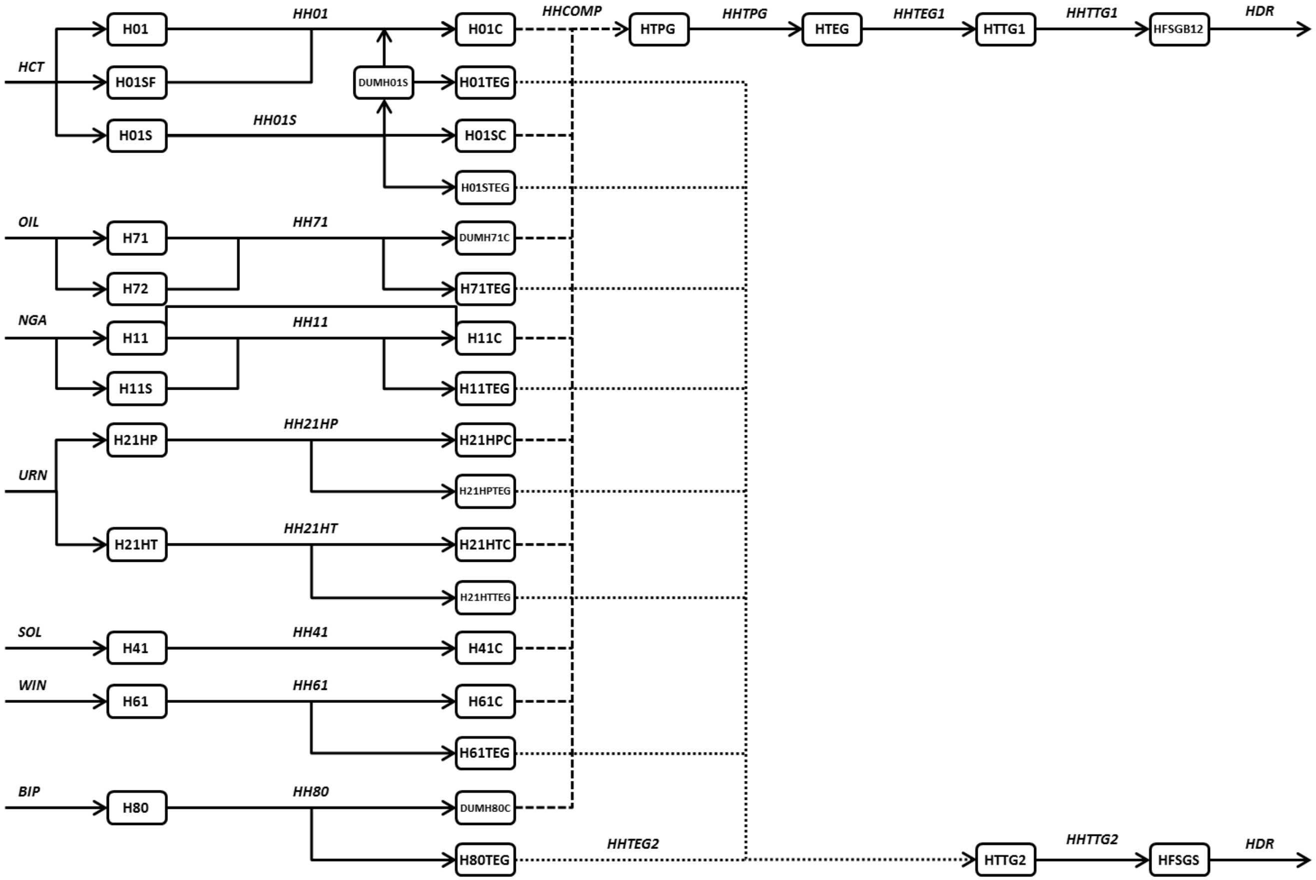

Figure 83: Modelling of the hydrogen chains in the GMM model. The abbreviations are explained in Table 42.

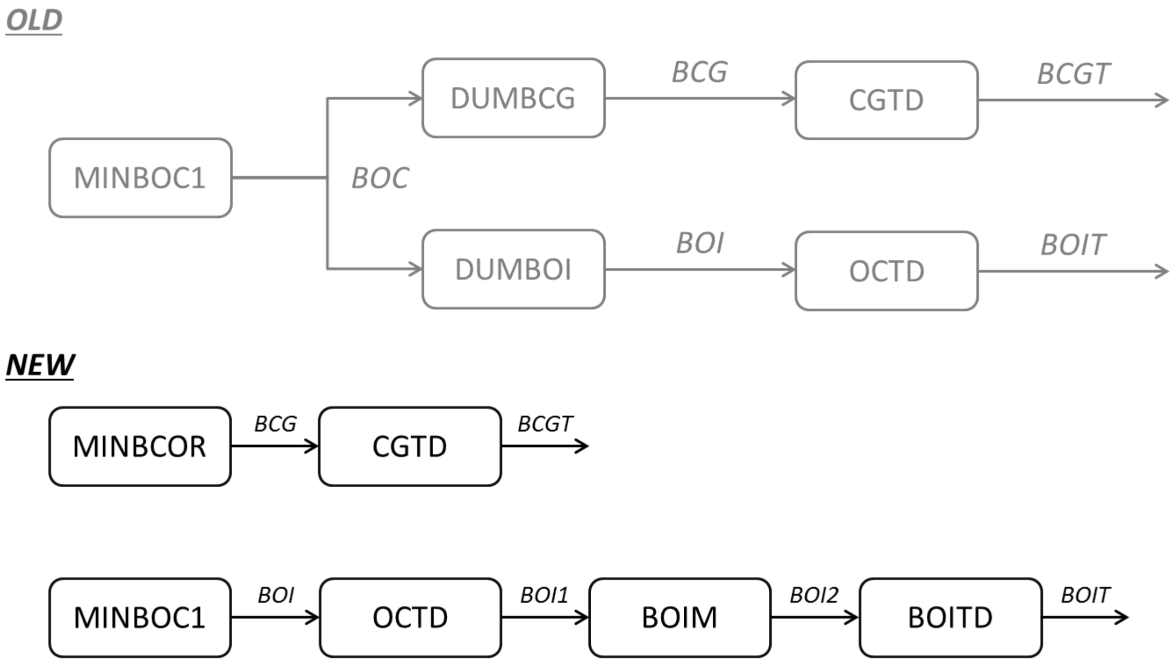

Figure 84: Modelling of the corn grain and oil crop chains in the GMM model. The abbreviations are explained in Table 42.

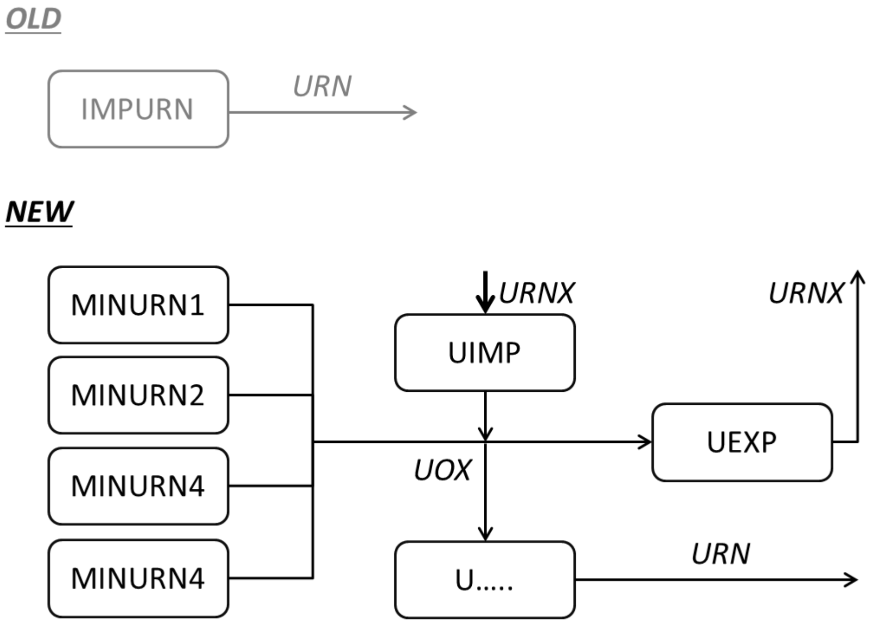

Figure 85: Modelling of the uranium chain in the GMM model. The abbreviations are explained in Table 42.

Table 42: GMM model processes and corresponding end LCI datasets. The naming of the LCI datasets corresponds to the one in SimaPro software [68]. {xxx} is a placeholder for the available ecoinvent region(s).

Sector	GMM model process	Description	LCI dataset	Reference
Coal	S12	Lignite Extraction	Lignite {xxx}| mine operation	[82]
	S11	Coal Extraction	Hard coal {xxx}| mine operation	[82]
	COT	Coal Transport	Hard coal {xxx}| market for	[82]
	CTI	Coal from Import	Hard coal {xxx}| market for	[82]
	SRI	DUMMY - Coal Feedstock	Hard coal {xxx}| market for	[82]
Oil	S13	Oil Extraction I	Petroleum {xxx}| petroleum and gas production, on-shore	[82]
	S14	Oil Extraction II	Petroleum {xxx}| petroleum and gas production, on-shore	[82]
	S15	Oil Extraction III	Petroleum {xxx}| petroleum and gas production, on-shore	[82]
	S16	Oil Extraction IV	Petroleum {xxx}| petroleum and gas production, off-shore	[82]
	S17	Oil Extraction V	Petroleum {xxx}| petroleum and gas production, off-shore	[82]
	OTI	Oil from Import	Petroleum {xxx}| market for	[82]
	SRA	Refinery Diesel	Diesel {xxx}| petroleum refinery operation	[82]
	DTD	Diesel T&D	Diesel {xxx}| market for	[82]
	SRJ	Dummy Technology - DSL Feedstock	Diesel {xxx}| market for	[82]
	DTI	Diesel from Import	Diesel {xxx}| market for	[82]
	DRS	Diesel Retail Station	Natural gas service station {xxx}| construction	[82]
	DRS1	Diesel Retail Station T1	Natural gas service station {xxx}| construction	[82]
	SR9	Refinery Gasoline	Petrol, unleaded {xxx}| petroleum refinery operation	[82]
	GTD	Gasoline T&D	Petrol, unleaded {xxx}| market for	[82]
	GTI	Gasoline from Import	Petrol, unleaded {xxx}| market for	[82]
	GRS	Gasoline Retail Station	Natural gas service station {xxx}| construction	[82]
	GRS1	Gasoline Retail Station T2	Natural gas service station {xxx}| construction	[82]

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Natural gas	S18	Nat Gas Extraction I	Natural gas, high pressure {xxx}| petroleum and gas production, on-shore	[82]
	S19	Natural Gas Extraction II	Natural gas, high pressure {xxx}| petroleum and gas production, on-shore	[82]
	S1A	Natural Gas Extraction III	Natural gas, high pressure {xxx}| petroleum and gas production, on-shore	[82]
	S1B	Natural Gas Extraction IV	Natural gas, high pressure {xxx}| petroleum and gas production, off-shore	[82]
	S1C	Natural Gas Extraction V	Natural gas, high pressure {xxx}| petroleum and gas production, off-shore	[82]
	S1D	Natural Gas Extraction VI	Natural gas, high pressure {xxx}| petroleum and gas production, off-shore	[82]
	SR5	Liquefaction Natural Gas	Natural gas, liquefied {xxx}| production	[82]
	SRG	Regasification LNG	Natural gas, high pressure {xxx}| evaporation of natural gas	[82]
	GGI	Gas from Import	Natural gas, high pressure {xxx}| market for	[82]
	NTD	Natural Gas T&D	Natural gas, high pressure {xxx}| market for	[82]
	SRK	DUMMY Technology - Natural Gas Feedstock	Natural gas, high pressure {xxx}| market for	[82]
Uranium	UOXTD	Transport of Uranium ore	Uranium ore, as U {xxx}| market for	[82]
	UYEL	Production of yellowcake	Uranium, in yellowcake {xxx}| production	[82]
	UYELTD	Transport of yellowcake	Uranium, in yellowcake {xxx}| market for	[82]
	UHEX	Production of Uranium hexafluoride	Uranium hexafluoride {xxx}| production	[82]
	UHEXTD	Transport of Uranium hexafluoride	Uranium hexafluoride {xxx}| market for	[82]
	UENR	Production of enriched Uranium	Uranium, enriched 4.0%, per separative work unit {xxx}| uranium production, centrifuge, enriched 4.0%	[82]
	UENRTD	Transport of enriched Uranium	Uranium, enriched 4.0%, per separative work unit {xxx}| market for	[82]
	UROD	Production of fuel elements	Uranium, enriched 4%, in fuel element for light water reactor {xxx}| uranium fuel element production, enriched 4%, for light water reactor	[82]
	URODTD	Transport of fuel elements	Uranium, enriched 4%, in fuel element for light water reactor {xxx}| market for	[82]
Stover	MINBST1	Stover	Sweet sorghum stem {xxx}| sweet sorghum production	[82]
	STTD	Stover T&D	Sweet sorghum stem {xxx}| market for	[82]
	BB1	Ethanol From Cellusosic Biomass / Stover	Ethanol, without water, in 95% solution state, from fermentation {xxx}| ethanol production from sweet sorghum	[82]

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Sugar crop	MINBSU1	Sugar Beet / Sugar Cane	Sugarcane {xxx}| production	[82]
	SUTD	Sugar Plants T&D	Sugarcane {xxx}| market for	[82]
	BS1	Ethanol from Sugar Crops	Ethanol, without water, in 95% solution state, from fermentation {xxx}| ethanol production from sugar cane	[82]
Oil crop	MINBOC1	Oil Crops	Rape seed {xxx}| production	[82]
	OCTD	Oil Crops T&D	Rape seed {xxx}| market for	[82]
	BOIM	Vegetable oil Production	Rape oil, crude {xxx}| rape oil mill operation	[82]
	BOITD	Vegetable oil T&D	Rape oil, crude {xxx}| market for	[82]
	BO1	FAEE for Oil crops Esterification	Vegetable oil methyl ester {xxx}| esterification of rape oil	[82]
Corn	MINBCOR	Corn Grains	Maize grain {xxx}| production	[82]
	CGTD	Corn Grains T&D	Maize grain {xxx}| market for	[82]
	BC1	Ethanol from Corn	Ethanol, without water, in 95% solution state, from fermentation {xxx}| ethanol production from maize	[82]
Wood residues	MINBWO1	Wood Residues	Wood chips, wet, measured as dry mass {xxx}| wood chips production, softwood, at sawmill Wood chips, wet, measured as dry mass {xxx}| wood chips production, hardwood, at sawmill	[82]
	BWTD	Wood Residues T&D	Wood chips, wet, measured as dry mass {xxx}| market for	[82]
	BW1	Wood to Biodiesel by Pyrolysis	Methanol, from biomass {xxx}| methanol production, from synthetic gas	[82]
	BW2	Wood to FT-Diesel by Gasification	Methanol, from biomass {xxx}| methanol production, from synthetic gas	[82]
	BW3	Wood to DME by Gasification	Synthetic gas {xxx}| production, from wood, at fixed bed gasifier Synthetic gas {xxx}| production, from wood, at fluidized bed gasifier	[82]
	BW4	Wood to SNG by Gasification	Synthetic gas {xxx}| production, from wood, at fixed bed gasifier Synthetic gas {xxx}| production, from wood, at fluidized bed gasifier	[82]
	BW5	Wood to Methanol by Gasification	Methanol, from biomass {xxx}| methanol production, from synthetic gas	[82]
	BMTD	Bio-Methanol T&D	Methanol, from biomass {xxx}| market for	[82]

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Domestic waste	DWTD	Domestic Waste T&D	Biowaste {xxx}| market for	[82]
	BWA	SNG from Anaerobic Domestic Waste Digestion	Biowaste {xxx}| treatment of biowaste by anaerobic digestion	[82]
Electricity and heat	E01	Coal Conventional Electric	Electricity, high voltage {xxx}| electricity production, hard coal	[82]
	E02	Coal Advanced Electric (supercritical, PFBC)	Electricity, at power plant/hard coal, PC, no CCS/2025/RER U	[59]
	E03	Lignite Conventional Electric	Electricity, high voltage {xxx}| electricity production, lignite	[82]
	E11	Natural Gas Combined Cycle (NGCC)	Electricity, high voltage {xxx}| electricity production, natural gas, combined cycle power plant	[82]
	E12	Gas Turbine	Electricity, high voltage {xxx}| electricity production, natural gas, 10MW	[82]
	E13	Gas Conventional	Electricity, high voltage {xxx}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical	[82]
	E15	Gas Fuel Cell	Electricity, low voltage {xxx}| natural gas, burned in solid oxide fuel cell 125kWe, future	[82]
	E1C	NGCC with CO2 seq.	Electricity, at power plant/natural gas, post, pipeline 200km, storage 1000m/2025/RER U	[59]
	E21	Nuclear Plant - Light Water Reactor (LWR)	Electricity, high voltage {xxx}| electricity production, nuclear, boiling water reactor	[82]
	E22	Advanced new nuclear power plant (NNU)	20_Electricity, nuclear, at EPR 2030 /RER	[24]
	E31	Hydro-electric plant	Electricity, high voltage {xxx}| electricity production, hydro, reservoir, non-alpine region	[82]
	E41	Solar Photovoltaics	Electricity, low voltage {xxx}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si	[82]
	E42	Solar thermal electric	electricity, solar trough, PCM-storage, at power plant, 200MW/MA U	[81]

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E61	Onshore Wind turbine	Electricity, high voltage {xxx}| electricity production, wind, >3MW turbine, onshore	[82]
E62	Offshore Wind Park	Electricity, high voltage {xxx}| electricity production, wind, 1-3MW turbine, offshore	[82]
E6A	Cogeneration Gas Turbine	Heat, central or small-scale, natural gas {xxx}| natural gas, burned in micro gas turbine, 100kWe	[82]
E6C	Cogeneration Coal	Heat, district or industrial, other than natural gas {xxx}| heat production, at hard coal industrial furnace 1-10MW	[82]
E70	Oil electric	Electricity, high voltage {xxx}| electricity production, oil	[82]
E71	Hard Coal Heating Plant	Heat, district or industrial, other than natural gas {xxx}| heat production, at hard coal industrial furnace 1-10MW	[82]
E72	Fuel Oil Heating Plant	Heat, district or industrial, other than natural gas {xxx}| heat production, heavy fuel oil, at industrial furnace 1MW	[82]
E73	Gas Heating Plant	Heat, district or industrial, natural gas {xxx}| heat production, natural gas, at boiler condensing modulating >100kW	[82]
E74	Biomass Heating Plant	Heat, district or industrial, other than natural gas {xxx}| heat production, hardwood chips from forest, at furnace 1000kW	[82]
E75	Geothermal Heating Plant	18_electricity, at geothermal power plant, Basel, 2030	[24]
E80	Biomass power plant	Electricity, at wood burning power plant 20 MW, truck 25km, no CCS/2025/RER U	[59]
E81	Geothermal electric	18_electricity, at geothermal power plant, Basel, 2030	[24]
E82	Biomass IGCC Power Plant	Electricity, at BIGCC power plant 450MW, no CCS/2025/RER U	[59]
E83	Biomass IGCC Power Plant w/ CO2 scrubber	Electricity, at BIGCC power plant 450MW, pre, pipeline 200km, storage 1000m/2025/xxx U	[59]
EC2	Coal Advanced Electric with CO2 scrubber	Electricity, at power plant/hard coal, post, pipeline 200km, storage 1000m/2025/RER U	[59]
EH2	Hydrogen Fuel Cell CoGen IND	PEM fuel cell system, with disposal, 2012	[81]
EH3	Hydrogen Fuel Cell CoGen R&C	PEM fuel cell system, with disposal, 2012	[81]

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	EIC	Coal IGCC with CO2 scrubber	Electricity, at power plant/hard coal, pre, pipeline 200km, storage 1000m/2025/RER U	[59]
	EIG	Integrated Coal-Gasification Combined Cycle (IGCC)	Electricity, at power plant/hard coal, IGCC, no CCS/2025/RER U	[59]
	ES1	Coal Conventioan Electric with DeSOx/DeNOx	Electricity, at power plant/hard coal, PC, no CCS/2025/RER U	[59]
Biofuels	ARS	Alcohol Retail Station	Natural gas service station {xxx}| construction	[82]
	S3M	Natural Gas to Methanol	Methanol {xxx}| production	[82]
	SR1	Gas Compression Station	Natural gas, from high pressure network (1-5 bar), at service station {xxx}| processing	[82]
	SR2	Gas Compression T1	Natural gas, from high pressure network (1-5 bar), at service station {xxx}| processing	[82]
	SRM	Coal to Methanol	Hard coal, burned in power plant/IGCC, no CCS/2025/RER U	[59]
	SRN	Coal to FT Liquids	Hard coal, burned in power plant/IGCC, no CCS/2025/RER U	[59]
	ATD	Alcohol T&D	Ethanol, without water, in 99.7% solution state, from fermentation, at service station {xxx}| market for	[82]
	BGTD	Bio-Syngas T&D	Synthetic gas {xxx}| market for	[82]
	BTD	Biodiesel T&D	Vegetable oil methyl ester {xxx}| market for	[82]
	ETD	Ethanol T&D	Ethanol, without water, in 99.7% solution state, from fermentation {xxx}| dewatering of ethanol from biomass, from 95% to 99.7% solution state	[82]
	MTD	Methanol T&D	Methanol {xxx}| market for	[82]
	SRL	Dummy Technology - Alcohol Feedstock	Ethanol, without water, in 99.7% solution state, from fermentation, at service station {xxx}| market for	[82]
	BBDTI	Biodiesel Trade Import	Vegetable oil methyl ester {xxx}| market for	[82]
	BETTI	Ethanol Trade Import	Ethanol, without water, in 99.7% solution state, from fermentation {xxx}| dewatering of ethanol from biomass, from 95% to 99.7% solution state	[82]
	BMTTI	Methanol Trade Import	Methanol {xxx}| market for	[82]
	BNGTI	Bio-SNG Trade Import	Synthetic gas {xxx}| market for	[82]

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Hydrogen	H01	Coal Gasification	H2, gaseous (30 bar) from hard coal gasification and reforming, at coal gasification plant, 2030	[81]
	H01SF	Coal Gasification w/ CO2 Seq. Future	H2, gaseous (30 bar) from HC gasification and reforming, at gasification plant, with CCS, 2030	[81]
	H01C	Compression H2 from Coal	Hydrogen compression, 30 to 450 bar, 2030	[81]
	H01TEG	Terminal Gas. Decentral H2 from Coal	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
	H01C	Compression H2 from Coal	Hydrogen compression, 30 to 450 bar, 2030	[81]
	H01S	Coal Gasification w/ CO2 Seq.	H2, gaseous (30 bar) from HC gasification and reforming, at gasification plant, with CCS, 2030	[81]
	H01SC	Compresstion H2 from Coal with CO2 Seq.	Hydrogen compression, 30 to 450 bar, 2030	[81]
	H01STEG	Terminal Gas. Decentral H2 from Coal w/CO2 Seq.	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
	DUMH01S	DUMMY H2 from Coal w/CO2 Seq.	Hydrogen compression, 30 to 450 bar, 2030	[81]
	H11	Natural Gas Reforming	H2, gaseous (30 bar), from steam methane reforming of NG, at reforming plant, 2030	[81]
	H11S	Natural Gas Reforming w/ CO2 Seq.	H2, gaseous (30 bar), from steam methane reforming of NG, at reforming plant, with CCS, 2030	[81]
	H11C	Compression H2 from Natural Gas	Hydrogen compression, 30 to 450 bar, 2030	[81]
	H11TEG	Terminal Gas. Decentral H2 from Natural Gas	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]

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H21HP	Nuclear HP Electrolysis 2020	Electricity, nuclear, at EPR 2030 /RER	[81]
H21HPC	Compression H2 from Nuclear HP Electr.	Hydrogen compression, 30 to 450 bar, 2030	[81]
H21HPTEG	Terminal Gas. Decentral from Nuclear HP Electr.	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
H21HT	Nuclear HAT Electrolysis 2030	Electricity, nuclear, at EPR 2030 /RER	[81]
H21HTC	Compression H2 from Nuclear HT Electr.	Hydrogen compression, 1 to 450 bar, 2030	[81]
H21HTTEG	Terminal Gas. Decentral from Nuclear HT Electri.	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
H41	Solar zn/ZnO to H2	Hydrogen, from hydrolysis of zinc (Solar thermal dissociation (STD)), at STD plant, LHV, corrected	[81]
H41C	Compression H2 from Solar Zn/ZnO	Hydrogen compression, 1 to 450 bar, 2030	[81]
H61	Central Wind+Electrolysis	Hydrogen, gaseous, from electrolysis (Wind 2030), w/o fuelling station 2030	[81]
H61C	Compression H2 from (Wind+) Electrolysis	Hydrogen compression, 1 to 450 bar, 2030	[81]
H61TEG	Terminal Gas. Decentral H2 from (Wind+) Electrolysis	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
H80	Biomass Gasification	H2, gaseous (30 bar), from steam reforming of biomass gas, at reforming plant, 2030/RER	[81]
DUMH80C	DUMMY Compression H2 from Biomass	Hydrogen compression, 30 to 450 bar, 2030	[81]
H80TEG	Terminal Gas. Decentral H2 from Biomass	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]

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	HTPG	H2 Transp. Pipeline 60 km	Transport, hydrogen, pipeline, 2030/CH U	[81]
	HTEG	H2 Terminal Gas. City Gates	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
	HTTG1	H2 Transport by Truck Gas. 40 km	Transport, hydrogen, >32t lorry EURO5, RER to CH (20km), 2030 (No H2 source)	[81]
	HFSGB12	H2 Fueling Station 1500 kg/day	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
	HTTG2	H2 Transport by Truck Gas. 160 km	Transport, hydrogen, >32t lorry EURO5, RER to CH (20km), 2030 (No H2 source)	[81]
	HFSGS	H2 Fueling Station 100 kg/day	hydrogen fuelling station, with high pressure storage 2030/RER/I U	[81]
End-use technologies	I11	Coal in Industry Thermal	Heat, district or industrial, other than natural gas {xxx}| heat production, at hard coal industrial furnace 1-10MW	[82]
	I12	Oil Products in Industry Thermal	Heat, district or industrial, other than natural gas {xxx}| heat production, heavy fuel oil, at industrial furnace 1MW	[82]
	I13	Gas in Industry Thermal	Heat, district or industrial, natural gas {xxx}| heat production, natural gas, at boiler condensing modulating >100kW	[82]
	I14	Biofuels with C	Heat, central or small-scale, other than natural gas {xxx}| biogas, burned in micro gas turbine 100kWe	[82]
	I15	Gaseous Hydrogen in Industry Thermal	Industrial furnace, natural gas {xxx}| market for	[82]
	I16	Biomass with C in Industry Thermal	Heat, district or industrial, other than natural gas {xxx}| heat production, wood chips from industry, at furnace 1000kW	[82]
	I17	Electricity in Industry Thermal	Auxiliary heating unit, electric, 5kW {xxx}| market for	[82]
	I19	Electric Heat Pump in Industry Thermal	Heat, central or small-scale, other than natural gas {xxx}| heat production, at heat pump 30kW, allocation exergy	[82]

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I1A	Natural Gas Heat Pump in Industry Thermal	Heat, future {xxx}| heat production, natural gas, at diffusion absorption heat pump 4kW, future	[82]
I1C	Solar Thermal in Industry Thermal	Heat, central or small-scale, other than natural gas {xxx}| operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water	[82]
I21	Electric Specific	Auxiliary heating unit, electric, 5kW {xxx}| market for	[82]
I22	Diesel Specific	Diesel, burned in diesel-electric generating set, 18.5kW {xxx}| diesel, burned in diesel-electric generating set, 18.5kW	[82]
I23	Hydrogen Replacement for Diesel	Gas motor, 206kW {xxx}| production	[82]
I24	Alcohol Replacement for Diesel	Heat, central or small-scale, other than natural gas {xxx}| biogas, burned in micro gas turbine 100kWe	[82]
I25	Hydrogen Fuel Cell Co-generation	PEM fuel cell system, with disposal, 2012	[81]
R11	Electric Appliances Res./Comm.	Operation, computer, desktop, with liquid crystal display, active mode {xxx}| processing	[82]
R12	Hydrogen Fuel Cell CoGen Res./Comm.	PEM fuel cell system, with disposal, 2012	[81]
R21	Coal Heating Res./Comm.	Heat, central or small-scale, other than natural gas {xxx}| heat production, hard coal briquette, stove 5-15kW	[82]
R22	Oil Heating Res./Comm.	Heat, central or small-scale, other than natural gas {xxx}| heat production, light fuel oil, at boiler 10kW condensing, non-modulating	[82]
R23	Gas Heating Res./Comm.	Heat, central or small-scale, natural gas {xxx}| heat production, natural gas, at boiler condensing modulating <100kW	[82]
R24	Electric Thermal Res./Comm.	Auxiliary heating unit, electric, 5kW {xxx}| market for	[82]
R25	Biomass with C Heating Res./Comm.	Heat, central or small-scale, other than natural gas {xxx}| heat production, wood pellet, at furnace 9kW	[82]
R27	Alcohol with C Res./Comm.	Heat, central or small-scale, other than natural gas {xxx}| biogas, burned in micro gas turbine 100kWe	[82]

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R28	Hydrogen Heating Res./Comm.	Gas boiler {xxx}| market for	[82]
R29	Electric Heat Pump Res./Comm.	Heat, central or small-scale, other than natural gas {xxx}| heat production, at heat pump 30kW, allocation exergy	[82]
R2A	Gas Heat Pump Res./Comm.	Heat, future {xxx}| heat production, natural gas, at diffusion absorption heat pump 4kW, future	[82]
R2C	Solar Thermal Res./Comm.	Heat, central or small-scale, other than natural gas {xxx}| operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water	[82]
T11	Coal-based Transport	Transport, freight train {xxx}| steam	[82]
T12	Oil-based Transport	Euro VI ICEV-D 28t	[27, 81, 82, 84]
T13	Gas-based Transport	Euro VI ICEV-NG 28t	[27, 81, 82, 84]
T14	Electricity-based Transport	Transport, freight train {xxx}| electricity	[82]
T16	Alcohol Fuel Cell Transport	Euro VI ICEV-E 28t	[27, 81, 82, 84]
T17	Hydrogen Fuell Cell Transport	FCEV 28t	[27, 81, 82, 84]
T2CH	CNG HEV	Transport, passenger car, medium size, natural gas-hybrid, EURO 5 {xxx}| transport, passenger car, medium size, natural gas, EURO 5	[27, 82, 83]
T2CI	CNG ICEV	Transport, passenger car, medium size, natural gas, EURO 5 {xxx}| transport, passenger car, medium size, natural gas, EURO	[82]
T2DA	Diesel Adv. ICEV	Transport, passenger car, medium size, diesel, EURO 5 {xxx}| transport, passenger car, medium size, diesel, EURO 5	[82]
T2DH	Diesel HEV	Transport, passenger car, medium size, diesel-hybrid, EURO 5 {xxx}| transport, passenger car, medium size, diesel, EURO 5	[27, 82, 83]
T2DI	Diesel ICEV	Transport, passenger car, medium size, diesel, EURO 3 {xxx}| transport, passenger car, medium size, diesel, EURO 3	[82]
T2EB	BEV	Transport, passenger car, electric {xxx}| processing	[82]
T2EH	Plug-In HEV	Transport, passenger car, medium size, petrol plug-in hybrid, EURO 5 {xxx}| transport, passenger car, medium size, petrol, EURO 5	[27, 82, 83]

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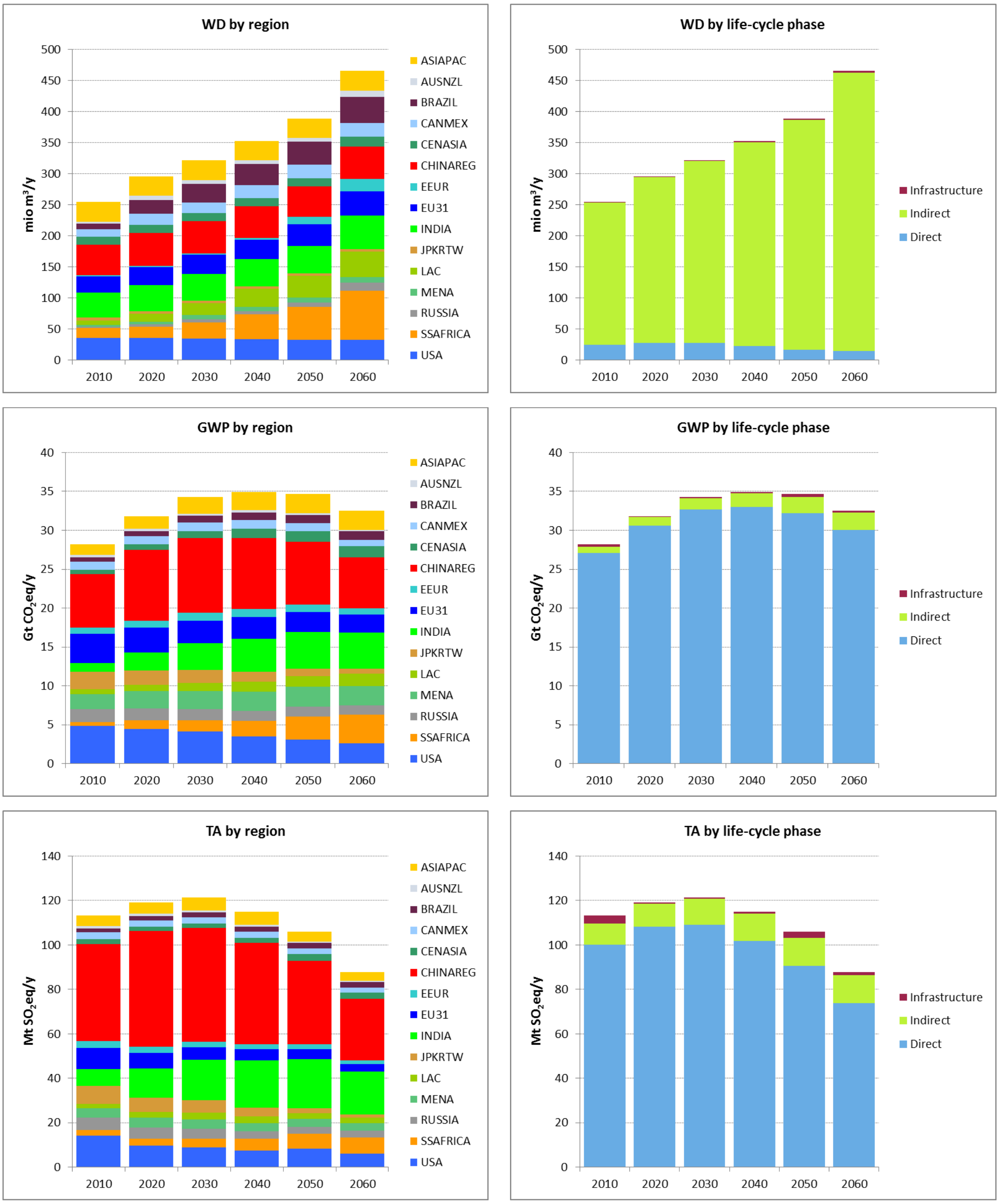
	T2GA	Gasoline Adv. ICEV	Transport, passenger car, medium size, petrol, EURO 5 {xxx}| transport, passenger car, medium size, petrol, EURO 5	[82]
	T2GH	Gasoline HEV	Transport, passenger car, medium size, petrol-hybrid, EURO 5 {xxx}| transport, passenger car, medium size, petrol, EURO 5	[27, 82, 83]
	T2GI	Gasoline ICEV	Transport, passenger car, medium size, petrol, EURO 3 {xxx}| transport, passenger car, medium size, petrol, EURO 3	[82]
	T2HF	HFCV	Transport, passenger car, medium size, hydrogen fuel cell hybrid/RER U	[27, 82, 83]
	T31	Jet Fuel Aircraft	Transport, freight, aircraft {xxx}| intracontinental	[82]
	T32	Jet Fuel Adv. Aircraft	Transport, freight, aircraft {xxx}| intercontinental	[82]
	T4EB	BEV City	Transport, passenger car, electric {xxx}| processing	[82]
	T4EH	Plug-In HEV City	Transport, passenger car, small size, petrol plug-in hybrid, EURO 5 {xxx}| transport, passenger car, small size, petrol, EURO 5	[27, 82, 83]
	T4GA	Gasoline Adv. ICEV City	Transport, passenger car, small size, petrol, EURO 5 {xxx}| transport, passenger car, small size, petrol, EURO 5	[82]
	T4GH	Gasoline HEV City	Transport, passenger car, small size, petrol-hybrid, EURO 5 {xxx}| transport, passenger car, small size, petrol, EURO	[27, 82, 83]
	T4GI	Gasoline ICEV City	Transport, passenger car, small size, petrol, EURO 3 {xxx}| transport, passenger car, small size, petrol, EURO 3	[82]
	T4HF	HFCV City	Transport, passenger car, small size, hydrogen fuel cell hybrid/RER U	[27, 82, 83]

Table 43: Global energy chain- and LCA-based indicator valuess for Modern JAZZ (WD = Water Depletion, GWP = Global Warming Potential, TA = Terrestrial Acidification, FE = Freshwater Eutrophication, ALO = Agricultural Land Occupation, PMF = Particulate Matter Formation, HT = Human Toxicity, POF = Photochemical Oxidant Formation). Direct impacts occur at the location of the process, indirect impacts occur elsewhere. The GMM model regions are presented in Figure 3.



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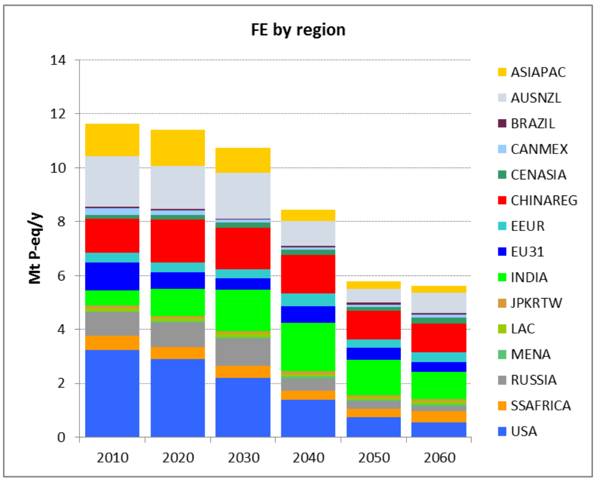

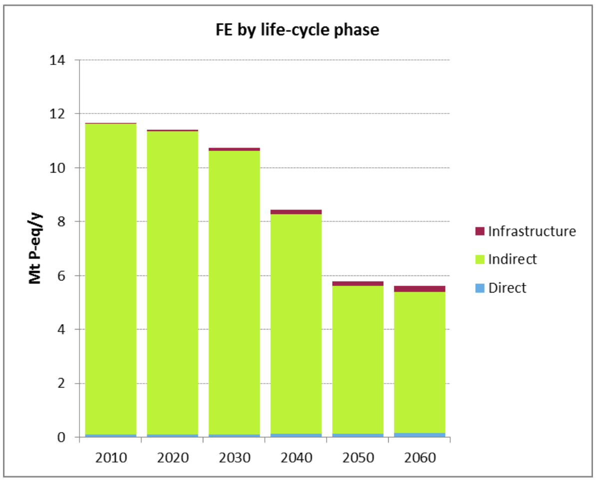

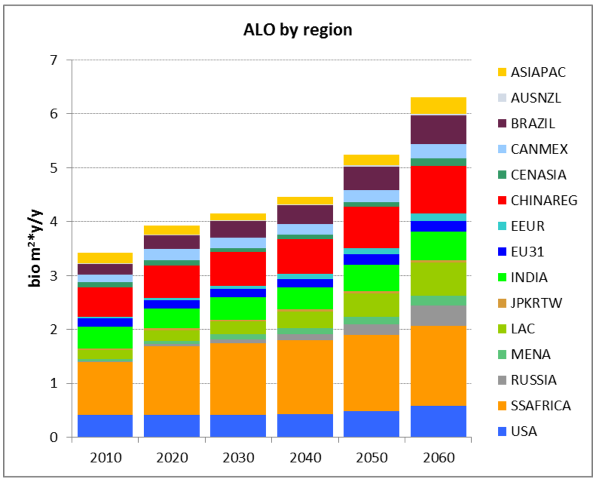

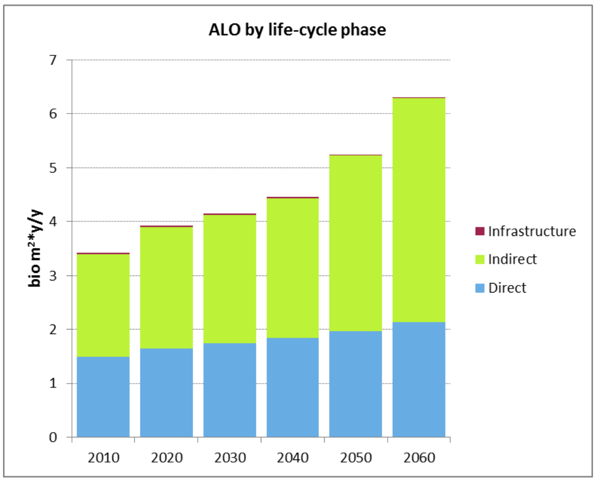

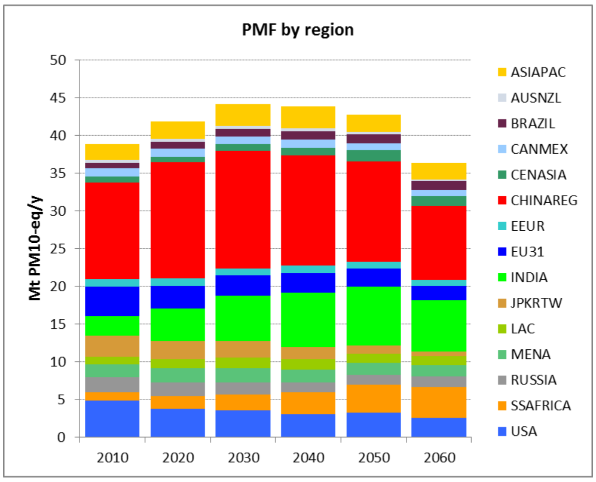

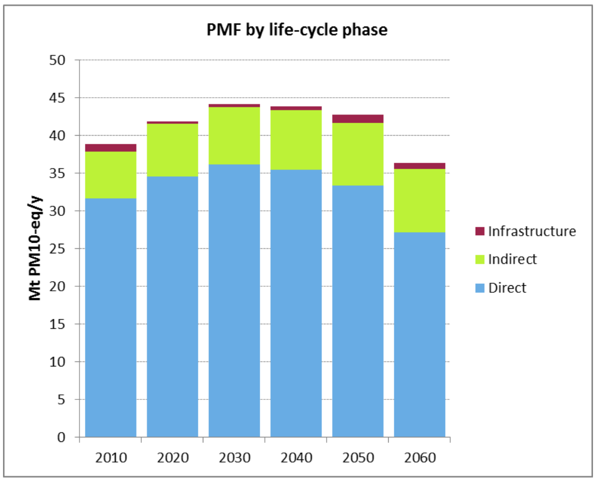

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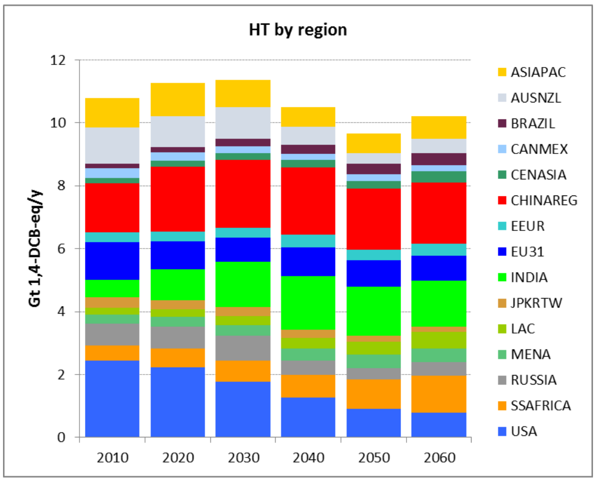

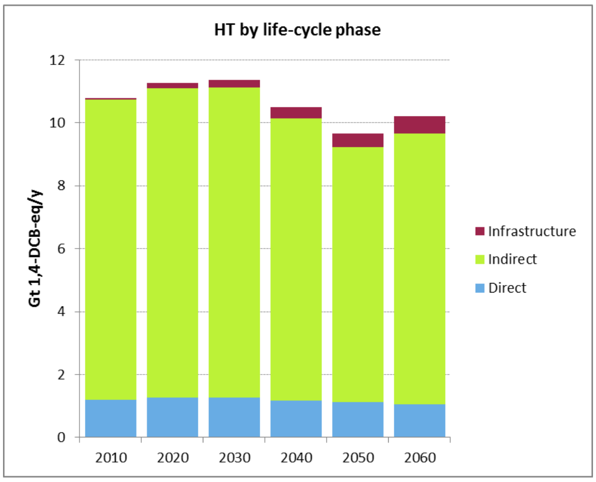

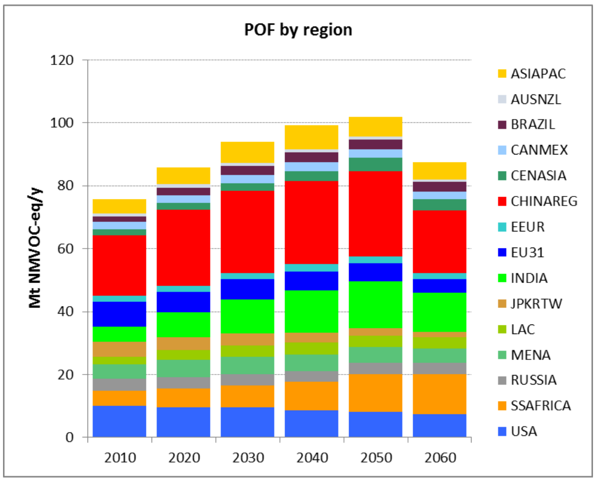

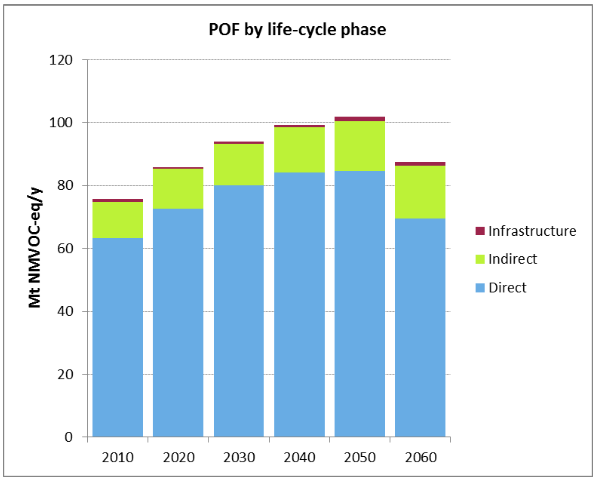

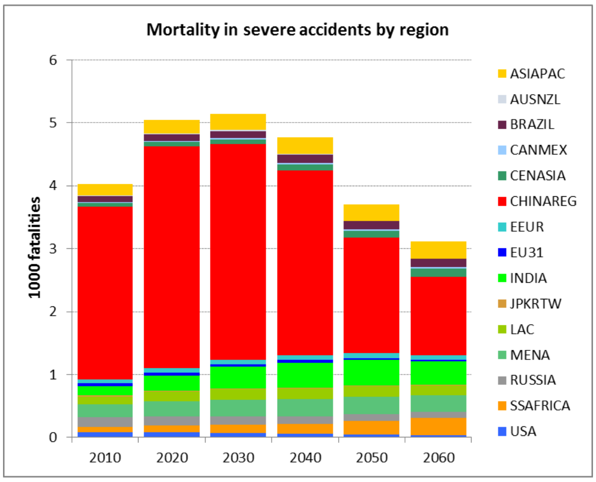

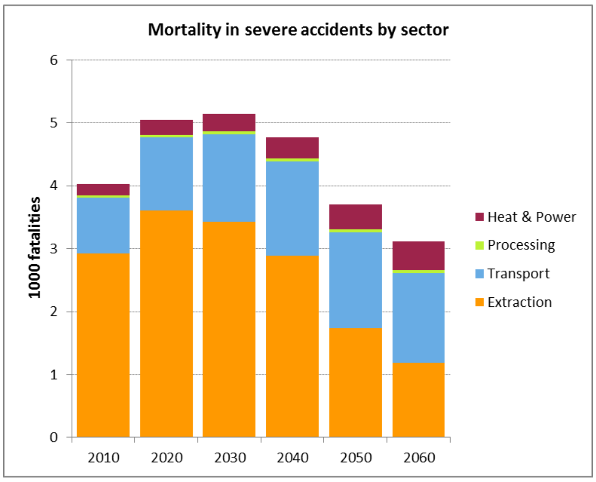

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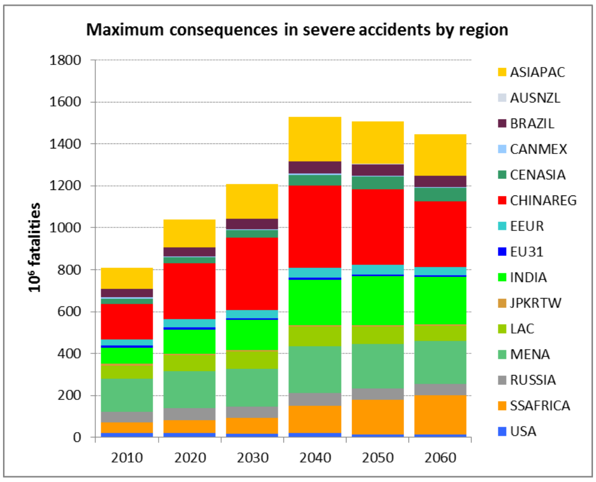


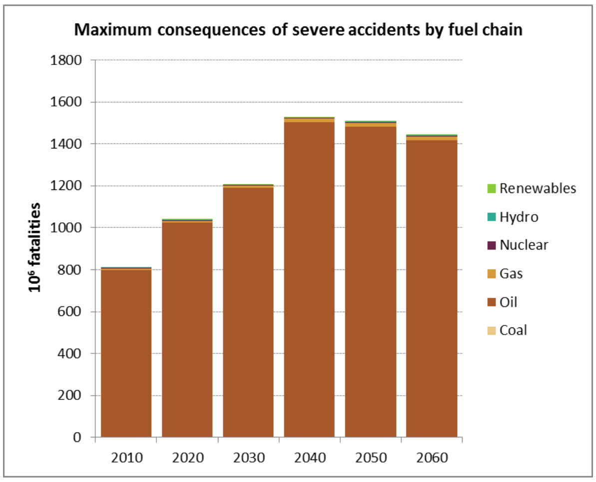
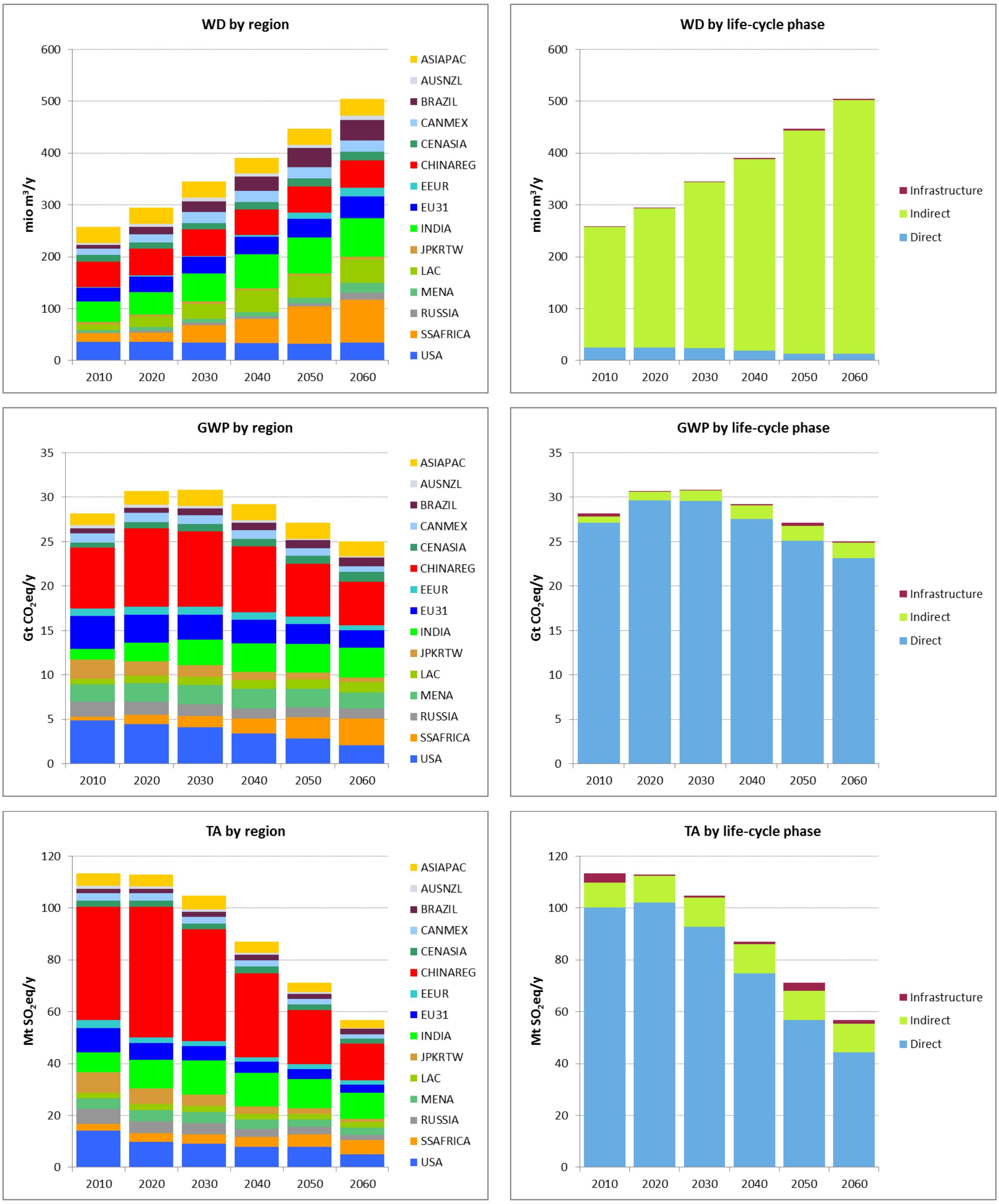


Table 44: Global energy chain- and LCA-based indicator values for Unfinished SYMPHONY (WD = Water Depletion, GWP = Global Warming Potential, TA = Terrestrial Acidification, FE = Freshwater Eutrophication, ALO = Agricultural Land Occupation, PMF = Particulate Matter Formation, HT = Human Toxicity, POF = Photochemical Oxidant Formation). Direct impacts occur at the location of the process, indirect impacts occur elsewhere. The GMM model regions are presented in Figure 3.



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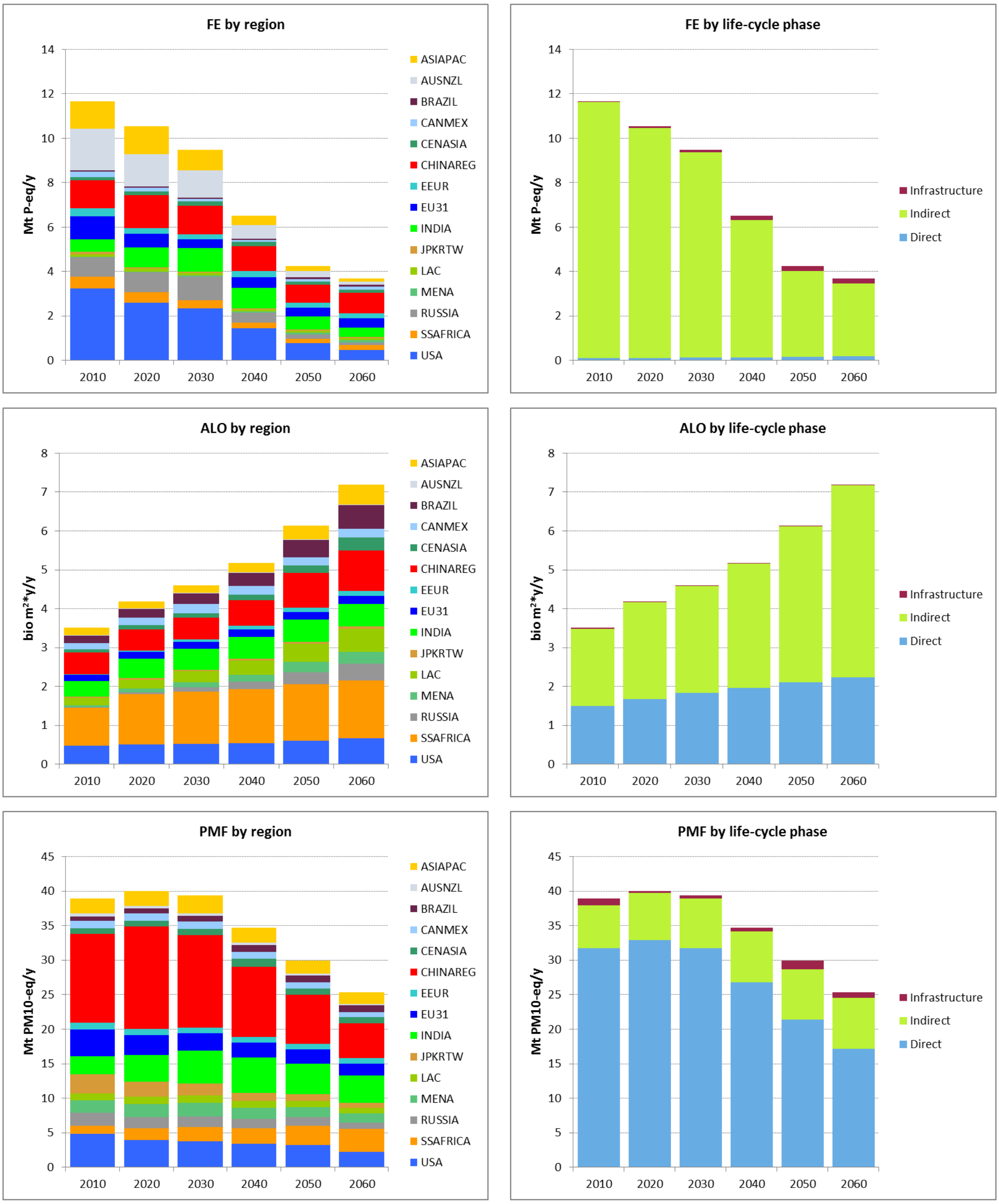

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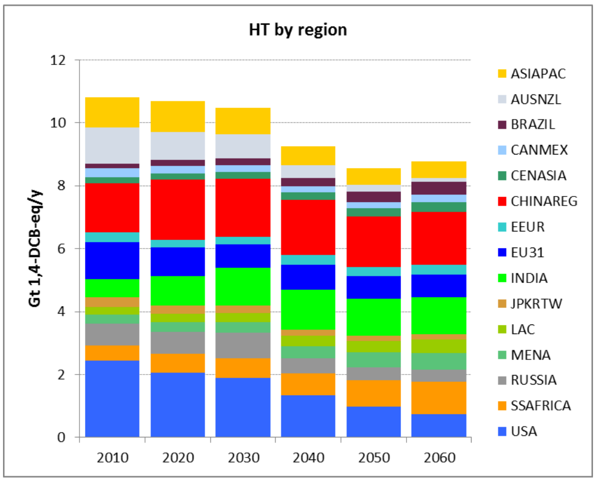

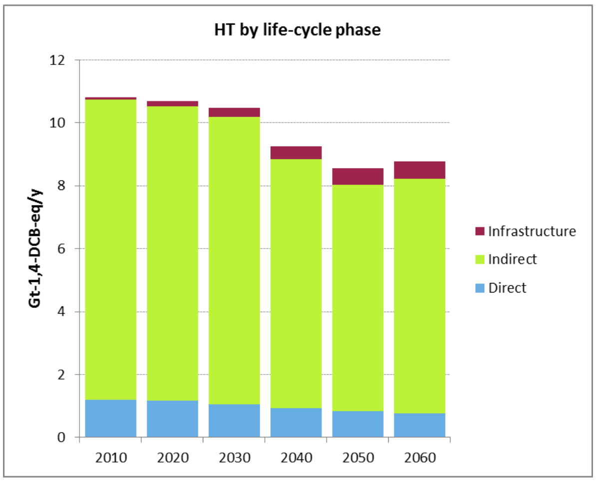

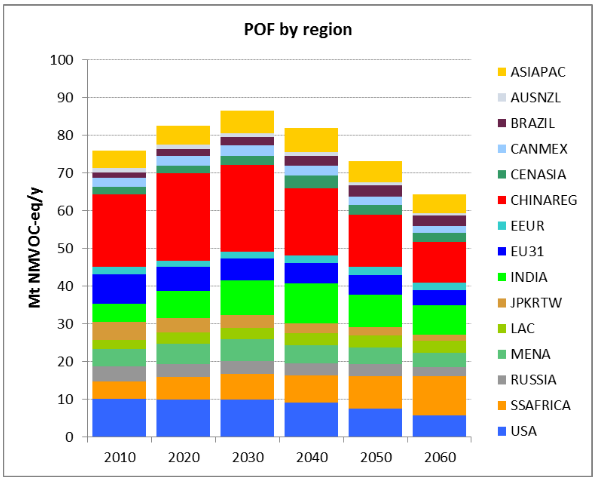

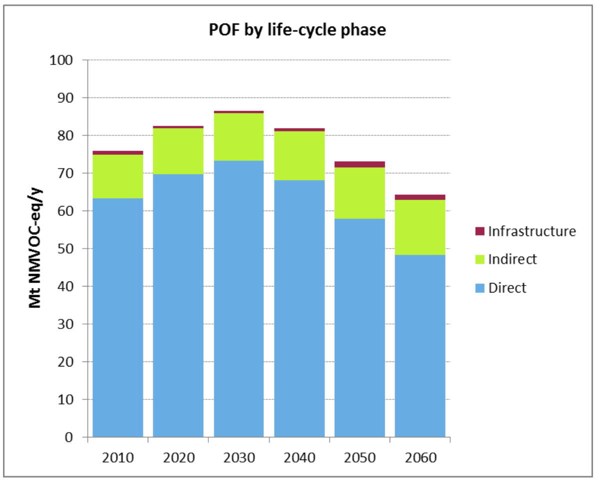

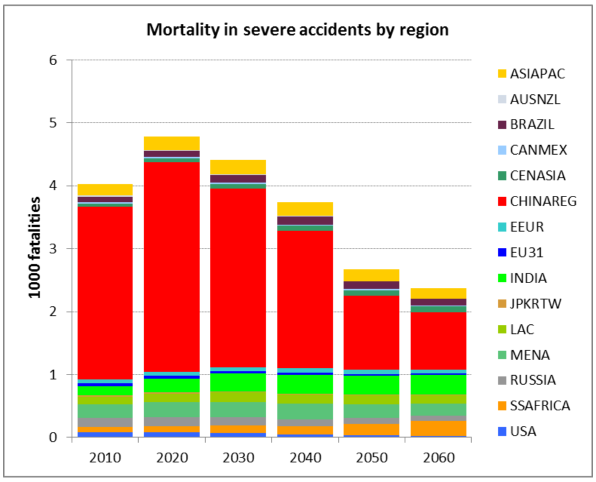

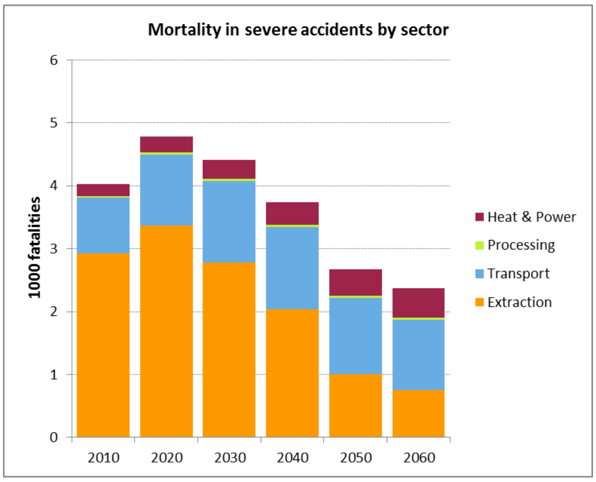

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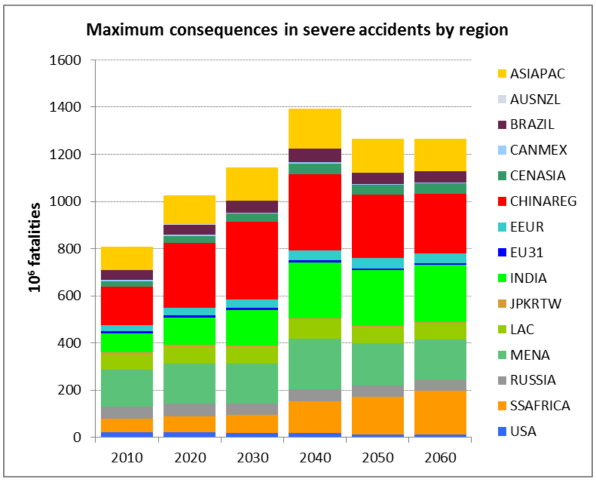


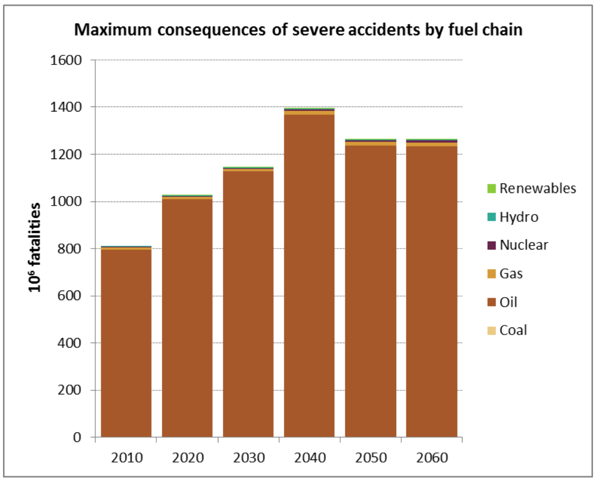
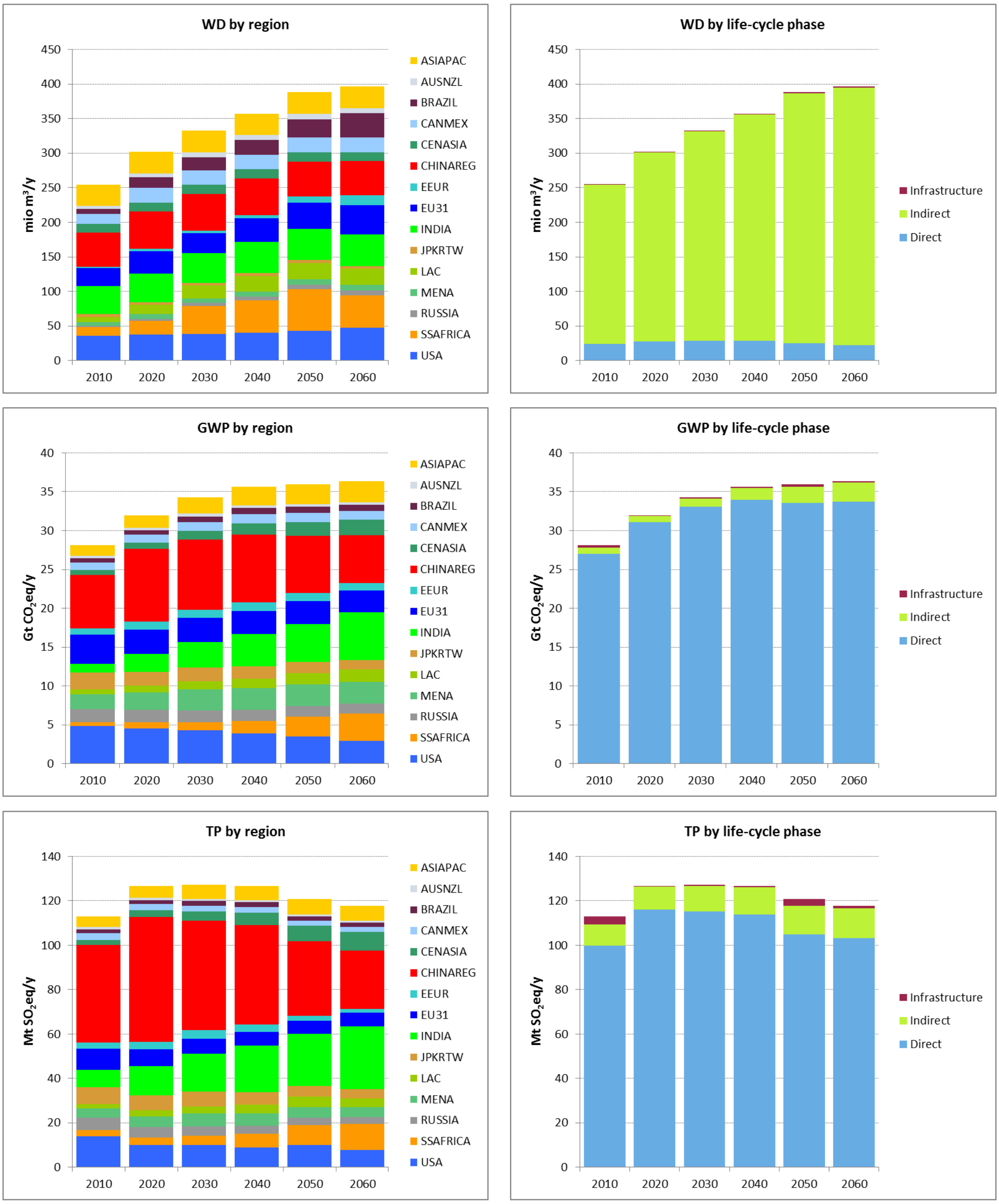


Table 45: Global energy chain- and LCA-based indicator valuess for Hard ROCK (WD = Water Depletion, GWP = Global Warming Potential, TA = Terrestrial Acidification, FE = Freshwater Eutrophication, ALO = Agricultural Land Occupation, PMF = Particulate Matter Formation, HT = Human Toxicity, POF = Photochemical Oxidant Formation). Direct impacts occur at the location of the process, indirect impacts occur elsewhere. The GMM model regions are presented in Figure 3.



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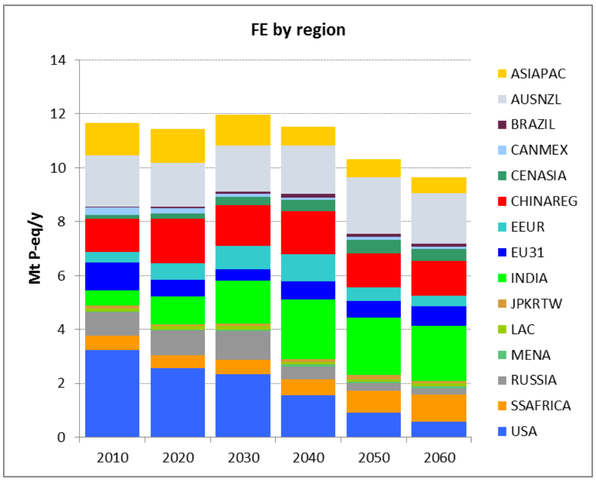
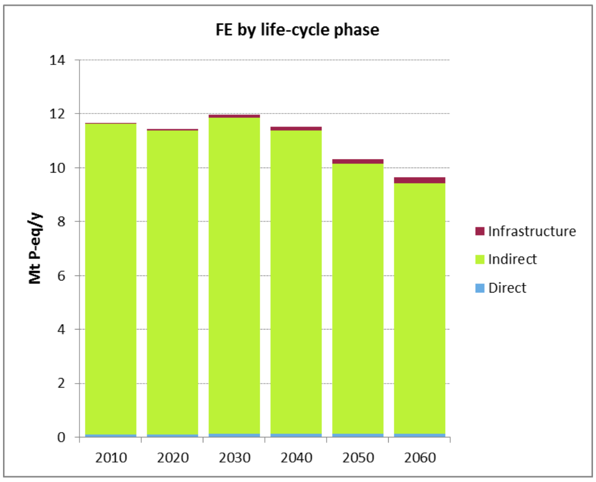
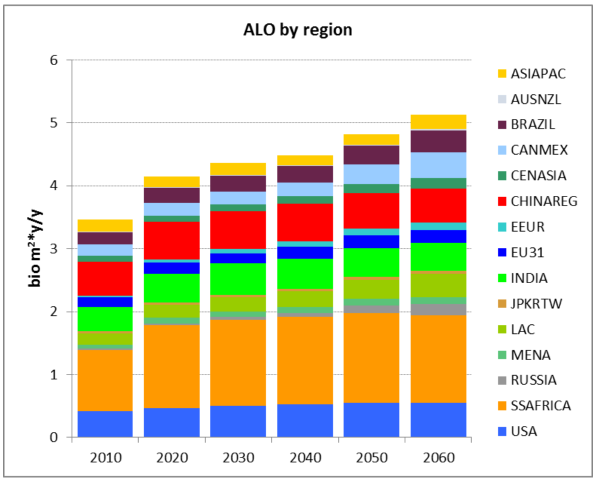
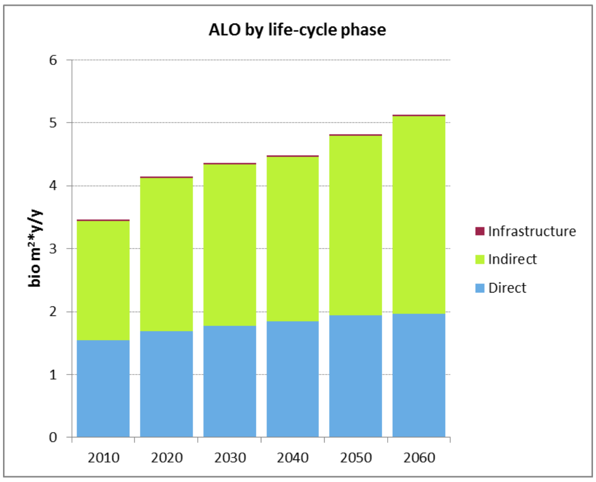
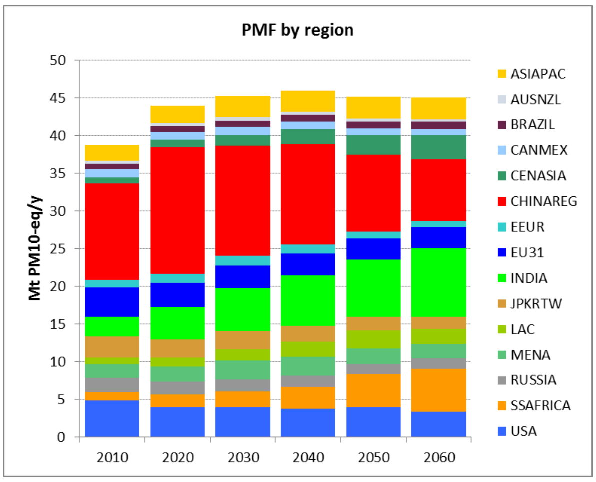
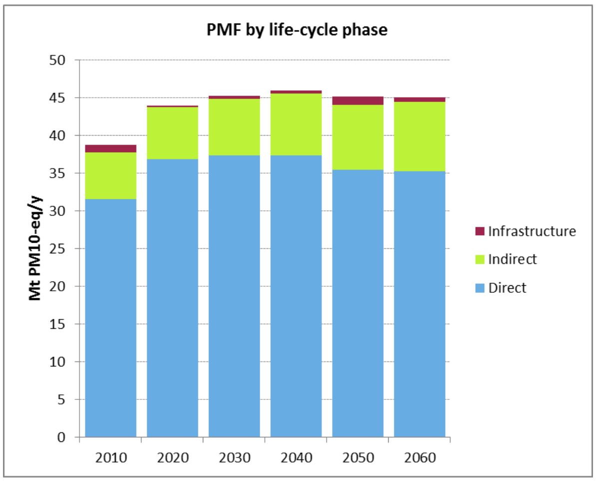

FE by region


FE by life-cycle phase


ALO by region


ALO by life-cycle phase


PMF by region


PMF by life-cycle phase

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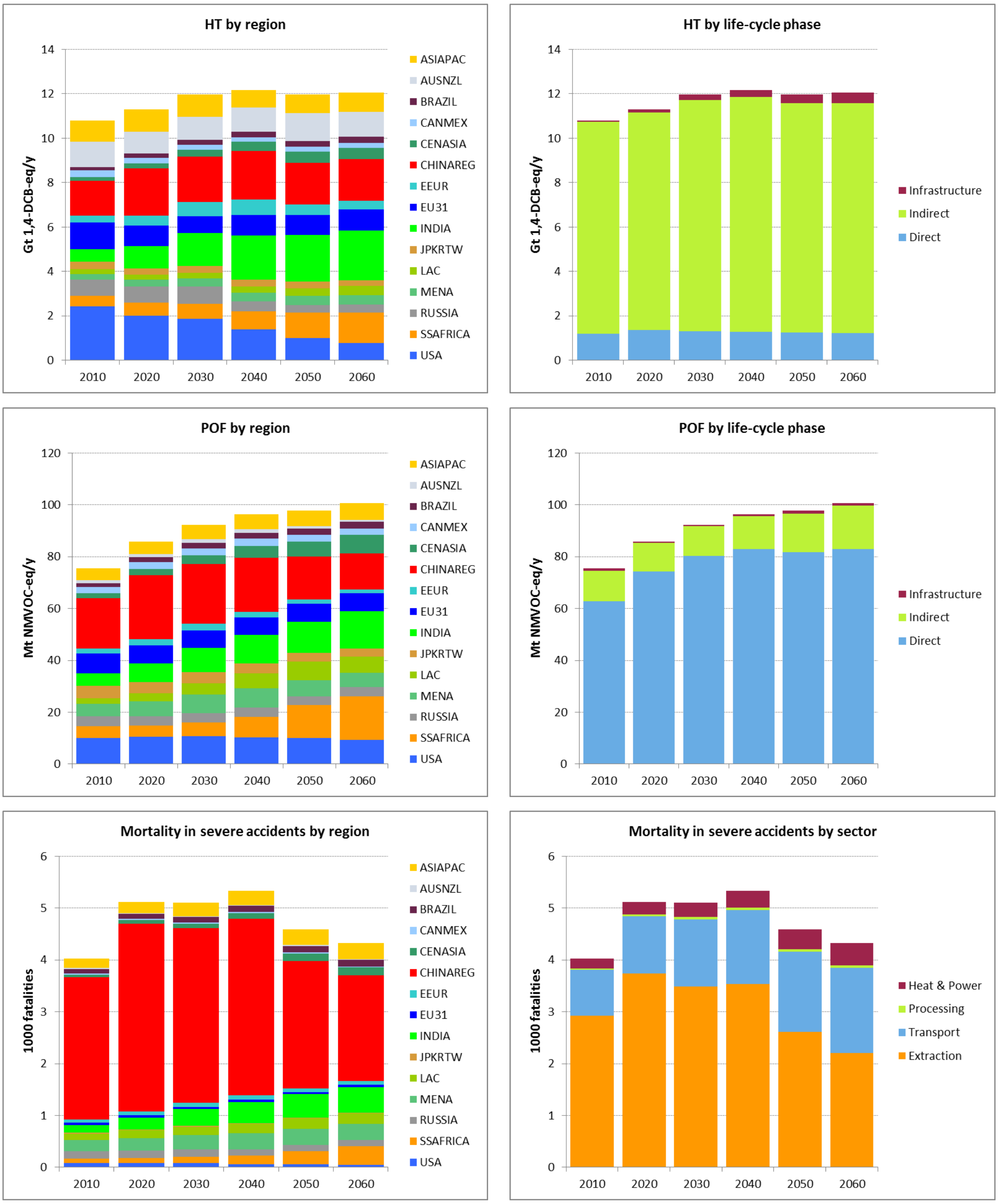

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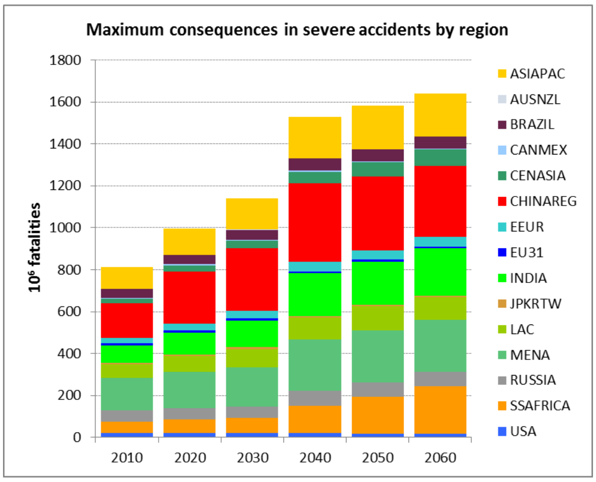
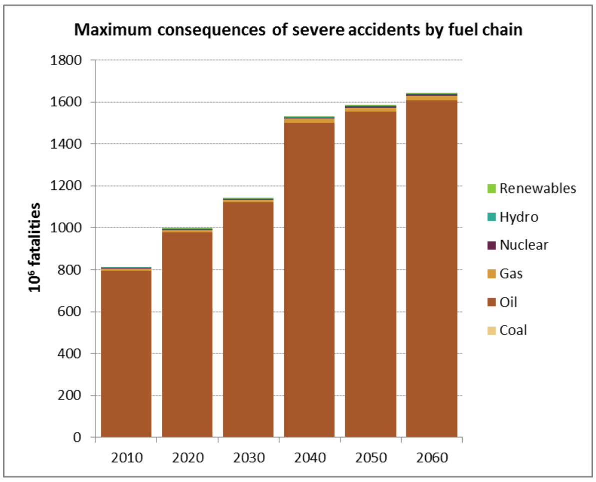


Maximum consequences in severe accidents by region



Maximum consequences of severe accidents by fuel chain

Table 46: Emissions of NO_x, PM2.5 and SO_2 in Modern JAZZ by region and life-cycle phase. Direct impacts occur on-site, i.e. at the location of the process, indirect impacts occur elsewhere. The GMM model regions are presented in Figure 3.

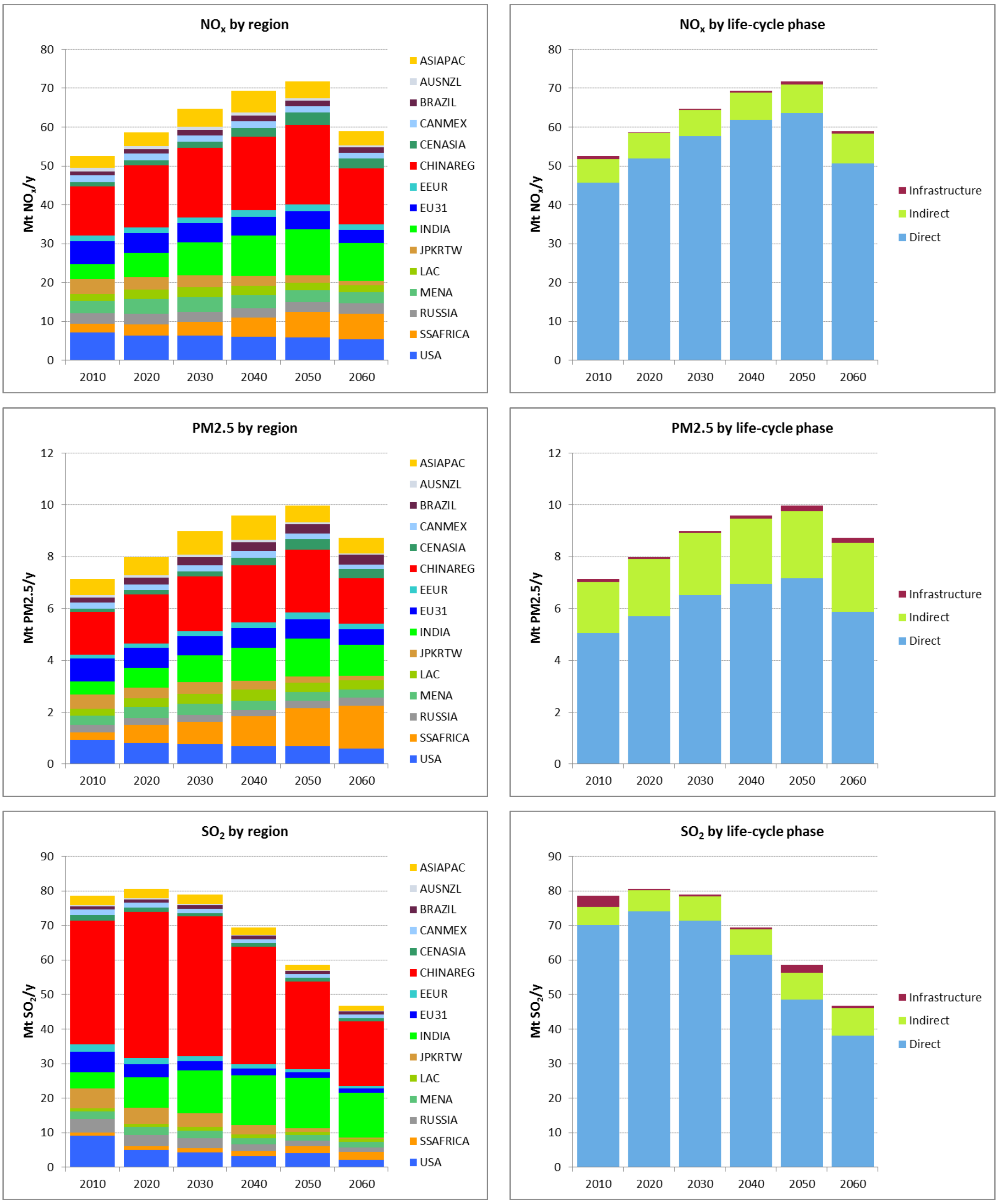


Table 47: Emissions of NO_x, PM2.5 and SO_2 in Unfinished SYMPHONY by region and by life-cycle phase. Direct impacts occur on-site, i.e. at the location of the process, indirect impacts occur elsewhere. The GMM model regions are presented in Figure 3.

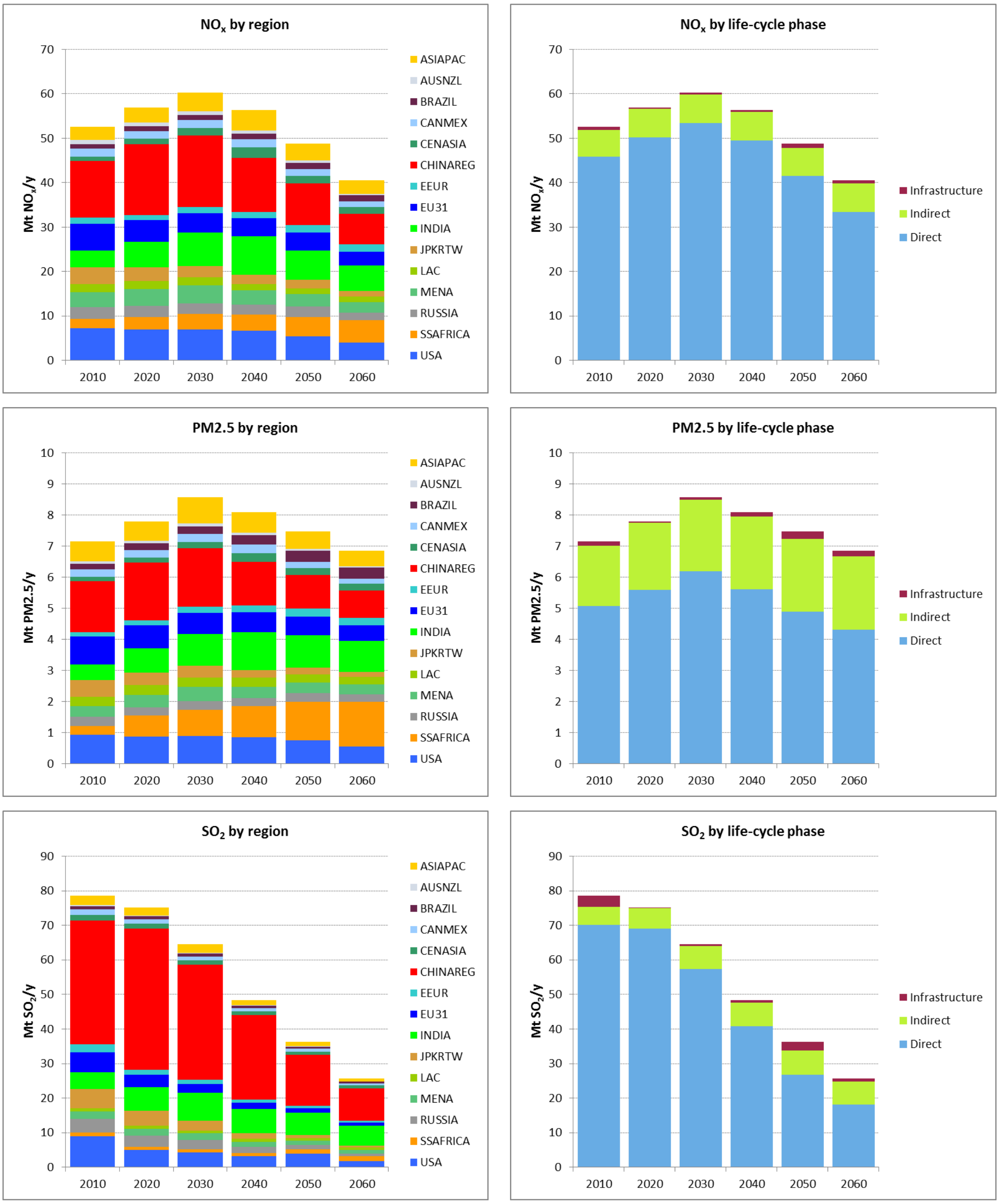
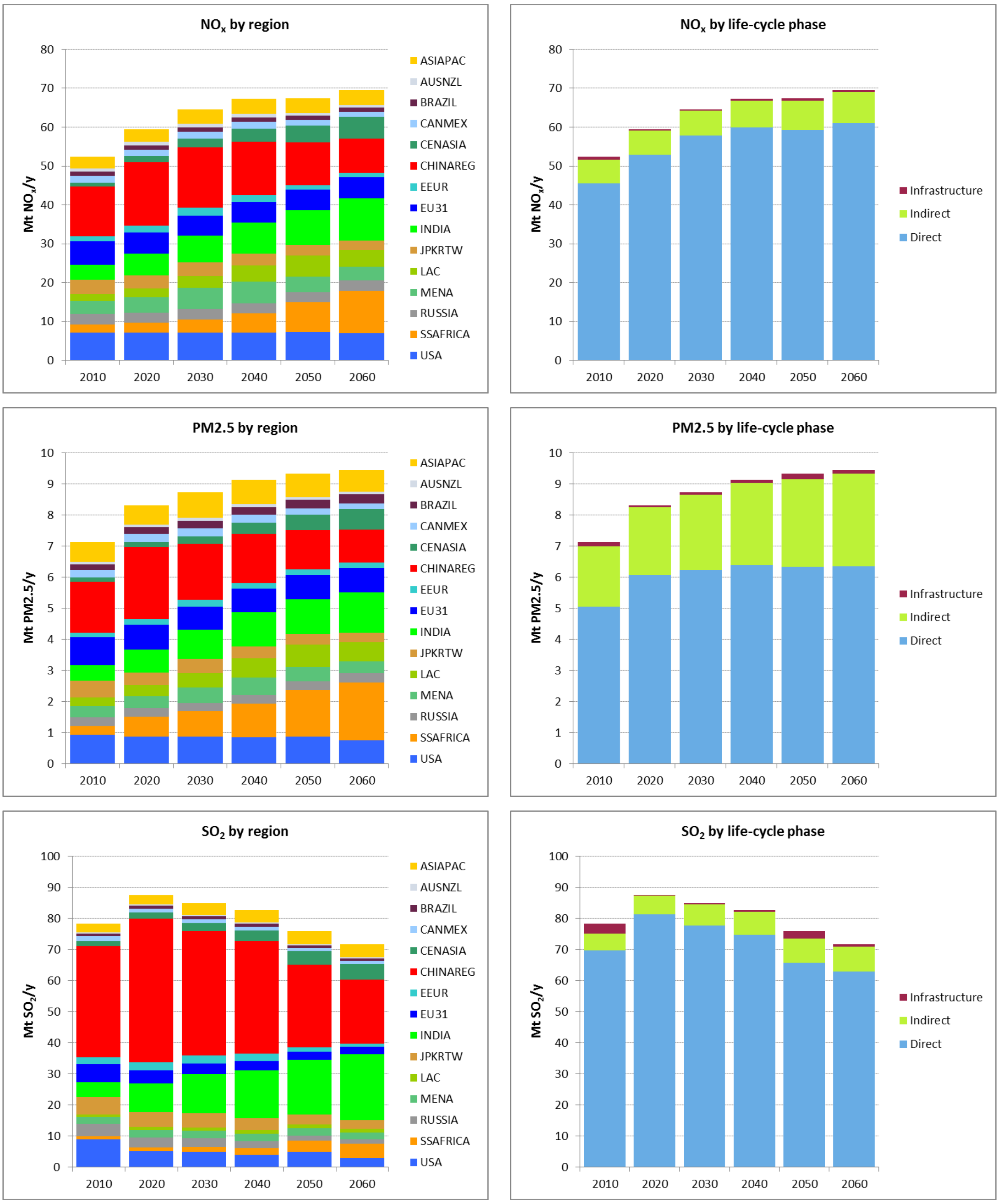


Table 48: Emissions of NO_x, PM2.5 and SO_2 in Hard ROCK by region and by life-cycle phase. Direct impacts occur on-site, i.e. at the location of the process, indirect impacts occur elsewhere. The GMM model regions are presented in Figure 3.



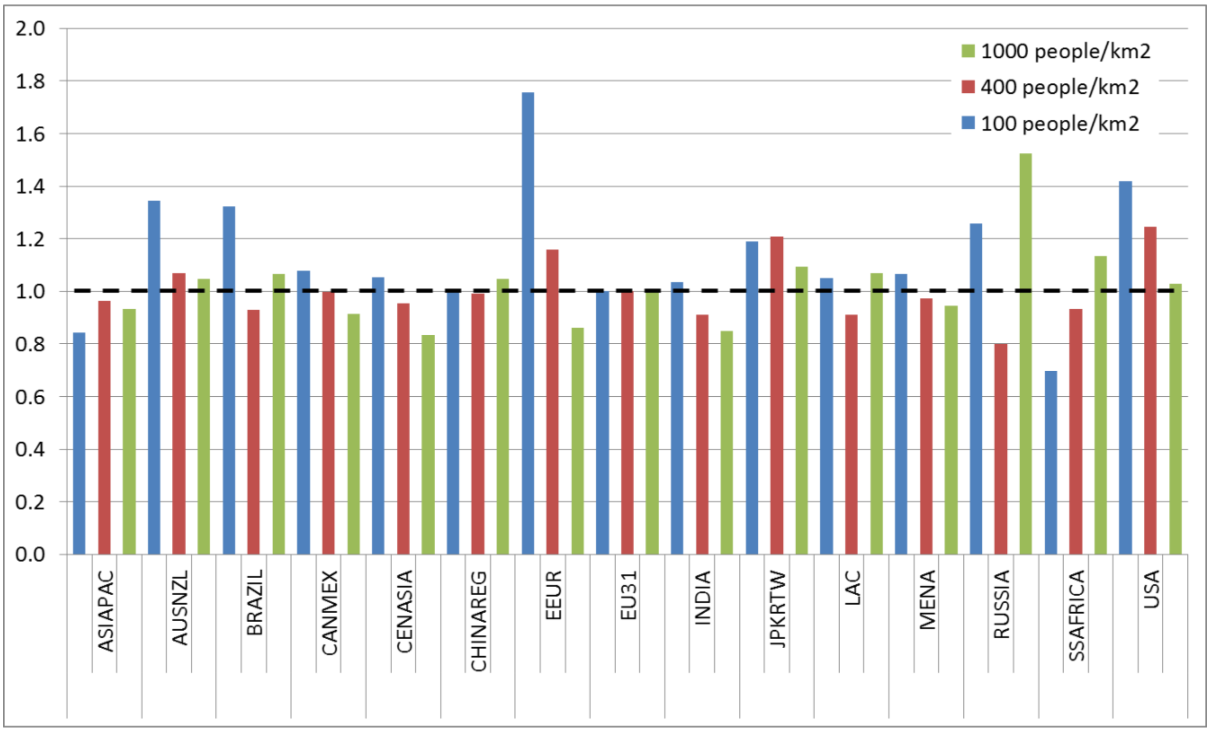


Figure 86: Population density factors (b_r) for different population density thresholds used for the regionalisation of the specific external cost data in Table 17. EU31 = 1 (dashed line). The GMM model regions are presented in Figure 3.

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Academic qualifications

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Peer-reviewed articles

Volkart K., Weidmann-Ordóñez N., Bauer C., Hirschberg S. (2017). Multi-criteria Decision Analysis of Energy System Transformation Pathways: A Case Study for Switzerland. *Energy Policy*, Vol. 106, pp. 155-168, DOI: 10.1016/j.enpol.2017.03.026

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Other research activities

Referee for:

- Environmental Science & Technology
- Journal of Cleaner Production
- International Journal of Greenhouse Gas Control
- Resources, Conservation & Recycling

Awards

2015 1st Prize for Best PhD Poster Presentation
wholeSEM Conference, Cambridge, UK

Fellowships

2016 wholeSEM fellowship
Research stay at University College London, UK

2016 Congress Future Energy Leader fellowship
World Energy Congress, October 2016, Istanbul, Turkey