The Strategy of Enough.

A Scenario Analysis of Decarbonization Pathways and Socio-Ecological Implications for German Carbon Neutrality

Master's thesis

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I. Pledge of Academic Integrity

I hereby declare that,

1. I have written the submitted Master’s thesis independently,
2. I have not used any sources or aids other than those declared and I have identified all content taken verbatim or in paraphrase from other works as such, and
3. the submitted Master’s thesis is or was neither completely nor in essential parts subject of another examination procedure.

Kaya Fiorella Margareta Dünzen

Freiburg, 08/01/2023

II. Abbreviations

BAU	Business as usual
BECCS	Bioenergy with Carbon Capture and Sequestration
BEV	Battery-driven electric vehicles
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
CH_4	Methane
CIB	Cross-Impact-Balance
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
EnSu	Energy Sufficiency Group
EJ	Environmental Justice
FAFOLU	Food, Agriculture, Forestry and Land-use
FED	Final energy demand
GHG	Greenhouse gas
GG	Green Growth
GDP	Gross Domestic Product
H_2	Hydrogen
IAM	Integrated Assessment Model
KSG	German Climate Change Act (dt. Klimaschutzgesetz)
Mt CO_2eq	megaton carbon dioxide equivalent
N_2O	Nitrogen dioxide
NET	Negative Emission Technology
pkm	person kilometer
RCP	Representative Concentration Pathway
RE	Renewable energy
RES	Renewable energy sources
SAS	Storyline-to-Simulation
SSP	Shared Socioeconomic Pathway
TRL	Technology Readiness Level
tkm	ton kilometer
TWh	Terawatt hours

III. Zusammenfassung

In dieser Arbeit wurden sechs qualitative Narrative quantitativ modelliert, die von der Forscher:innengruppe EnSu erstellt wurden. Diese Narrative umfassen vier Energiesuffizienz-Szenarien, von denen drei auf Degrowth basieren, sowie zwei wachstumsbasierte Szenarien, die einem business-as-usual-Ansatz entsprechen. Die Szenarien beschreiben mögliche Zukunftspfade für ein klimaneutrales Deutschland im Jahr 2050. Die Modellierung erfolgte mithilfe des *2050 Pathways Explorer* von Climact, einem Simulationstool zur Erstellung von Dekarbonisierungspfaden durch die Einstellung von Ambitionsniveaus in verschiedenen Sektoren des Energiesystems. Die Übersetzung der Narrative in das Modellierungstool erfolgte mittels SAS (Alcamo, 2008). Im ersten Modellierungsdurchlauf war es leider nur in Szenario GG1 möglich, die Grundvoraussetzung der Klimaneutralität für Deutschland bis 2050 zu erreichen. Für die anderen Szenarien war eine weitere optimierte Modellierung notwendig.

Die modellierten Dekarbonisierungspfade der Szenarien sind äußerst ambitioniert, wobei die Suffizienzszenarien im Vergleich zu den Zielen der Deutschen Bundesregierung für 2030 deutlich ehrgeiziger sind. Zudem sind alle Szenarien mit dem Pariser 1,5°C-Ziel kompatibel. Szenario GG1 und S3 verfügen über den größten Puffer zum CO_2-Budget für Deutschland.

Die vorliegende Masterarbeit ist in eine wachstumskritische Perspektive eingebettet, weshalb die sozio-ökologischen Implikationen der Szenarien ausführlich untersucht wurden, um versteckte Bedingungen und Folgen offenzulegen. Es zeigt sich, dass die herausragende Performance von GG1 und GG2 einerseits auf überschätzenden Annahmen zur Technologie- und Waldsenkenentwicklung beruht. Andererseits sind diese Szenarien stark von Importen und energieintensiven Sekundärenergieträgern wie Wasserstoff und efuels abhängig, was zu einer Externalisierung von Umweltkosten führt. Diese Abhängigkeiten und negativen Implikationen sind in den Suffizienzszenarien deutlich reduziert. Außerdem ermöglichen reduzierte Energiebedarfe eine einfachere Integration von Umweltgerechtigkeit. Jedoch war beispielsweise in S1 die Annahme von umstrittener Direct Air Capture notwendig, um die Emissionen auf den Zielwert zu senken. In S2 und S3 haben sich aufgrund von fehlerhaften Angebot- und Bedarfsdynamiken Abweichungen von den eigentlichen Narrativen im finalen Energiebedarf bezüglich efuels ergeben, die bei einer erneuten Modellierung korrigiert werden müssen. Des Weiteren zeigt Szenario S4, dass ein hoher Grad der Individualisierung nur schwer in Dekarbonisierungsstrategien zu integrieren ist, insbesondere bei einem geringen Anteil an lokaler erneuerbarer Energieproduktion.

Folglich ist eine signifikante Reduktion des Energiebedarfs eng mit der Überwindung des Wachstumsimperativs verbunden. Dies erfordert jedoch eine unverzügliche und umfassende sozial-ökologische Transformation von Lebensstilen, Gesellschaft und Produktionsweisen, die vor allem politisch vorangetrieben und gefördert werden muss.

1 Introduction

Greta Thunberg shook the entire world at the UN Climate Summit in New York in 2019 with her statement on "[...] all you can talk about is money and fairytales of eternal economic growth. How dare you! [...]"[1]. In doing so, she focused attention on a not unfamiliar key issue in climate change mitigation. The most emission pathway models used for political decision-making in climate protection assume a continuity of economic activity. This neglects the undeniable relationship of emission and economic growth, especially in the energy and resource intensive modes of production and living in Global North countries (Kuhnhenn et al., 2020). Economic growth is the key driver of rising greenhouse gas emissions. The genesis of this crises does not inherently stem from human beings themselves, but rather from a specific economic system, that hinges on perpetual expansion, primarily benefiting a privileged minority of affluent individuals. This system, driven by the quest to decouple GDP growth from its ecological impacts, has come under scrutiny (Hickel, 2020). Yet, in the realm of mainstream climate policy, a crucial premise centers on achieving a substantial decoupling of economic growth from emissions. This decoupling is deemed necessary to accomplish the required emission reductions essential for reaching specific climate objectives, such as the imperative to limit the global mean temperature increase to below 1.5°C. However, based on current knowledge and empirical evidence, the feasibility of attaining such a decoupling appears highly improbable, if not altogether unattainable (Keyßer & Lenzen, 2021).

Climate change is undoubtedly one of the most pressing challenges of our time, demanding urgent and transformative action to secure a sustainable future for our planet (IPCC, 2023). As nations strive to curb greenhouse gas emissions and achieve ambitious climate targets, the exploration of potential decarbonization pathways and their conditions and implications becomes crucial. However, alternative growth trajectories are mainly neglected in discussion (Kuhnhenn, 2018). Recent publications by Keyßer & Lenzen (2021), Kuhnhenn et al. (2020) or Samadi et al. (2017) present evidence on beyond growth potentials in climate change mitigation, while pursuing a degrowth trajectory. The global upheavals brought about by the COVID-19 pandemic and the energy crisis triggered by the Russian aggression against Ukraine have precipitated significant behavioral changes. These changes have amplified the importance of sufficiency and emphasized the values of solidarity, care-oriented economies, safeguarding livelihoods, collective action and the provision of essential services (Best & Zell-Ziegler, 2022). As a consequence, emissions have shown a decline, exemplifying the potential of such shifts for achieving reduced environmental impact (UBA, 2023a). Traditionally, the preferred method for such adaptations has been efficiency. However, a focus on energy

[1] Greta Thunberg to world leaders: 'How dare you? You have stolen my dreams and my childhood', 0:52-0:57.

sufficiency may address the multitude of crises facing humanity today, including biodiversity loss, inequality and climate change all at once (Best et al., 2022).

This thesis explores the innovative approach of energy sufficiency to unravel its untapped potentials in addressing the aforementioned challenges. It explores climate action, quantifying six qualitative narratives envisioning a climate-neutral Germany in 2050. The narratives, thoughtfully crafted by the EnSu research group offer glimpses into four distinct energy sufficiency scenarios, three of which embrace the principles of degrowth, one emphasizes a-growth and two growth-based narratives that align with a business-as-usual approach. Each narrative paints a unique picture, encompassing diverse perspectives on energy sufficiency and sustainable development. The green growth scenarios, GG1 and GG2, prioritize economic expansion with sustainable technology-driven solutions. GG1 emphasizes individualization and economic position, while GG2 takes a more moderate approach, focusing on climate protection and inland renewable energy potential. On the other hand, the four sufficiency scenarios, S1, S2, S3 and S4, break away from the growth-driven paradigm. They center on addressing global challenges like climate change and social inequality through reduced energy consumption and a focus on health, environmental justice and sustainability. Each sufficiency scenario presents a unique vision for a sustainable future, with S1 being growth agnostic, S2 skeptical of novel technologies, S3 adopting energy sufficiency with a fast technology switch, and S4 emphasizing a high individualization rate.

To explore these narratives quantitatively, the *2050 Pathways Explorer* by Climact was employed as the simulation tool of choice. This powerful tool facilitates the creation of decarbonization pathways based on selected ambition levels within various sectors of the energy system. The narratives provided by EnSu were seamlessly translated into the modeling tool using SAS by Alcamo (2008), setting the stage for comprehensive analysis.

This thesis examines climate-neutrality pathways for Germany in 2050, their 1.5°C Paris Agreement compatibility and the scenarios conditions and implications. It starts with the State of Research (Chapter 2) on planetary boundaries, climate neutrality and the CO_2 budget. The Theoretical framework (Chapter 3) explores growth, degrowth, and sufficiency. Methodology (Chapter 4) outlines scenario development and modeling. Results (Chapter 5) presents key findings on emissions and energy demand. Discussion (Chapter 6) analyzes decarbonization trajectories, their socio-ecological implications and a research reflection.

As the urgency of climate action intensifies, this master thesis offers valuable insights into the potential futures that await a climate-neutral Germany in 2050. By quantitatively modeling the narratives, and scrutinizing the underlying implications, this research seeks to contribute to the broader conversation on sustainable climate mitigation pathways.

2 State of Research

The following Chapters present relevant research subjects of this thesis, which investigate the modeling of conventional and beyond growth emission pathways to effectively mitigate climate change. Furthermore, the context of planetary boundaries and climate mitigation is thoroughly illustrated. Respective objectives are mainly integrated into climate neutrality targets, complemented by the subsequent conceptualization of CO_2 budgets. Therefore, alternative emission pathway modeling in the context of beyond growth is outlined as necessary, to meet the ambitious emission reduction goals. Finally, extensive research questions are derived.

2.1 Planetary boundaries

In 2009, Rockström et al. introduced their groundbreaking concept on the planetary boundaries which led to a new universal approach on sustainability policy development. They defined nine boundaries: climate change, ocean acidification, stratospheric ozone depletion, interference with the global phosphorous and nitrogen cycles, rate of biodiversity loss, global freshwater use, land-system change, aerosol loading and chemical pollution. These boundaries aimed to set environmental limits where humanity can operate safely within Earth's system. An exceedance of each boundary would substantially decrease Earth's livability for humanity and affect our societies. Later in 2015, Steffen et al. updated the quantification by Rockström et al. and confirmed the trespassing of three of the nine defined boundaries. Since then three more boundaries were crossed, with 'freshwater' and 'novel entities' (formerly 'chemical pollution') being the latest ones in 2022 (Persson et al.; Wang-Erlandsson et al.). Now, 'ozone depletion', 'ocean acidification' and 'climate change' remain as not trespassed yet.

However, exceeding of the boundary 'climate change' could make Earth possibly unlivable for humanity, since a global temperature rise of 1.5°C could trigger various tipping points causing a domino effect in global climate change (Armstrong McKay et al., 2022). Tipping points are considered to be key elements in the Earth's climate system. Once exceeded they become self-perpetuating and irreversible. Armstrong McKay et al. identified various tipping points close to toppling. This is extremely worrying especially when considering the fact, that the global temperature could possibly exceed 1.5°C within the next year, due to El Niño (Ludescher et al., 2023). For the years 2011-2020, humanity has caused global warming with a resulting global surface temperature of 1.1°C above the reference period of 1850-1900. On a global scale, emissions increased continuously. Climate change impacts atmosphere, oceans, cryosphere and biosphere, affecting humanity in multiple ways, through extreme climate and weather events (IPCC, 2023). The examination by Armstrong McKay et al. (2022) highlights the necessity of the 1.5°C target of 2015 Paris Agreement and that it is non-negotiable.

Mitigating climate change and its underlying cause, the containment of greenhouse gas (GHG) emission has to be the top priority, considering every feasible available measure.

2.2 Climate neutrality

Many terms are used synonymously for the concept on balancing human impact on climate change. To avoid misunderstandings clarification is provided. In 2015 Rogelj et al. compiled the first conceptualization of carbon neutrality, climate neutrality, (net) zero carbon or GHG emissions. The underlying concept was initially coined by the IPCC in 2014. The authors outlined, that pathways preventing a global temperature rise above 2°C would require cumulative emissions to be limited significantly with near-zero GHG emissions by the end of the century. However, near-zero or absolute zero emissions are an implausible concept, according to Rogelj et al. (2015), although there are calls for urgently adopting zero emission strategies (Kemfert, 2021). Zero GHG emissions would imply no anthropogenic emissions in any sector, which is highly unlikely, especially in the agricultural sector. Moreover, a complete elimination of carbon emissions, especially in the energy-intensive industry sector, is deemed highly improbable. Consequently, the idea of ‘defossilization’ emerged in such cases as an alternative to ‘decarbonization’. Defossilization aims to transition from carbon-intensive fuels, such as coal, to less carbon-emission-intensive alternatives like gas. Nevertheless, the preferable fuel switch should strive for full decarbonization i.e., a fuel switch to renewable energy sources (RES), while defossilization should primarily apply in sectors with high energy intensity, such as chemical or steel industry (Agora Energiewende & Wuppertal-Institut, 2019; Veksha et al., 2023). Yet, these residual emissions need counterbalancing by conventional or novel negative emission technology (NET) to minimize their negative atmospheric impact. This concept is called net-zero emissions and still allows such sectoral carbon emissions. It implies that the global total annual anthropogenic CO_2 emissions are reduced to zero by actively removing an equivalent amount of residual emissions caused by human activities. These negative emissions are achieved by conventional NET methods, like afforestation or novel carbon removal technologies, like Direct Air Capture (DAC) (Smith et al., 2023).

However, when net anthropogenic CO_2 emissions cease and reach zero, the warming caused by CO_2 also halts. Consequently, the temperature level is determined by the cumulated emissions reached at that point and is expected to remain fairly stagnant due to carbon pools exchange cycles of 40 to 200 years. This is unless emissions drop further below net-zero by actively removing emissions through conventional or novel NETs (Fankhauser et al., 2022).

Net-zero carbon or CO_2 emission are synonymous with the scientific term ‘carbon neutrality’ and are often referred to as ‘climate neutrality’. The IPCC (2018) defines the latter as reaching a state where human activities have a neutral impact on the climate system. This is achieved by balancing any remaining GHG emissions with negative emission i.e., carbon dioxide removal (CDR), while also considering the regional or local bio-geophysical consequences of human actions that can influence the local climate. Generally, net-zero emission targets are considered to be more scientific, than ‘neutrality’ concepts, since neutral human influences could also apply to air pollutants, or land-use changes affecting the albedo (Rogelj et al., 2015).

The concepts of achieving net-zero emission reductions are primarily integrated into national climate neutrality targets, aligning with the objectives of the Paris Agreement to curb global temperature rise to ideally 1.5°C. Their policy specifications and objectives depend on the implementing country, and net-zero emission pledges experienced an uptake since 2020 (Höhne et al., 2021). In the case of Germany, the government strives for GHG neutrality by 2045. This entails achieving a balance between GHG emissions output and removal. To support this objective, the German Climate Change Act (KSG) underwent amendments on August 31, 2021, resulting in heightened ambitions outlined by law. Stricter sectoral emission reduction targets were established for the period between 2023 and 2030, along with the implementation of yearly reduction goals. The efforts were complemented by monitoring and measurement plans. These adaptations happened in the context of the EU *Fit-for-55* approach, as the EU aims for lowering its emissions by 55 % in 2030 and ambition adoption of the German GHG neutrality in 2045 (Presse- und Informationsamt der Bundesregierung, 2022, 2023). By 2030, Germany aims to reduce its emissions by 65 % - compared to 1990 levels. With 88 %, the reduction goal for 2040 is quite ambitious. Once GHG neutrality is achieved by 2045, Germany plans to pursue negative emission balances by actively removing emissions using natural sinks in particular (Presse- und Informationsamt der Bundesregierung, 2022).

While carbon neutrality only addresses CO_2 emissions, the German approach of GHG neutrality extends the net-zero emission concept to other GHGs. As mentioned previously the neutrality concept allows a broader definition of balancing human influences. GHG emissions of methane (CH_4) or nitrogen dioxide (N_2O) vary in their emission pathways, radiative forcings and atmospheric lifetimes, which lead to different influences on the climate. Mitigation of global warming generated by GHG emissions (mostly measured in CO_2eq) is only applicable for timescales longer than a decade due to their interactions and lifetimes (Fankhauser et al., 2022; Joos et al., 2012). The integration of more GHGs is challenging due to the variety of metrics, which influence the choices on normative judgements about the trade-offs between policy targets (Rogelj et al., 2015). Currently there are no market-ready solutions for an effective abatement of neither N_2O or CH_4 (Kanter et al., 2020; Nzotungicimpaye et al., 2023). Consequently, temperature implications of net-zero GHG concepts are less clear than pure CO_2 consideration. To achieve net-zero CO_2 emission pathways the concept of CO_2 budgets emerged, as explained in the following Chapter.

2.3 German CO_2 budget

Starting from 2018, the IPCC established an extensive worldwide CO_2 budget. This residual budget is a vital guideline for determining allowable emissions to limit global warming to a specific temperature threshold with a certain probability (Rogelj et al., 2018). To achieve the ambitious 1.5°C target, a residual budget of 500-400 Gt CO_2 from 2022 onwards has been defined, ensuring a 50-67 % probability of attaining the objective relative to the reference period (1850-1990). However, the CO_2 budget's calculation comes with severe uncertainties affecting its final amount (Matthews et al., 2021).

Overall, the CO_2 budget provides robust decision-making tool for climate protection measures and sector-specific emission reduction targets. National carbon budget allocations can be framed in two different approaches. The first, known as 'grandfathering' approach, distributes the remaining carbon budget among nations based on their current emission shares. This method takes into account lock-in effects and path-dependencies, recognizing the challenges associated with mitigating emissions from countries in the Global North. The second approach allocates the carbon budget equal per capita. This allocation method accounts for international equity as each person on the planet receives the same budget (Williges et al., 2022). However, none of the approaches considers historical emission contributions. Both approaches face significant criticism, when taking international climate justice into account. Fossil fuel-dependent nations with substantial (financial) resources can support a just transition to climate-friendly systems better. Furthermore, it can be argued that these countries may 'deserve' a relatively smaller CO_2 budget, due to historical emission contributions (Mengis et al., 2021).

Currently, various CO_2 budgets exist for Germany. According to Mengis et al. (2021) the German budget ranges from 5.6-13.3 Gt CO_2 using the 'grandfathering' approach, and 3.5-8.3 Gt CO_2 in the equal-per-capita approach. Both estimates are based on Matthews et al. (2021). However, the most recent calculations by the SRU (2022) base on the actualized global CO_2 budget by the IPCC (2021). As revised figures for Germany indicate, the maximum budget from 2022 are at 3.1 Gt CO_2 (1.5°C and 50 % probability), and 2 Gt CO_2 (1.5°C and 67 % probability). If emission reductions proceed linear under the recent political and economic developments, the budgets deplete in 2031 or 2027 (SRU, 2022).

The depicted figures outline the highly constrained landscape of German climate policy, emphasizing the pressing necessity for policymakers to enact shifts and decisive measures to expedite climate protection initiatives. Here, pathways that deviate from current projections could be useful to identify ambition and implementation gaps and how to address them accordingly.

2.4 Emission pathway modeling in the context of beyond growth

In climate change research, emission pathways are used to describe a possible future development of GHG emissions at the defined target level. Various variables, such as socio-economic components, technological and sector-specific developments and their resulting possible GHG emissions as well as savings potentials are taken into account. The most popular scenarios of this type are the SSPs (Shared Socioeconomic Pathway) produced by IAM (Integrated Assessment Models) and published by the IPCC. These IAM scenarios are often used to study interdependent relationships between social and biophysical systems in full complexity. The SSPs have their origin in the former RCP (Representative Concentration Pathway) scenarios which describe absolute GHG concentrations projections in the atmosphere (IPCC, 2013). They assume radiative forcing in Watt per m^2 of increasing GHG concentration by 2100 and corresponding temperature levels. While RCP 8.5 corresponds to a business-as-usual (BAU) scenario and temperature increase of 1.4-2.6°C, RCP 2.6 assumes significant mitigation efforts and negative emissions (0.4-1.6°C). The RCP 6 and 4.5 scenarios each fall in between (van Vuuren et al., 2011). After revision, the RCP scenarios were extended to five SSPs in the Sixth IPCC Assessment Report (van Vuuren et al., 2017). The SSPs depict expected socioeconomic changes until 2100 and take assumptions on population, GDP growth, technological progress, energy and resource use into account (IPCC, 2021). Eight years after the Paris Agreement, which set the a limitation in global surface temperature rise, GHG emissions still increase and mitigation pathways became even narrower (IPCC, 2023).

When examining the emission trajectories, there is one basic assumption all climate mitigation scenarios rely on: a continuous or an increase in economic growth. First and foremost, economic growth and climate change are fundamentally related and often neglected when developing such mitigation scenarios (Kuhnhenn, 2018). An economic system's material or energy flow based on fossil fuels automatically result in carbon emissions. This relation is also described as Kaya Identity by Kaya and Yokobori (1997). Furthermore, increasing economic growth ignores the fact that infinite growth is impossible on a finite planet. Not only due to resource availability but also resulting social and environmental injustices (Adler, 2022).

Due to the significant role of economic growth in driving emissions, numerous scenarios fall short in achieving the necessary emissions reductions to limit global temperature rise at 1.5°C. The prevailing climate mitigation policies rely on a 'decoupling' of economic growth from carbon emissions in order to achieve the Paris Agreement (Kuhnhenn et al., 2020; Keyßer & Lenzen, 2021). However, Parrique et al. (2019) provide robust evidence, that achieving such 'absolute decoupling' appears highly unlikely or impossible (refer to Chapter 3.1.2 for clarification). Moreover, most mitigation scenarios heavily rely on high-risk technologies, such as CDR or carbon capture technologies as a last resort in emission reduction. Depending on these technologies presents significant challenges due to their insufficient technological readiness and market maturity, as well as uncertainties surrounding sustainability and feasibility (Sovacool et al., 2023). By relying on economic growth and technological solutions, the huge potential that societal transformation offers, is totally neglected (SRU, 2023). Yet, there is a high need for alternative mitigation scenarios to safeguard the 1.5°C target without such hypothetical technologies and a continuation of the growth paradigm.

Although various qualitative scenarios, storylines and frameworks envision an alternative future that achieves decoupling from environmental limits while providing collective well-being (e.g. see Raworth, 2018), there has been limited quantitative modeling conducted on alternative growth trajectories. In 1972, Meadows et al. took the first steps in modeling growth-limiting scenarios, significantly shaping the discourse. However, the following passage will focus on more recent authors. In 2007 Victor & Rosenbluth published their work on "[…] why developed countries should consider managing without growth […]" (p. 492). They evaluated the pursuit of worldwide economic growth as impossible, due to the environmental and resource availability constraints, and confirmed Meadows et al. (1972). Furthermore, they discussed the negative impact of economic growth on well-being. Their study emphasized that policy objectives like full employment, poverty eradication, and environmental protection don't require or depend solely on economic growth. In 2011 Victor updated this work on low/no growth and extended it by its implication for climate change mitigation. The scenario modeling demonstrated high potentials for degrowth and low/no growth scenarios, compared to BAU on mitigating climate change while providing wellbeing. Although assumptions on macroeconomic scenarios were only applied for Canada, the results fit to any high-consumption economy.

The findings of Victor (2011) are further supported by the recent publication by Kuhnhenn et al. (2020). The *Societal Transition Scenarios* proposed an alternative mitigation pathway, which not only meets the 1.5°C limit, but also reduces the Global North countries dependency on unsustainable high-risk technologies. The studies focus was rather on consumption reduction and respective influences on economic growth, which is why these technologies lost their significance. The alternative outline encompasses changes in production, consumption, governance, culture and individual behavior and serve as an initial, yet global framework for climate mitigation situated within the degrowth paradigm. This challenges the current predominance of NETs as dominant key solution. Their momentum increased in the recent years as the climate crisis escaladed.

The work of Keyßer & Lenzen (2021) deals even more comprehensively with such degrowth scenarios and their implications. In their review they examined degrowth as well as low energy demand scenarios and compared their performance in risk indicators for feasibility and sustainability with the 1.5°C IPCC scenarios. The findings suggest that degrowth scenarios effectively reduce numerous significant risks related to feasibility and sustainability. However, considerable obstacles persist for degrowth in terms of political and economic feasibility.

However, these assumptions and conclusions of Keyßer & Lenzen (2021) were already issued by Samadi et al. in 2017. They took the idea of degrowth in mitigation scenarios further and explored the potential benefits of integrating sufficiency, especially energy sufficiency in energy system modeling. Their literature review showed that behavioral and lifestyle sufficiency changes and their potentials are mostly neglected for public policy goals such as emission mitigation. Yet, integrating sufficiency seems to be indispensable for the achievement of such objectives. A focus on energy-sufficient lifestyle changes in particular is generally recommended for the integration in energy system scenario studies.

These potentials of energy sufficient implications were confirmed for the case of Germany by Wiese et al. in 2021. To outline concrete transition pathways for a climate neutral Germany, various scenario studies with different options and sectoral objectives emerged over the years. Wiese et al. conducted a meta-analysis on eight of those climate neutrality studies, which at least achieve a 95 % reduction of GHG by 2050. They explored their resp. key strategies, like an installation uptake of renewable energy (RE), biomass usage, the import of synfuels i.e., efuels and hydrogen (H_2) and a reduction of energy demand. They concluded, that demand-side solutions that reduce the respective demand, offer a higher potential to mitigate significant challenges and pressures accompanied by some climate mitigation strategies. This applied to land availability and extreme RE uptake, extensive usage of biomass for energy production, sustainability of energy (carrier) imports, reliance on fossil fuels and socio-ecological implications of respective negative emissions. By reducing the energy demand the transformation towards a climate-neutral energy system becomes sustainably feasible. However, such reductive demand-side solutions are still underrepresented in energy system modeling and alterations in energy service demand behavior, but should be in focus.

As the elaboration on beyond growth in mitigation pathway modeling indicates, the discourse is changing. Only recently, in its actualized Sixth Assessment Report, the IPCC included alternatives to the hegemony growth and focused on sufficiency's potential in mitigating CO_2 emissions (IPCC, 2022b). This challenging of the growth paradigm further legitimizes the modeling of alternative growth trajectories for combating the climate crisis.

2.5 Research gaps and deduction of research questions

As Greta Thunberg said at the World Economic Forum in 2019 “I want you to act as if the house is on fire, because it is”[2]. Urgent action is desperately needed to mitigate climate change in the small timeframe left. Considering beyond growth trajectories may be the most feasible solution, as various authors exploring alternative emission pathways suggest. Especially low energy demand scenarios and sufficiency measurements could pave the way to achieve the 1.5°C target, while addressing pressing challenges beside climate change, like the biodiversity crisis and global inequality. As noted by Wiese et al. (2021), demand-side solutions are neglected in energy system modeling. Their potential identified by Samadi et al. (2017), Kuhnhenn et al. (2020) and Keyßer and Lenzen (2021) suggest an in-depth analysis to identify alternative trajectories for emission reduction based on energy demand reduction.

The research group EnSu is dedicated to explore energy sufficiency-based solutions to the climate crisis and has created qualitative narratives for a climate neutral Germany in 2050. In total, two narratives strive for green growth, while four are sufficiency-based.

To fill the research gap concerning the potentials of alternative growth trajectories, especially in terms of energy demand reduction to combat climate change, these narratives are quantitatively modeled using an energy system simulation tool. Accordingly, the following research questions are discussed and answered throughout this master’s thesis:

What are the possible decarbonization trajectories that Germany can follow by 2050 based on modeled scenarios?

Which scenarios are in compliance with the German CO_2 budget?

How do socio-ecological implications vary based on the conditions required for different scenario trajectories?

[2] Greta Thunberg: Our House Is On Fire | Forum Insight, 5:40-5:45.

3 Theoretical framework

The following Chapters explore the theoretical framework this Master's thesis. Since the whole thesis comes from a growth critical perspective, first dimensions of such growth criticism are provided. EnSu defined three alternative growth dependency trajectories in their construction on energy sufficiency narratives, namely *green growth*, *independence of growth* and *degrowth*, which are highlighted. The theoretical framework concludes with an illustration on (energy) sufficiency, as the focus scenarios rely on a sufficiency-oriented reduction of energy demand.

3.1 Growth

Growth per se is a natural biophysical process, since almost all entities grow quantitatively as an aspect of development. However, growth is also an internalized value system, that shapes our policies and lifestyle choices. This hegemonial growth imperative portrays (economic) growth as essential, positive and inevitable (Kallis et al., 2018). The following Chapter deconstructs the aforementioned.

3.1.1 Economic growth

Economic growth refers to the increase in the performance of an economic unit i.e., national economy. It is mostly measured using Gross Domestic Product (GDP), which represents the quantitative, market-shaped substance of all goods and services that are statistically recorded. Therefore, economic growth can be understood as the increase in GDP between two measurement points (Adler, 2022). Generally, the economic process converts energy and resources to goods, services and residues. Historically, economic growth is a relatively recent social and political objective. GDP was first measured in the 1930s and its growth emerged as goal in the 1950s which is continued until today (Kallis et al., 2018).

According to Adler (2022), economic growth is inherently linked to the capitalistic accumulation process, where the quantitative aspect of growth is derived from capital valorization. In this process, the surplus generated by economic units is shared and utilized for productive purposes, leading to extensive growth. The generation of economic surplus, as analyzed by Karl Marx, is crucial for economic growth and capitalist profit. It is generated through acquiring commodities in production. The exploitation of labor power and nature are the sources of it. The value of goods excludes inputs and represents newly created value, known as surplus value. Increasing surplus value involves methods like extending the working day or enhancing labor productivity. Energy sources also plays a crucial role in productivity growth. Other avenues include capital turnover, credit utilization, cost reduction, infrastructure improvement and expanding commodity production. These mechanisms drive economic growth and capitalist's wealth accumulation. In capitalism, growth is driven by the urge to accumulate and reinvest, motivated by competition and the pursuit of profit. Economic growth is marked by increasing the value of investments over time, often measured by GDP. Capitalist market actors have no inherent limit in their pursuit of surpluses, tied intrinsically to growth. While such growth is commonly associated with capitalist market economies, it also occurs in socialist systems. However, growth is not only prevalent in economics but rather represents a hegemonic concept that legitimizes interest-driven neo-liberalistic strategies, policies and projects as serving a general interest and thus makes it possible to reject other goals with reference to the priority of economic growth or to place them under the reservation of growth. It is heavily integrated in all ways of living and decision processes (Schmelzer, 2017).

While there is no universally accepted qualitative criteria for evaluating economic development in growth-oriented societies, economic growth assumes the role of a quantitative measure. This is based on the implicit agreement that it is a general condition for various socially valued goals such as income, wealth, socio-economic stability and competitiveness. Respectively GDP is used to reflect a societies well-being (Adler, 2022). However, GDP as a measurement for well-being, prosperity or even economic output of a society is limited and widely known as controversial. First of all, GPD increases not only with the flow of commodities and services considered as 'good'. Also, expenditures on war, catastrophes, epidemics or environmental pollution increase the GDP. Secondly, GDP heavily relies on unpaid reproductive care work of mostly women. Yet, it is not reflected in the GDP, which is why it is considered to be gender-blind. The same issue applies to subsistence work and utilized environmental services, which are not considered in the equation unless they are commodified (Kallis et al., 2018; Kubiszewski et al., 2013; Kallis et al., 2018).

By challenging economic growth, both the inherent growth imperative and capitalism are criticized. While growth critique advocates blame the relationship of economic growth and the utilization of nature as cause for the multiple crisis humanity finds itself in, economists and growth advocates strive for *greening* growth as the most feasible approach. Such greening relies on substituting the energy systems throughput by renewable sources and technological innovations for efficiency gains. By that the utilization of natural resources a decoupling from negative effects on nature should be achieved (Hickel & Kallis, 2020). The following Chapter explores the concept of green growth in more detail.

3.1.2 Greening growth

As response to the climate crisis and the ecological implications, green growth emerged as the dominant notion at the Sustainable Development conference in Rio in 2012. Theoretically, green growth pursues the continuation of economic expansion while being consistent to Earth's ecology. It relies on the assumption of absolute decoupling GDP growth from resource use and environmental impact (Hickel & Kallis, 2020). In order to comprehend the concept of decoupling negative environmental impacts (such as climate change or biodiversity loss) and resource use (materials or energy) from GDP growth, it is essential to consider the preceding debate. Parrique et al. (2019) defines ‘coupling’ as the interdependency of two variables, where one drives the other, causing them to evolve in tandem. However, decoupling occurs when this connection ceases to exist. In the context of GDP growth, which acts as the driving force, it is intrinsically linked to the increase in negative environmental impacts and resource utilization. To ensure compliance with planetary boundaries, it is essential for global economies to decouple both the negative environmental impacts and resource use from the continuous rise in global GDP (Hickel & Kallis, 2020).

However, one defines green growth, it relies on the premises that technological change and the substitution of primary energy sources will improve ecological efficiency of economies. This concept is generally promoted as the leading national and international policy for instance by the EU’s *Green New Deal* and *Fit for 55* to prevent climate change and other dimensions of ecological disruptions (European Commission, 2023). However, there is no empirical evidence that supports the theory of green growth.

First, to achieve green growth, a permanent and absolute decouple of resource use i.e., resource throughput from GDP is necessary. Yet, no empirical data shows absolute decoupling at a global scale in the long-term (Hickel & Kallis, 2020). This is mainly because achieved (resource) efficiency gains, are eaten up by the continuous economic growth premises. This dynamic also known as rebound effect. It was first described by Jevons in 1865 (Santarius, 2012). The more efficient a resource is utilized, the lower the costs and the higher the final utilization rate. This is also the essence of growth in a capitalistic society. Although growth seems to become cleaner and greener by substituting the energy i.e., fossil fuels by RES, used to accelerate growth, this is unlikely to spare total resources (Kallis et al., 2018). Second, green growth requires a permanent absolute decoupling of carbon emissions from GDP, at a fast rate to prevent the exceedance of the carbon budget for 1.5 or 2°C. While there is historical evidence of a relative decoupling of the aforementioned relationship, absolute decoupling is considered to be theoretically possible, yet empirical data shows the high unlikeliness of its achievement (Hickel & Kallis, 2020). Both carbon emissions and GDP increased steadily. While the switch from fossil fuels to RE can actually decouple this dynamic in the long-term, the necessary pace is key to stay within the designated carbon budget. More growth equals automatically to a higher energy demand, which is difficult to cover with RE in the short amount of time left (Hickel, 2020).

Yet, the question remains, if green growth will be the promised silver bullet and at what cost. When considering the urgency and pace humanity has to act, to achieve the emission reduction necessary for the Paris Agreement thresholds, a continuation of economic growth as the most fitting option is questionable. As the aforementioned debate illustrates, green growth is a theoretical and possible outcome. However, this inherent growth-based solution of absolute decoupling, is considered to be a myth. It isn't profound enough to build policies around it. Especially since the effects lead to the opposite (Ward et al., 2016). Hickel and Kallis (2020) conclude, it is more plausible to achieve the necessary reductions in resource utilization as well as emissions by not relying on growth. Especially since there is no evidence that growth would lead to the necessary decoupling. Further they suggest degrowth of production and consumption in high income countries. They argue for a more comprehensive and transformative approach that goes beyond decoupling and questions the primacy of economic growth in achieving sustainability.

3.1.3 Criticism of growth

As the preceding discussion of economic growth and its recent green coating shows, to strive for growth is inherently and fundamentally controversial. Historically, resentments on growth already date back to the 17th and 18th century (Adler, 2022). This thesis, however, is embedded in the contemporary growth critique as answer to the established growth paradigm of the 1950s and 1960s. This criticism of growth differs in its expressions by focusing on different aspects.

When considering the criticism of growth, biophysical implications and constraints are often considered as obvious dimension. The most important work, the Limits of Growth, were published by Meadows et al. (1972) and influenced the discourse significantly until today. Here, they criticize the concept of exponential growth of both economy and population, which is not possible in its unlimited manner. By that they define their *limits to growth* based on physical eternities, like resource availability and environmental capacities, which restrict endless growth dynamics. Pursuing unlimited growth will result in negative environmental effects. Here, the depletion of natural resources, environmental pollution, climate change and social injustice are inevitable. These statements and assumptions are backed by prediction scenarios depicting the Earth's future for 2100. The work by Meadows et al. (1972) built the foundation for further research and discourses located in the ecological criticism of growth like the work by Rockström et al. (2009) already presented in Chapter 2.1. Their framework further supports the negative implications for humanity following a continued economic growth. Bringing Earth's systems to its capacities or even trespassing those boundaries increases socio-ecological risks for humanity and creates intra- and intergenerational conflicts. Especially, since even more boundaries became close to trespassing or even were exceeded in the recent years (Steffen et al., 2015; Persson et al., 2022; Wang-Erlandsson et al., 2022).

Further, there are socio-economic dimensions of growth criticism, which debate the results from the pursuit of economic growth as the overarching objective. Here the qualitative dimension of growth is criticized especially in early industrialized nations. Central in the debate is the meaningfulness of the GDP and what it reveals about prosperity in such societies. Continued growth is not only associated with ecological-social problems and risks, it is also not socially desirable (Adler, 2022). Already in the 1970s, Hirsch illustrated the *social limits of growth*. He argues that economic growth is not only constrained by physical factors but also by social considerations. Hirsch highlights the shift from material needs to social goods as societies become wealthier. He suggests that beyond a certain point, the benefits of growth in well-being become marginal, leading to negative social and environmental consequences. Hirsch also discusses the hedonic treadmill effect, where increased consumption fails to provide lasting satisfaction (Hirsch, 1976). Furthermore, growth is coupled to increasing social costs, like stress, uncertainty and fear of relegation (Schmelzer & Vetter, 2021). Hirsch emphasizes the importance of social cohesion, warns against increasing inequality and identifies trade-offs between growth and other societal goals. Ultimately, Hirsch calls for a balanced and sustainable approach to development that prioritizes social, environmental and distributive factors (1976). His criticism continues to be justified, as the neoliberal promise of a trickle-down of the growing wealth of the top income and wealth segments has not happened. On the contrary, social inequality has grown (Piketty, 2014). Further, Jackson (2017) concludes that prosperity is also and especially possible without growth, and that GDP does not indicate progress in this regard. This is not to be confused with non-growth, which would lead to a collapse of the current economy, but rather controlled growth in sectors particularly worthy of growth, such as healthcare and education.

However, it is important to mention that growth comes with social benefits in less well-situated countries. However, their potential in growing qualitatively is deeply disturbed by the power relations established by Global North countries in the Global South (Adler, 2022). As already illustrated in Chapter 3.1.1, the accumulation of profits as capital acts as foundation of expansive growth dynamics in societies. The underlying pressures and motives of capitalism both perpetuate natures extraction and generate growth. Besides natures, wage labor is exploited massively to skim surplus generated by externalized costs. Natures metabolism is not accounted for in such equations, nor are the social-ecological implications of *cheap work* in Global South countries. Closely intertwined with the critique of capitalism are dynamics resulting from it, such as modes of production, appropriation and socialization, as a source of inequality of class, gender and North-South inequality. By that it accesses spatially-geographically non-capitalist or not (yet) commodified spaces, both socially, and geographically, to use as markets, source of cheap resources, labor, spaces for cost externalization, and as sinks of negative environmental impacts. This imperial way of life with its externalization of costs and the resulting exploitation of the Global South is seen by many as another precondition for growth (I.L.A. Kollektiv, 2019). These disparities must be reduced against the background of international efforts for global justice and a recognition of loss and damages. For example, prosperity in the Global North is based on extractivism in the Global South. Yet, this dynamic doesn't seem to end with Global North's reliance on Global South's resources to transition the current energy system to *green* alternatives (Adler, 2022). These only present the the growth-critical dimensions considered necessary for this thesis, although there are more which consider dimensions of feminism, cultural criticism, growth subjectivity, utilitarianism and consumerism and industrialist structures and globalization (Adler, 2022). The presented debate shows the far-reaching consequences that growth, or rather the hegemonically embedded growth imperative, has on a wide variety of scales and levels. However, the question remains on how to change such inherently critical growth-dependent implications. One possibility offers the concept of degrowth, which is illustrated in the following Chapter.

3.2 Degrowth

Economic growth has a long history of dynamic stabilization for modern and capitalistic societies. However, the necessary decoupling of GDP and environmental impacts to turn growth *green* is not evidently backed (Hickel, 2020). This circumstance led to a call for degrowth in science and economy. Both evolution of the discourse and conceptualization are covered in the following Chapter.

3.2.1 Evolution of the degrowth discourse

The debate for degrowth already dates back to the 1970s. The discourse was highly influenced by Georgescu-Roegen, who linked economic activity to the thermodynamic law of entropy (1971). By that he illustrated the irreversible utilization of nature through the anthropogenic metabolism. However, his arguments are mainly used by 'radical' growth critics of different movements, e.g. Altvater (2010), Kallis (2016) and Schmelzer & Vetter (2021) (see Adler, 2022). The publishment of the already mentioned *Limits of Growth* by Meadows et al. (1972) increased the momentum on growth criticism. Furthermore, Daly (1999) has coined the discourse with his steady state economy, which is highly influenced by his mentor, Nicolas Georgescu-Roegen. Adler (2022) summarizes the boundaries to growth defined by Daly as, the growth of the economic subsystem is limited by the predefined size of the entire ecosystem, by its dependence on ecosystems as a source and sink, and by the complex ecological dynamics that are more likely to be destroyed the more the size of the economic subsystem or the amount of throughput grows in relation to the entire ecosystem (Daly, 2007). By that Daly further proves the necessity of an alternative economic system which aims to achieve sustainable development and maintenance of a stable level of resource consumption in within Earth's boundaries. These thoughts highly influenced the degrowth discourse when it emerged in France in the 1990s and 2000s. Primarily, Serge Latouche criticized the principle of sustainable growth in 2002 based on the limits by Georgescu-Roegen and Daly (Adler, 2022).

The term degrowth originated from the french *décroissance* and was first used in 1972 by Andre Gorz. The term of degrowth officially emerged in 2008 after the first international degrowth conference in Paris. This marked the official renaissance of growth criticism in France, which highly influenced the international degrowth debate (Adler, 2022).

In Germany, the debate formed slightly different. Growth criticism developed before the financial crisis in 2007, as well as in France. Afterwards the respective publications increased significantly. Here, rather the concepts of *Postwachstum* (eng. translation: post-growth) emerged with illustrating post-growth economies, societies and policies. Central figures are e.g. Passadakis & Schmelzer (2010), Seidl and Zahrnt (2010), Paech (2005, 2012) and Adler & Schachtschneider (2017). The interpretations of post-growth are often not identical to degrowth and sometimes even contradict each other (Schmelzer & Vetter, 2021). This complicates the conceptualization and clear distinguishment of both concepts. Since a conceptual and holistic examination of this discursive landscape is not focus of this work, Adler's approach (2022, p. 114) is used, which includes "[…] growth critique or postgrowth as comprehensive designations of the various ideological-political and theoretical directions and concepts. Postgrowth and degrowth, on the other hand, are umbrella terms for all emancipatory disruptions formulated in the sense of degrowth". Consequently, various definitions and interpretations of degrowth, that emerged over the recent years are explored briefly in the following Chapters.

3.2.2 Concept of degrowth

Generally speaking, degrowth is more than just the opposite of growth. It is a concept consisting of both, academic debate and activistic action, which challenge the hegemonial growth paradigm. It combines various approaches that aim to create alternatives futures, principles and practices to provide well-being, justice and sustainability. This transformational perspective is often defined as the equitable downscaling of production and consumption to increase humanities well-being and ecological conditions (Schneider et al., 2010). By the systemic reduction of resource use and energy throughput, energy demand decreases and a transition to RE technologies is more achievable at a fast scale. Further the pressure on the environment as source and sink is reduced,by decreasing the systems material throughput (Hickel, 2020). This includes mainly Global North economies and GDP-growth. However, it shouldn't be understood as the literal negative GDP growth, since this would lead to recession in our current growth-based economies and systems, if it is not accompanied with social transformation. Slowing down the economic activities is not the end goal but a likely outcome when transitioning the economy towards equitable well-being and environmental sustainability. Generally, capitalism as we know is fundamentally incompatible with degrowth. Even though in theory growth is not inevitable under capitalism, in practice the system generates growth though the dynamic of competition, private property and the availability of cheap labor and energy supply. Degrowth therefore forfeits its critical value if it is not embedded in a broader critique, aimed at changing growth-dependent institutions and systems (Kallis et al., 2018).

How such a transformation of our current system should happen, varies based on the chosen concept. They all have in common, that quantitative growth i.e., GDP shouldn't be the main focus in societies to provide well-being and prosperity. Qualitative growth in growth-worthy sectors should rather be focused to reach the aforementioned. Yet, there are more focus specific definitions of degrowth, as van den Bergh (2011) illustrates with the definition on GDP degrowth, consumption degrowth, work-time degrowth, or physical degrowth. Adler (2022) clusters the German degrowth and post-growth movements by three: anti-capitalism, reform-based movement and sufficiency.

However, planned degrowth is politically highly unlikely, given the established interest and power relations (Kallis et al., 2018). Yet, it offers a no-regret-action in tackling multiple crisis at once, while providing a better life for all.

3.2.3 Independence of growth

In the context of the EnSu narratives, independence of growth is considered to be the prerequisite for degrowth, since the rejection of the GDP indicator is necessary. This fairly new differentiation in the concept of degrowth is further conceptualized by van den Bergh (2011) who distinguishes degrowth from so-called agnostic growth (a-growth). As well as others, van den Bergh criticizes GDP's ability to measure welfare and prosperity. Consequently, it should be neglected when considering economics, as they should be agnostic about GDP growth. By removing the focus on GDP information in such macroeconomic and political discussions, it becomes impossible to assess whether growth is occurring or not. Consequently, the paradigm of GDP growth or even the degrowing of GDP loses its foundation. He emphasizes, however, that opposing GDP or unconditional GDP growth does not necessarily mean rejecting all forms of growth. Disregarding GDP information as a societal objective implies that it cannot be considered as neutral or unimportant in relation to GDP growth. This neutrality provides a rationale for using the term 'GDP a-growth'. This term is preferred by van den Bergh, particularly because degrowth is deemed too vague and open to interpretation, as his definition of degrowth contexts shows. This conceptualization is concurred by Raworth (2018), who also advocates for an agnostic attitude towards growth. However, this point of view does not imply countries shouldn't care about growing. Agnostic growth rather means that the economy should promote human welfare regardless of GDP growth. Not the quantity of growth but its quality matters, as long as it stays inside the planetary and social boundaries i.e., the doughnut and promote human welfare and prosperity. To achieve such, economic systems need to become financially, politically and socially independent from economic growth. Subsequently, both cited authors match in their definition on agnostic growth as both strive for an independence of growth. Furthermore, such independence of infrastructure and institutions, described by Raworth (2018) is the main focus of Petschow et al. (2018), who work on precautionary post-growth. They add specific growth dependent and independent sectors to the discussion. Further, instruments on how to increase social security systems independency of growth are presented. For the remaining sectors, further research is advised.

Finally, the distinctive need formulated by van den Bergh (2010) arises from the clearly negative impressions on degrowth. He further concludes that the social and political feasibility of a-growth is higher than of the presented degrowth concepts, since a-growth is likely to be perceived less radical than the presented forms of degrowth. By being just indifferent and agnostic about growth further transformative opportunity windows could open, even though both degrowth and a-growth share the same believe system in neglecting GDP to measure and provide for human's prosperity.

However, Kallis et al. (2018) criticize, that by ignoring GDP the economy will either grow or not and if it does not then there should be plans for managing without growth. They legitimately note, that given deeply embedment of GDP in the existing institutional and political structures, a-growth approaches must advance as part of broader transformational system change.

3.3 Sufficiency

Sufficiency in one of the three sustainability strategies. Unlike the other sustainability strategies, efficiency and consistency, sufficiency aims to achieve absolute and significant reductions without compromise (Sachs, 1993). The notion comes from the latin 'sufficiere', which translates to 'enough'. Consequently, sufficiency is about the question of the right measure (Schneidewind & Zahrnt, 2013). While being integrated in science, civil society and also in the degrowth debate, it is often neglected in politics (Zell-Ziegler et al., 2021). Yet it offers exceptional advantages for staying within the planetary boundaries, resilience, well-being and environmental justice (Burke, 2020; Wiese et al., 2022). Furthermore, it can serve as guiding principle for technological transformation strategies (Saheb, 2021) and in lowering the negative impacts of the rebound effect (Alcott, 2008; Figge et al., 2014).

The following Chapters aim to illustrate the sufficiency discourse, conceptualize sufficiency and provide deeper knowledge on the potentials of the energy sufficiency concept.

3.3.1 Conceptualization of the sufficiency discourse

As early as the 1990s, Wolfgang Sachs shaped the sufficiency discourse with his four E's (in German, four D’s in English: Deceleration, Disentanglement, Decommercialization, and Decluttering) (Sachs, 1993; Schneidewind, 2017). Further, Huber defined sufficiency in the context of sustainable development in order to conserve nature (2000). According to Jungell-Michelsson and Heikkurinen (2022), Princen marked the beginning of a more comprehensive interpretation of the concept in 2003 by presenting sufficiency as a common-sense notion that, under specific circumstances, particularly ecological constraints, can serve as fundamental principles for social organization. Since then, there has been a continuous development of the sufficiency concept. Yet sufficiency offers particular potential for reducing emissions, as the 2022 IPCC report clearly shows. Here, sufficiency is defined as holistic policies and lifestyle changes to reduce demands in energy, material, water and land-use to an end where both human basic needs and planetary boundaries are met (IPCC, 2022b).

However, the definition on sufficiency and what sufficiency implies varies based on the concept and discipline behind it. Albeit, sufficiency strategies share two dimensions of providing both means and end in itself (Jungell-Michelsson & Heikkurinen, 2022). Sufficiency as an end refers to the establishment of quantitative thresholds commonly known as consumption corridors, which tackle both excessive consumption and deprivation concurrently. Sufficiency as means signifies a strategic approach to achieve sustainability objectives (Spengler, 2016). These strategies drive sustainability by implementing changes in social practices and introducing social innovations. However, the basic understanding of sufficiency in the research literature is very diverse, ranging from individual to societal-transformative approaches and political actions (Lage, 2022). The literature analyzed by Jungell-Michelsson and Heikkurinen (2022) reveals that the concept of sufficiency is quite broad, ranging from a sustainability ideology to socilogical and behavioural approaches. Sufficiency is often illustrated as a certain lifestyle that distinguishes from the hegemonial and dominant consumerism. It’s often related to social movements practising voluntary simplicity, anti-consumerism or slow consuption as well as downshifting. Sufficiency is defined by its normative shift and transition of values from more at a faster pace, to the opposite, a rather needs-based orientation. The aformentioned frames sufficiency as a primarily consumer-based approach focusing on the individual responsibility. In this individual-based discourse, Niko Paech, the most popular German sufficiency advocate, can also be situated. He developed his sufficiency-based post-growth economy in. Sufficiency is understood as "[...] voluntary less [...]" and deliberately "not as morally motivated renunciation [...]" (Adler, 2022, p. 383f.). This position, however is argued by Lorek and

Spangenberg (2019), who frame sufficiency rather as a field of action which encompasses broader aspects and considerations.

In his literature review Lage (2022) also explored sufficiency's various concepts but rather focuses on their inherent notion on social change. First, sufficiency is described as a strategy towards different sustainability goals. While all concepts aim to reduce environmental damage some also claim to pursuit both ecological and social problem solving. Such co-benefits are associated with enhancing wellbeing and social and environmental justice. However, this is no unique feature to sufficiency, as all sustainability strategies pursue both social and ecological goals. Yet, there are sufficiency-specific implementations of these goals, which use sufficiency as a consumption corridor and a transition towards an alternative economy, namely degrowth. These implementations utilize sufficiency as safe-operation corridors, ensuring basic needs are met while limiting environmentally damaging social practices, particularly consumption. This minimum limit describes lower limits of consumption where a decent life fulfilling basic human needs is possible and contextualizes sufficiency in social justice debates. The upper consumption limit on the other hand should prevent overconsumption and exceedance of planetary boundaries, available carbon budgets and provide a "safe and just operating space for humanity" (Raworth, 2012, p. 4). Again, social dimensions and ecological safeguarding are not exclusive to sufficiency as sustainability strategy, but limits on consumption and production of services or products are. However, such limits to consumption depend on different social, political and cultural contexts and are not generalizable. This applies in particular to the lower consumption limits (Fuchs et al., 2021). A distinction between satisfaction and needs limit consumption patterns in these sufficiency approaches, as Gough (2020) frames it. Finally, concrete consumption corridors definitions are still under debate and quantitative approaches lack (Di Giulio & Fuchs, 2014). However, the research by O'Neill et al. (2018) highlights the importance of engaging in this discourse and adopting an approach that aligns a life within the mentioned corridor. Especially, since all 150 countries examined by O'Neill et al. were unable to meet essential social needs without surpassing the planetary boundaries outlined by Raworth's doughnut concept (2012). Within this context, alternative economies like a-growth or degrowth are frequently proposed as means to establish the consumption corridor. In this scenario, the decoupling of wellbeing from economic growth enables the adoption of sufficiency as a strategy to achieve social and ecological objectives integrated into the economy (Lorek & Spangenberg, 2014). Consequently, these concepts of sufficiency highlight the interplay between sustainability and the critique of infinite economic growth on a finite planet (Meadows et al., 1972). While sufficiency, which advocates for a critical view of growth, is commonly linked with degrowth, the precise relationship between these two concepts often remains ambiguous, since they can overlap. On one hand, sufficiency is occasionally considered a prerequisite for degrowth, necessitating a shift in cultural values. On the other hand, a degrowth society is viewed as the outcome of practicing sufficiency (Alexander, 2015). In the work of Schmelzer and Vetter (2021), for instance, sufficiency is regarded as one of the various dimensions of a post-growth paradigm.

This discourse underscores the difficulties in distinguishing sufficiency concepts, particularly because sufficiency serves as both a strategy and an objective in pursuing sustainability. While Darby and Fawcett (2018) suggest that these goals entail a focus on consumption patterns aligned with sufficiency, emphasizing the need to prioritize resource efficiency and reduced consumption levels, Jungell-Michelsson and Heikkurinen (2022) interpret the analyzed sufficiency concepts rather as vision or end in themselves.

As already mentioned, sufficiency offers severe advantages outlined by Wiese et al. (2022). For example, sufficiency plays a vital role in preventing the transgression of planetary boundaries by drastically reducing the reliance on high-risk technologies such as geo-engineering, carbon capture and storage or secondary energy carriers as hydrogen and efuels. Further, sufficiency reduces unintended adverse effects of the other sustainability strategies efficiency and consistency. While efficiency can result in rebound effects, sufficiency can significantly reduce them (Santarius, 2012). The same applies to the consistency. The shift to RE could lead to a higher energy consumption due to lower energy prices, however, if sufficiency i.e., demand reduction is pursued, such rebound shouldn't happen. However, Best et al. (2022) note that there can be discrepancies depending on the scale. A consumption reduction in one group may lead to an increase of demand in others (Alcott, 2008; Sorrell et al., 2020). Furthermore, Wiese et al. (2022) emphasizes the potentials of sufficiency in well-being and prosperity and sovereignty and resilience and on justice and freedom. Finally, sufficiency offers a fast and cost-effective no-regret-option for transforming technologies and infrastructure for climate protection.

3.3.2 Energy sufficiency

The concept of energy sufficiency is integrated in the sufficiency discourse. Already in the late 2000, Muller mentioned energy sufficiency as a necessity for liberal, global north-societies to provide social justice whilst preventing negative impacts from energy consumption on others (2009). However, the concept was first defined in a holistic manner by Darby and Fawcett in 2018. The underlying principle of saving energy is a historically well-established adaptive strategy in times of energy scarcity and dates back to the early modern period as Hesse and Zumbrägel illustrated (2022).

Darby and Fawcett (2018, p. 8) define energy sufficiency as "[…] a state in which people's basic needs for energy services are met equitably and ecological limits are respected". To frame their ambitions on providing basic needs while respecting these limits, a sufficiency doughnut, inspired by Raworth (2012) is illustrated. The inside of the doughnut focuses on the accessibility of human basic needs (e.g. health, shelter, mobility, participation, work) through sufficient energy services and intact ecosystems. The authors emphasize, that the doughnut's inside, work, shelter, mobility, etc. are redefined thought sufficiency. Furthermore, the definition on basic needs varies heavily on local conditions, as described in the previous Chapter. The doughnut's outside is limited by planetary boundaries and thus provide a safe operating space for humanity. Moreover, these external limits relate to the energy's source and potential atmospheric impacts, material supply and demand for infrastructure development and potential land and water use to provide the necessary energy services.

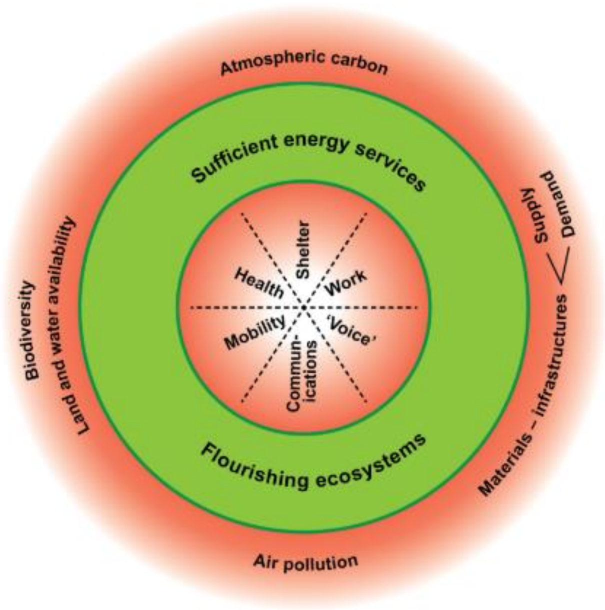

Figure 1. Sufficiency doughnut by Darby and Fawcett (2018).

The term 'energy sufficiency' differs compared to the sufficiency definitions elaborated in the previous Chapter. While sufficiency is also defined by behavioral lifestyle changes this definition refuses to focus on sufficiency's relation to action and individual decisions. Darby and Fawcett (2018) criticize to focus solely on a reduction of energy demand, as it diverts the attention from ensuing universal access to sufficient energy services for people with missing access. By the incorporation of such needs in the sufficiency terminology, social well-being and justice dimensions are included. Moreover, by sufficiency's focus on individual decisions and actions to change lifestyles, the unconscious and routine nature of energy consumption activities are neglected. Energy sufficiency exceeds the reduction of energy demand by individual decisions and improved efficiency by incorporating them in a systemic manner. Finally, supply and demand infrastructures influence the individual access. Both design and construction of such infrastructures can facilitate lock-ins in high or low consumption patterns.

The proposed definition of energy sufficiency considers sufficiency as an overall achievable goal and organizing principle broadening diverting from the individual. Darby and Fawcett (2018) refer to energy services rather than to energy, because energy is more than just a commodity. It has social, ecological and strategic values. Resulting energy services, i.e., benefits provided by the use of energy, have a subjective dimension and its valuation varies based on the specific context. Furthermore, ambient ‘free’ energy, activities and materials can contribute to the availability of services e.g., as room temperature can substitute the functionality of clothing. Moreover, non-energy initiatives, like, planners, or natural processes can both create or deny energy service access by changing the landscape and action space. The usage of the term ‘energy services’ provides the opportunity for a sufficient energy use and is useful for developing policies around such services, as Darby and Fawcett (2018) illustrate.

This concept of energy sufficiency is the base of the work by EnSu. They define energy sufficiency as a strategic approach to achieve significant reductions in energy-based services consumption. This is accomplished by promoting inherently low-energy activities, aiming to attain a state of ‘enoughness’ that guarantees long-term sustainability (Best & Zell-Ziegler, 2022; Zell-Ziegler et al., 2021). Best and Zell-Ziegler (2022) distinguish three transformation paths towards energy sufficiency, as illustrated by social change theories outlined by Lage (2022). They highlight the limitations of individual consumption reduction due to the unlikelihood of widespread voluntary self-deprivation among the global middle and upper classes. Further, they suggest the use of policy instruments like taxes, incentives, and regulations, requiring a strong state and participatory processes for implementation. Moreover, social movements are mentioned, focusing on power dynamics and aiming for systemic change towards egalitarian, democratic, and ecologically sustainable economies. Finally, they advocate for systemic change and a shift in production and consumption logics. Furthermore, they present the policy option available for energy sufficient transformation, and what potential such a change offers.

4 Methodology

The following Chapters, explain the used methods and their application for this context.

4.1 Research design and approach

In this master thesis, six different qualitative context scenarios i.e., narratives are quantitatively modeled for Germany in 2050. They all show decarbonization paths with the goal of climate neutrality in the target year. In the following, the background of the context scenarios as well as the modeling tool used are presented. This is followed by a more detailed examination of the method used to transfer the context scenarios into the modeling tool and the conditions under which the data were ultimately collected and further prepared for analysis.

4.2 Development of scenarios for energy sufficiency by EnSu

The junior research group “The role of energy sufficiency in energy transition and society" (EnSu) aims to systematically integrate sufficiency strategies into energy system modeling. Its research explores the real-world implementation of energy sufficiency strategies and the societal conditions required for their effective establishment.

EnSu seeks to overcome existing limitations in energy system modeling by incorporating sufficiency measures, which are often neglected due to their non-quantifiable nature. As energy and climate policies heavily depend on these models, the inadequate representation of sufficiency measures in policy frameworks is concerning. To address this gap, EnSu is developing a so called ‘sufficiency module’ that is integrable into different energy models. This module will capture sufficiency approaches for climate and energy scenarios empirically, allowing for the assessment of their impact through the use of relevant data.

4.2.1 EnSu’s definition of energy sufficiency

EnSu does not provide a clear definition of energy sufficiency within the scope of their work yet. However, they emphasize that all energy transition strategies, namely sufficiency, efficiency and consistency, are required to achieve the 1.5° objective. Thus, all strategies of sustainability are combined. First, EnSu defined sufficiency as achieving a significant reduction in energy consumption through the implementation of social innovations, the phased elimination of unsustainable structures, and the promotion of behavioral changes. This approach is further enhanced by integrating efficiency measures. Efficiency is defined as using relatively lower amounts of energy while achieving the same objective. Additionally, consistency is added to the concept by substituting fossils with RES. Through its research, EnSu aims to investigate what sufficiency policies are required to ensure people use fewer resources. Especially since sufficiency is almost only discussed in politics under appeals to save calls for restraint or individual responsibility (EnSu, 2023).

The EnSu framework generally aligns with the energy sufficiency concept presented by Darby and Fawcett (2018) and is highly inspired by their wording and framing of energy service usage and dimensions in energy policy development.

4.2.2 Context scenarios and narratives

The context scenarios used in this master's thesis were developed in 2021/2022 in a participatory multi-stakeholder process using the cross-impact balance (CIB) method. CIB is a useful and meaningful method to develop consistent scenarios for qualitative datasets without requiring complex mathematics. It enables the identification of plausible arrangements of impact networks characterized by qualitative definitions (Weimer-Jehle, 2023).

First the 'context' is defined by identifying 'Descriptors', which are likely to have a significant direct or indirect influence on the energy system. Each Descriptor was assigned with 2-4 'alternative futures' that have different characteristics. In the following context scenario development process, different combinations of descriptors and their expressions are evaluated based on their potential interactions and interdependencies. These were analyzed by using the CIB matrix method. In this process, participants assign factors ranging from -3 to +3 that quantify the relative influences. Each number listed in Table 1 reflects the potential promoting or inhibiting impacts on the Descriptor expressions. For further info on the CIB matrix please refer to Appendix Chapter 8.5.

Table 1. Factor quantification and their qualitative influence on the descriptor expressions combinations. Based on the CIB method.

factor quantification	qualitative influence
-3	strongly inhibiting influence
-2	moderately inhibiting influence
-1	weak inhibiting influence
0	no influence
+1	weakly promoting influence
+2	moderately promoting influence
+3	strongly promoting influence

Finally, an algorithm examines potential combinations of Descriptor expressions and evaluates their internal consistency by considering the promoting or inhibiting factors of each Descriptor expression. As a result, consistent context scenarios are identified. They are primarily available in tabular form, as shown in Table 2. The six chosen EnSu context scenarios are based on ten Descriptors, each of which can have 2-4 different expressions (signified as A-D). Descriptor explanations are available in text form and are provided in the Appendix Chapter 8.4. Overall, the scenarios were defined to match a climate neutrality objectives for 2050. However, climate neutrality is not explicitly defined by EnSu, which is why net-carbon neutrality was assumed for this thesis. Two context scenarios assume green growth, one sufficiency-based scenario, assumes independence of growth (further referred to as a-growth), and three sufficiency-based scenarios assume degrowth. Three of the scenarios are moderate, so-called ‘mean’ scenarios, while the other are more extreme scenarios, so-called ‘no mean’ scenarios. The following Table 2 presents the tabular context scenarios and distinguishes in ‘mean’ or ‘no mean’ scenarios.

Table 2. Context scenarios and their descriptor expressions developed by EnSu. “M” indicates “mean” scenario; NM indicates “no mean” scenario. Bold descriptor expressions indicate differences between the scenarios.

	M	NM	M	M	NM	NM
Descriptors/expression	**GG1**	**GG2**	**S1**	**S2**	**S3**	**S4**
1) Individualization	1a	**1b**	1c	1c	1c	**1a**
2) Growth independencies	2a	2a	**2b**	2c	2c	2c
3) Demand for energy service	3a	**3b**	3c	3c	3c	3c
4) Wealth distribution and property relationship	4a	**4b**	4b	4b	4b	4b
5) Domestic potentials of land for renewable energy production	5a	**5c**	5b	**5c**	5b	**5a**
6) Resource availability, externalization and international distribution	6a	**6b**	6c	6c	6c	6c
7) Technological development	7d	**7c**	7b	**7a**	7b	7b
8) Speed of technology uptake	8b	8b	8a	8a	**8b**	8a
9) Priority setting for/discource on climate protection and planetary boundaries	9a	**9b**	9c	9c	9c	9c
10) Housing and supply structure	10a	**10c**	10c	10c	**10a**	10c

By the end of 2022, the tabular context scenarios were transferred into qualitative narratives with the following titles: *GG1: Energy imports and fast shift, GG2: RE uptake all over Germany, S1: Middle of the road, S2: Inland transformation, S3: Urbanized conviviality, S4: Individualized & degrowth society*. During the process of this thesis the context scenario for GG2 changed to a more moderate “no mean” scenario. While the title remains the same, the narrative text has not been updated yet.

A translation of the qualitative narrative into a quantitative scenario, as done in this thesis, is a logical development from the previous steps of the EnSu group. Chapter 4.4 explains this translation process and what needs to be considered in this context.

4.3 The Function and Scope of the *2050 Pathways Explorer*

The open-source tool *2050 Pathways Explorer* operated by CLIMACT is used for the quantitative modeling of qualitative context scenarios. This tool, currently in Release v34.0, 25/07/2023 and is a web-based open-source application (Climact, 2023a, 2023c). It provides a user-friendly interface and has been tested in various countries (Lefebvre et al., 2022). This tool has its roots in the *2050 Calculators* developed by David MacKay since 2010, which have been implemented in over 50 countries (Climact, 2023b). Furthermore, the tool allows for the modeling of country-specific energy transition scenarios based on realistic and transparent assumptions. The assumptions and their sources are provided for each lever, ensuring that they can be theoretically reproduced (Climact, 2023c).

The *2050 Pathways Explorer* is a simulation tool designed to explore different energy scenarios. Unlike optimization tools that aim to determine the optimal solution based on specific objectives, the *2050 Pathways Explorer* does not require the user to enter an objective or target value. Instead, the user can set various levers to simulate and visualize the results based on underlying assumptions and subjective objectives. While optimization tools focus on finding the best solution based on predefined objectives, simulation tools like the *2050 Pathways Explorer* allow users to explore and compare multiple scenarios without a specific optimization goal (Law & Kelton, 2000; Calafiore & El Ghaoui, 2014). However, there can be an overarching objective, such as climate neutrality by 2050 in this case.

The *2050 Pathways Explorer* provides a dynamic representation of an energy system and its interactions over time. By adjusting the levers and parameters within the tool, users can explore different scenarios and observe how the system responds. The underlying assumptions of the tool, such as the behavior of energy technologies, resource availability and socioeconomic factors, influence the simulation outcomes. Users can simulate a wide range of settings and examine the implications of different choices on energy generation, emissions, costs and other relevant factors. A setting is made by configurating ambition levels in the so-called lever groups. There are eight lever groups, with 189 setting options, i.e., levers (*2050 Pathways Explorer Release v31.0, 11/04/2023*). The lever's ambition levels range from 1 to 4. While 1 indicates a continuation or a deterioration of the current trends, level 4 represents transformational change. In a few cases, only A and B were distinguished, indicating either endogenous or exogenous modeling. While A represents modeling based on demand generated by the model, B indicates the possibility for selecting input through designated levers. This applies, e.g., for the lever group *Cost* or whether industrial material production should rely on internally or externally assigned levers (Climact, 2023a, 2023c). In this paper, all assignable levers were set exogenously. Further info on the adjustable levers can be found in Chapter 8.7 in the Appendices.

There are several options to receive the results after modeling. Since the focus of this thesis is set on GHG emissions and energy demand, corresponding data were selected for download.

While the *2050 Pathways Explorer* provides a dynamic and complete energy system model, with all relevant sectors and their emissions, it does not include macro-economic analysis. Furthermore, the model calculates costs retrospectively without incorporating cost optimization into its calculations (Climact, 2023a).

At the emissions level, the tool only addresses CO_2, CH_4 and N_2O. Emissions in CO_2 equivalent (CO_2eq) presented in the usual reporting format include all gases and are consequently higher (~4%). Official historical sources were used to calibrate the emissions data until 2019, while data for the period from 2019 to 2022 does not fully align with official sources and are more of an estimated reflection of actual data. Furthermore, sectoral model results may not add up to the total model results, because some sectors were aligned to non-official sources or inconsistent data. For Germany, the background data wasn't challenged (Climact, 2023c).

4.4 Translation of qualitative narratives to quantitative scenarios

The following Chapters elaborate on the integration of the qualitative narrative in the quantitative modeling tool by using the story-to-simulation (SAS) approach by Alcamo (2008).

4.4.1 From storyline to simulation

Scenario analysis has a long history and a diverse array of methods and techniques. While scenarios typically encompass narratives about the future, many scenario exercises now feature quantitative analyses, particularly in the environmental domain as in IPCC scenarios.

Qualitative scenarios describe possible futures in the form of words or visualizations (often referred to as narratives or storylines). They offer an understandable vehicle for communicating scenarios' messages while also illustrating the dimensions and interconnected nature of environmental issues. They are better suited to raise awareness about potential societal and environmental consequences in the future and may also propose potential solutions. They can also integrate the view of multiple stakeholders. In general, they don't provide numerical information and are often called 'unscientific' because their assumptions are not transparent and their development is often not replicable (Alcamo, 2008; Kosow & Gaßner, 2008).

In contrast, quantitative scenarios typically rely on computer models and fulfill a practical role of supplying numeric values for scientific and policy applications. They are considered to have 'greater transparency' in terms of underlying assumptions because they are accessible in written from, in contrast to the undocumented assumptions made in qualitative scenarios. Nevertheless, the precision of numeric values can create a false sense of certainty about future outcomes. In addition, the computer models employed in quantitative scenarios may contain implicit assumptions which affect their transparency. Furthermore, models have a limited ability to capture the complexity of environmental issues and often provide only a limited perspective on the future. Generally, the basics of modelling can be challenging for non-experts and even basic assumptions can be difficult to understand (Alcamo, 2008; Kosow & Gaßner, 2008).

Here, the story-to-simulation (SAS) method (by Alcamo, 2008) has emerged as dominant approach for converting qualitative components into quantitative scenarios (Kemp-Benedict, 2013). Integrating both scenario types, the qualitative component and a quantitative scenario, into a unified scenario exercise has demonstrated certain advantages. The narratives are translated into measurable parameters and subjected to empirical validation (Alcamo, 2008).

There are certain challenges associated with constructing and modeling hybrid scenarios, particularly in integrating interdisciplinary knowledge. Prehofer et al. (2021) suggest combining SAS with prior scenario context development using CIB and subsequent narrative development, performed here. This approach is proposed to address imbalances between simple storyline procedures and model complexity. This provides more comprehensive system representation by combining and integrating qualitative and quantitative information.

Although the SAS methodology is tailored to a specific type of scenario exercise, where pre-existing models are matched to scenario narratives developed by a storyline team, this approach is more prevalent on a global level. In contrast, a different approach is often taken for smaller scenario development, where quantitative analysis is required but no pre-existing model is available or identified prior to scenario narrative development. Here, Kemp-Benedict (2013) recommends indicator-driven scenario quantification. Yet, model development would have exceeded this work's scope, so the *2050 Pathways Explorer* was combined with SAS.

Table 3 explains how the respective steps of the SAS were integrated within the scope of this work and resulted in a scenario analysis. The EnSu group was responsible for performing steps 1-3 and represents the storyline group. Step 4 involves identifying and quantifying the driving forces in the EnSu narratives Descriptor expressions (see Chapter 8.4). Instead of working with the actual narratives, these Descriptors were analyzed and assigned to the available levers in the *2050 Pathways Explorer*. In Step 5, the scenario indicators i.e., the *2050 Pathways Explorer* levers are quantified based on the assigned driving forces. This involves selecting the levers most appropriate ambition levels, based on the narrative Descriptors assigned in Step 4. Steps 6-10 are beyond the scope of this paper. Chapter 4.5.1 discusses the implementation of Steps 4 and 5 in more detail.

Table 3. Incorporation of the SAS approach by Alcamo (2008) into the scope of this work.

SAS approach to scenario analysis by Alcamo (2008)		**Incorporation of SAS within the scope of this master thesis**
1.	Establish a scenario team panel.	= EnSu
2.	Propose scenario goals and outlines.	Goals and outlines are proposed by EnSu
3.	Revise scenario goals and outlines and create a first draft of storylines.	Development of first narratives done by EnSu
4.	Quantify driving forces of scenarios based on draft storylines.	The EnSu context scenario descriptors were mapped to the 2050 Pathways Explorer levers.

5.	Modeling team quantifies scenario indicators based on assigned driving forces.	Quantification here refers to assigning the various ambition levels of the *2050 Pathways Explorer*.
6.	Revise storylines based on modeling teams reports.	Beyond the scope of this work.
7.	Repeat steps 4, 5, 6 until an acceptable draft is achieved.	Beyond the scope of this work.
8.	Distribute draft scenarios for general review.	Beyond the scope of this work.
9.	Revise scenarios based on general review.	Beyond the scope of this work.
10.	Publish and distribute final scenarios.	Beyond the scope of this work.

4.4.2 Advantages and Drawbacks of SAS (Alcamo 2008)

Alcamo's (2008) SAS approach has been used in various scenario models (see e.g. Booth et al., 2016; Kok & van Delden, 2013; Mallampalli et al., 2016). By integrating SAS with cutting-edge computer models to obtain quantitative data on environmental changes and their underlying factors, SAS generates trustworthy outcomes that aid in scenario development and ensure the coherence of scenarios.

However, the SAS approach contains certain drawbacks. First, storyline quantification requires application and knowledge of modeling. As the methodology critique will later confirm, good models are not always available or suitable for association with a qualitative input. Moreover, SAS is time-consuming and cost intensive, but can be neglected in this context. More central are the so-called 'reproducibility problem' and the 'conversion problem'. The ability to replicate an analysis is central to scientific credibility. Unfortunately, the storyline may not meet this standard, because it was developed in a separate group process, in which many of the basic ideas or mental models remain unknown to the simulation group. To circumvent this, intensive communication was maintained with the storyline group during the modeling process. Also, the CIB approach used in the storyline process made the assumptions behind the narratives more comprehensible and its combination is recommended for this context (Prehofer et al., 2021).

Another drawback of SAS is the so-called 'conversion', first from storyline assumptions to model inputs and second back from model outputs to storyline inputs. For this context, only the first conversion problem is relevant, since a fine tuning of the EnSu narratives is beyond the scope of this paper. The first conversion problem appears when the assumptions in the storylines need to be translated into numerical model inputs, represent Step 5 (see Table 3). This can be done through expert judgement or the modeler decides how to translate text in numerical values (in this case, the *2050 Pathways Explorer*'s ambition levels). The translation can be supported by an extensive literature review.

For this paper, a mixed approach was used. The translation was done to best personal judgement, supported by an extensive literature review for the respective levers (see Table 5). Again, the issue of reproducibility arises, as relying on 'best judgment' lacks transparency and makes replicability more difficult, which impacts the scientific credibility of the scenario analysis. To circumvent this, the assumptions for the levers were discussed with the EnSu group in various feedback rounds to minimize credibility issues. In Chapter 8.7 of the Appendix further info on the sources and input used for the levers is provided.

4.5 Data collection and analysis

4.5.1 Preparation for modeling

As previously described in Chapter 4.4 the context scenario descriptors provide the input for the modeling in the *2050 Pathways Explorer*. The following Chapter explores the procedure within Steps 4 and 5 in more detail.

Step 4 quantifies EnSu narrative's driving forces using ten Descriptors and their expressions (see Chapter 8.4). In a first step, these Descriptors (expressions) were roughly assigned to the 189 levers of the *2050 Pathways Explorer* for the 6 context scenarios. In a second step, a finer assignment of the descriptor expressions followed. Table 4 exemplifies how this assignment is made, in the case of lever group *'Demographics and long term'* for scenario GG1:

Table 4. Exemplified Step 4 of the SAS in GG1 for the lever group 'demographics and long term'. Column 'Assigned descriptors (expression)' shows which descriptor (expressions) were assigned to the corresponding levers.

Lever level 1	**Lever level 2**	**Lever Explanation**	**Assigned descriptor (expressions)**
Demographic and long term	Population	Set the evolution of the country population	0
Demographic and long term	City or countryside	Determine the share of population living in urban and rural areas	1(a), 10(a)
Demographic and long term	House hold size	Determine the number of persons per household (on average). It impacts the number of total appliances used in the country	1(a)
Demographic and long term	Waste management	Waste managements	1(a), 3(a), 9(a)

Although most levers can be assigned based on the Descriptors, they are not detailed enough to match the highly detailed levers of the *2050 Pathways Explorer*. Therefore, for 20 levers an assignment was done with the support of the storyline team (see Table 27).

After assigning one or more Descriptor expressions to all levers, a quantification of the Descriptors followed in Step 5. The chosen assignments of Step 4 form the basis for decision making in Step 5. Quantification of the Descriptors is performed via the assigned levers of the *2050 Pathways Explorer* by selecting the most appropriate ambition levels for the context scenarios. In most cases, multiple Descriptor expressions were assigned to a single lever, so their relative influence had to be evaluated. For this purpose, results of the CIB process were used. As mentioned in Chapter 4.2.2, a CIB matrix is needed to map the influence of different Descriptor expressions on each other before creating the final context scenarios. Chapter 8.5 in the Appendices provides further info on CIB matrix. Whenever two or more Descriptors influence a lever, the six factors, from -3 to +3 of the CIB matrixes were used to balance their relative influence (see Chapter 8.5). It was particularly necessary to distinguish between the sufficiency scenario S1 and the remaining sufficiency scenarios, as Descriptor expression *2b Independence of growth* predominates instead of Descriptor *2c*, which refers to degrowth. Here, mainly the relative influence on Descriptor *3c Sufficiency-oriented reduction in service demand* was key. While Descriptor *2b* has a 'moderately promoting influence' on Descriptor *3c*, Descriptor *2c* has a 'strongly promoting influence' on Descriptor *3c*. Consequently, model levers assigned to *3c* had to have a higher ambition level when Descriptor *2c* was included in the context scenario. Further information on evaluations like this can be found in Chapter 8.7.

Furthermore, it was necessary to consult external literature to determine the most appropriate ambition levels for the context scenarios. Selecting of the best possible level in this case also means that ambition levels can be excluded that are far above what the current state of research assumes. This applies, for example, for ambition level 4 of the '*Demographic and long term'* lever *'Waste management'.* Here, ambition level 4 is quantified as 0.29 Mt of cumulative emissions of CO_2, CH_4 and N_2O. However, even the ambitious *GreenLife* and *GreenSupreme* scenarios by UBA (2019) assume at least 0.7 Mt emissions in the waste sector for 2050. According to Prognos et al. (2020) zero emissions aren't possible in the *Waste* due to the nature of the waste management process. Consequently, ambition level 4 was excluded and ambition level 3 was chosen as the most ambitious emission reduction in *Waste*. Further information on evaluations like this can be found in Chapter 8.7.

For these decisions, central literature on German climate neutrality was consulted first, such as the 2019 RESCUE study by UBA, two climate neutrality studies for Germany with the target year 2045 and 2050 by Prognos et al. (2020, 2021) and the recent publication by Ragwitz et al. (2023), which refers to the aforementioned studies and also includes other climate neutrality studies such as Ariadne (2021) and dena (2020) and also publishes new results. In addition, lever specific literature was consulted. Table 5 shows the literature used for the lever groups.

Table 5. Overview of literature used within 6 of 7 lever groups. For the lever group 'Imports/Exports' no additional literature was needed.

Lever Group	Supporting literature
Buildings	Bürger et al., 2019; UBA, 2019; Bao et al., 2020; Prognos et al., 2020, 2021; BBSR, 2021; HIC & ffe, 2021; Hennenberg & Böttcher, 2023; Ragwitz et al., 2023
Transport	Prognos et al., 2020, 2021; Ragwitz et al., 2023
FAFOLU	Willett et al., 2019; Semba et al., 2020; FAO, 2023; Hennenberg & Böttcher, 2023
Industry	Agora Energiewende & Wuppertal-Institut, 2019; Prognos et al., 2020, 2021; Ravikumar et al., 2021; Ragwitz et al., 2023; Smith et al., 2023; Statista, 2023a, 2023b
Energy production	Lübbert, 2005; Bömer et al., 2010; Presse- und Informationsamt der Bundesregierung, 2020; Bracke & Huenges, 2022; BASE, 2023; Ragwitz et al., 2023; Smith et al., 2023
Demographic and long term	UBA, 2019; UBA, 2022

The quantification of the Descriptors based on *2050 Pathways Explorer* ambition levels was done to 'best personal knowledge'. As mentioned in Chapter 4.4.2, 'best knowledge' is often not replicable. To prevent this, the assumptions i.e., the chosen ambition levels, were discussed with EnSu. After a first draft as well as initial test modeling, various Tables with the assumptions made were handed to EnSu in order to get feedback. The following Table gives an overview on who provided feedback for which respective sector i.e., lever group:

Table 6. Overview provided feedback by EnSu group member respective sector, i.e., lever group. No extensive feedback was required for lever groups 'AFOLU', 'Demographic and long term' and 'Import/Export'.

Lever group	Feedback provided by EnSu group member:
Buildings	Luisa Cordroch
Transport	Johannes Thema
Industry	Frauke Wiese, Jonas Lage, Benjamin Best
Energy production	Carina Zell-Ziegler

Subsequently, the feedback received on the chosen ambition levels was incorporated and prepared for the final modeling, which concludes Step 5 of the SAS. Further information on the set ambition levels can be found in Chapter 8.7. Final modeling was performed using *2050 Pathways Explorer Release v31.0, 11/04/2023* on 04/28/2023. Accordingly, no literature published after the final modeling can be included in the data basis. The graphs and data of the final modeling were downloaded and prepared for further analysis.

4.5.1.1 Modeling for climate neutrality

As mentioned in Chapter 4.2.2, the EnSu narratives assume climate neutrality in 2050. However, climate neutrality was not defined in detail, which is why a net-zero 2050 ($\leq$ 0 Mt CO_2eq) was generally aspired in modeling. Unfortunately, only GG1 was able to meet this objective, while residual emissions remained in the other scenarios. To meet this basic assumption of the EnSu narratives, a second optimized modeling round was performed in order to achieve climate neutrality. For instance, in S3, in *Transport* the electrification potential of marine, inland waterways and aviation was increased to ambition level 4, as was the electrification fuel switch potential for *Industry*. Both adjustments were necessary to lower the residual emissions. For further information on lever alterations refer to Chapter 8.9.

For various reasons it was difficult to achieve climate neutrality in the sufficiency scenarios. Thus, an attempt was made to expand the ambition levels within the interpretation of the Descriptors as much as possible without deviating from the original narratives. It was targeted to reach < 10 Mt CO_2eq in 2050 which was achieved for all sufficiency scenarios, except S4.

4.5.1.2 Limitations

Unfortunately, the *2050 Pathways Explorer* partly did not allow satisfactory quantification in some cases and therefore did not provide optimal modeling results. On the one hand, various ambition levels and thus partly whole levers were 'dead'. This means that the ambition levels were not based on any obvious data. In the tool, these ambition levels were marked with '0' in the lever description. Table 28 in the Appendices gives an overview of the affected levers. On the other hand, a number of levers contained uncertainties and potential errors due to personal interpretation, as their lever descriptions were ambiguous or did not match the corresponding lever graphs. Table 29 in the Appendices gives an overview on the affected levers.

Another fundamental difficulty arose from the fact that the lever group *'Costs'* did not translate to the total GHG emissions. To address potential misconception, the *2050 Pathways Explorer* team was consulted, but no response was received by the end of the empirical phase. Consequently, 10 *'Cost'* levers were not included in the final modeling. Accordingly, a very convincing and sound statement can be made for 156 levers; only a reasonable statement can be made for the 17 levers that contain potential misunderstandings.

4.5.2 Comparison with the German climate neutrality objective

In order to compare the modeling results with the German ambitions for climate neutrality stated in the KSG 2021, some data sets had to be prepared. First, the projected sectoral emission trends for the 2030 objective were collected from the accompanying report to the UBA dataset (UBA, 2023a, 2023c). In a next step, the sectoral emissions of the EnSu scenarios for 2030 were compiled in tables to compare the differences (see Chapter 8.10).

Table 7. Sectoral emission reduction objectives of the KSG 2021 for Germany for 2030. All data are from UBA, 2023c, except for FAFOLU (UBA, 2023a). Values in Mt CO_2eq.

Target Year	Energy supply	Industry	Buildings	Transport	Agriculture	Waste and Others	FAFOLU	Total
2030	108.1	119.4	65.9	83.7	57.3	5.0	-25.0	414.5

4.5.3 CO_2 budgeting

In order answer to the second answer research question, the German CO_2 budget resulting from the modeled scenarios is calculated. An assumed German carbon budget of 3.1 Gt CO_2 from 2022 (50 % percentile) was taken from the SRU (2022) report (see Chapter 2.2).

To calculate the remaining budgets of the scenarios, Germany's historical emissions (in CO_2eq) were compared with the emission levels from 2000 to 2022 (in CO_2eq) of the *2050 Pathways Explorer* scenarios to calibrate them, if necessary. First, the historical total emissions of the modeled scenarios were compared which began to differ from 2020 onwards. Subsequently, the real German historical emissions, retrieved from UBA (2023c) emission overview of the KSG sectors 1990-2022 were compared with the scenario outputs. These historical emissions differed from year 2000 onward as visible in Figure 2 and Figure 36 (see Appendices).

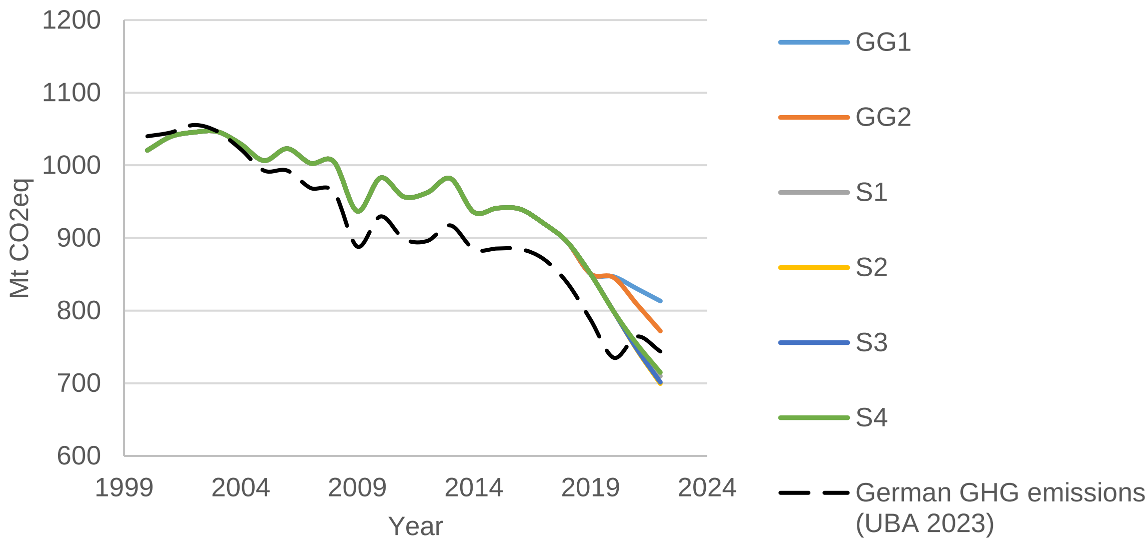

Figure 2. Comparison of historical real GHG emissions for Germany by UBA (2023c) and historical data of the modeled scenarios in the optimized setting for climate neutrality from 2000 to 2022.

Although it is unfortunate that the German historical emissions between 2000 and 2022 differ from the emissions in the tool, a calibration was only performed for 2022 to prevent misinterpretation in the margin of the remaining budgets.

Since the CO_2 budget is solely based on CO_2 emissions, it was not possible to continue the calculation with GHG emissions (in CO_2eq). For this purpose, the percentage of CO_2 in the GHG emissions (CO_2eq) of Germany (real values by UBA, 2023c) in the period from 2000 to

2022 was calculated. Of these 22 percentages, the average of 87.57 % was used. Subsequently, for each scenario (both initial and optimized for climate neutrality), the share of CO_2 based on the average for Germany (87.57 %) was extracted from the total emissions per scenario of the time series 2020-2050. To perform the final calculation of CO_2 budget specified by SRU (2022), the historical emissions values for Germany from 2022 were combined with the CO_2 emissions of the scenarios from 2025 to 2050. This approach was chosen to approximate the actual emissions values and avoid any misinterpretations regarding the remaining budget. The results are presented in Chapter 5.3.

4.5.4 Sensitivity analysis

Furthermore, a sensitivity analysis was performed to evaluate the lever's influence on the modeling. For this purpose, a one-way sensitivity analysis was most appropriate. This method belongs to the category of local sensitivity analysis. In this method, one input parameter is changed by a certain factor or percentage at a time, while the other parameters remain fixed. To assess significant local sensitivity, each parameter can be tested by increasing it by its standard deviation, and measuring the resulting change in output. This sensitivity measure accounts for the variability of the parameter and its impact on the model output (Hamby, 1994). However, data compilation and analysis of this kind would have been beyond the scope of this work. Hence, the local sensitivity analysis results should be interpreted with caution.

In the context of the *2050 Pathways Explorer*, only the input parameter levers got changed to ambition level 4 while all other levers remain at ambition level 1. Five parameters that could affect GHG emissions or final energy demand (FED) were selected as input factors. Initially, all levers were set at ambition level 1 to establish baseline model outputs for GHG emissions and FED. Some basic assumptions applied, to ensure maximum comparability with scenario results. Population development in the *'Demographics and long term'* group followed the scenarios on ambition level 3, and the modeling of *Material production (Industry)* and *Oil production capacities (Energy production)* were set at ambition level 1. Table 30 in the Appendix presents the selected parameter for FED or GHG emissions.

This approach offers certain advantages. It is straightforward, few simulation runs are required and the results are easy to interpret and apply. However, it has shortcomings, especially with respect to the interdependencies of input parameters and their interactions with the results (Hamby, 1994; Saltelli, 1999). This challenge is amplified by the general function of the *2050 Pathways Explorer*, since ambition level 1 (see Chapter 4.3) represents either a continuation or a deterioration of trends and thus affects the parameters chosen for sensitivity anyway.

To address this deficiency, a more powerful approach to exploring the sensitivity of a model than a one-way analysis would be to examine multiple values for the modeled output. Such multiway sensitivity analyses i.e., global sensitivity analyses are rather complex and are typically performed using statistics such as correlation methods, regression models, variance-based models, or screening (Iooss & Lemaître, 2015). Extensive work with background data was beyond the scope of this work. Nevertheless, a modified multiway analysis was performed, that fits the scope of this work. This modified global sensitivity analysis is inspired by the one-way analysis, but changes levers at a lower level of resolution (lever level 2), rather than at the highest (lever level 4). Moreover, levers were combined to explore interdependencies e.g., between *Floor area (Buildings)* and *Residential low-carbon heating solutions (Buildings)*. The chosen levers were set to ambition level 4, as in the local sensitivity analysis. Table 31 in the Appendices presents the chosen parameter.

At this point, a further statistical examination of the data sets would be beneficial, but this would exceed the scope of this work. Both local sensitivity analysis and modified global sensitivity analysis are not ideal in this context and should be interpreted cautiously. However, the final sensitivity analysis was performed using *2050 Pathways Explorer Release v32.1, 16/05/2023* on 23/05/2023. The received data of the local and modified global sensitivity analysis is presented in Chapter 5.4 in tornado charts. Tornado charts are a helpful for comparing the relative importance of different input factors (Eschenbach, 1992).

5 Results

The subsequent Chapters explore the modeling results of greenhouse gas (GHG) emissions and final energy demand (FED) of the *2050 Pathways Explorer*. While focus Chapters provide a general overview, they rely on an extensive dataset illustrating final energy consumption, sectoral GHG and more. As their analysis would exceed the scope of this work, external data is available (see Chapters 8.3) and only a clarifying selection compiled in Chapter 8.11. Further the scenarios' 1.5°C target compatibility is examined (see Chapter 5.3), the scenarios are further analyzed and compared (see Chapter 5.4), and the sensitivity analyses are presented (see Chapter 5.5). For more details on data compilation, refer to Chapter 4.5.

5.1 Greenhouse gas emissions

The following Chapters comprehensively present the GHG emissions of the second optimized modeling run. The first modeling run, which is closer to the original EnSu context scenarios, cannot be discussed in detail. Yet, data tables and figures are available in the Appendix (see Chapter 8.8.1). However, in the scenario specific Chapters, both modeling run's 2050 emissions are compared to give an impression of required adjustments for climate neutrality.

5.1.1 Overview of both modeling runs

In the first modeling run, no scenario reached climate neutrality in 2050, except GG1 as shown in Figure 3. Since net-zero emissions in 2050 were the basic condition of the EnSu narratives to meet, further lever adjustments were necessary (see Chapter 4.2.2). Consequently, the climate neutrality scenarios are the main focus of this analysis. The scenario's results of the first modeling run aren't presented in detail but in their relation to the further optimized modeling results. Their results are provided in the Appendix (see Chapter 8.8.1).

Since the emissions first began to differ in 2020, the starting year of the presented emission pathways is 2019. Furthermore, Germany's actual emission data is pictured for reference. Obviously in both modeling runs, the recent historical emissions differ significantly from the actual German GHG emissions. Therefore, the scenarios emissions from 2025 are focused.

The following Figure 3 illustrates the emission pathways of the first modeling run. Scenarios GG2, S1, S2 and S3 decrease their emissions similarly from 2025 onwards and their pathways are difficult to distinguish. However, the sufficiency scenarios historical modeled emissions are generally lower than the actual German emissions. GG1 and S4 are considered outliers because they differ significantly from the other scenarios, which cluster between 0-50 Mt CO_2eq in 2050.

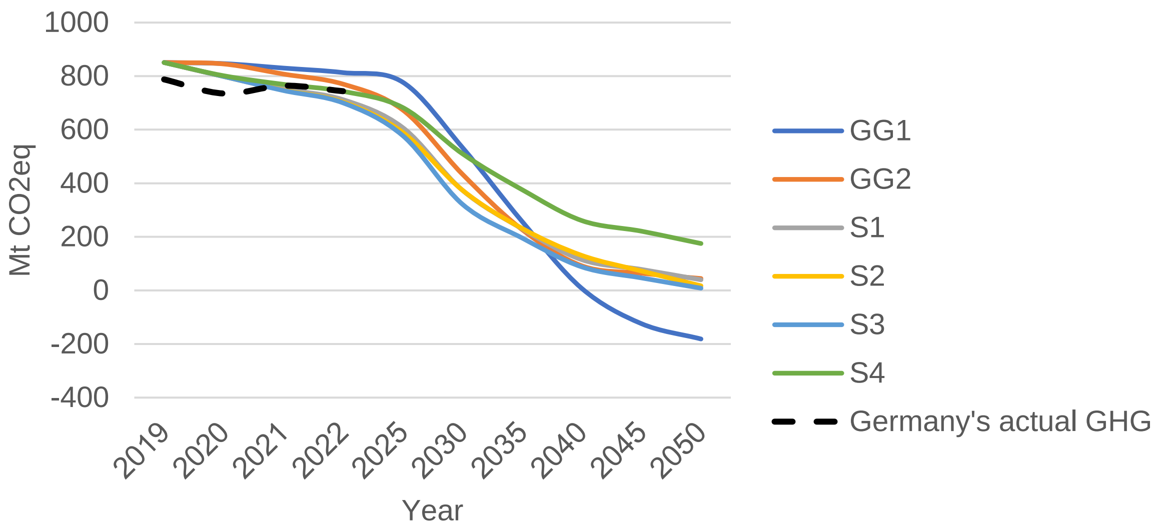

Figure 3. GHG emissions in Mt CO_2eq between 2019 and 2050 for all the EnSu scenarios in the initial modeling run. The dotted line indicates Germany's actual emissions by UBA, 2023b.

Figure 4 illustrates the GHG emissions in the optimized modeling run. The sufficiency scenarios follow aligned decarbonization trajectories, with GG2 joining their cohort in 2030. Again, the historically modeled emissions differ significantly from the actual German emissions, as the green growth scenarios emissions are initially higher, while the sufficiency scenarios emissions are significantly lower. Moreover, all scenarios do not exceed 50 Mt CO_2eq, while GG1 demonstrates notably high negative emissions in 2050.

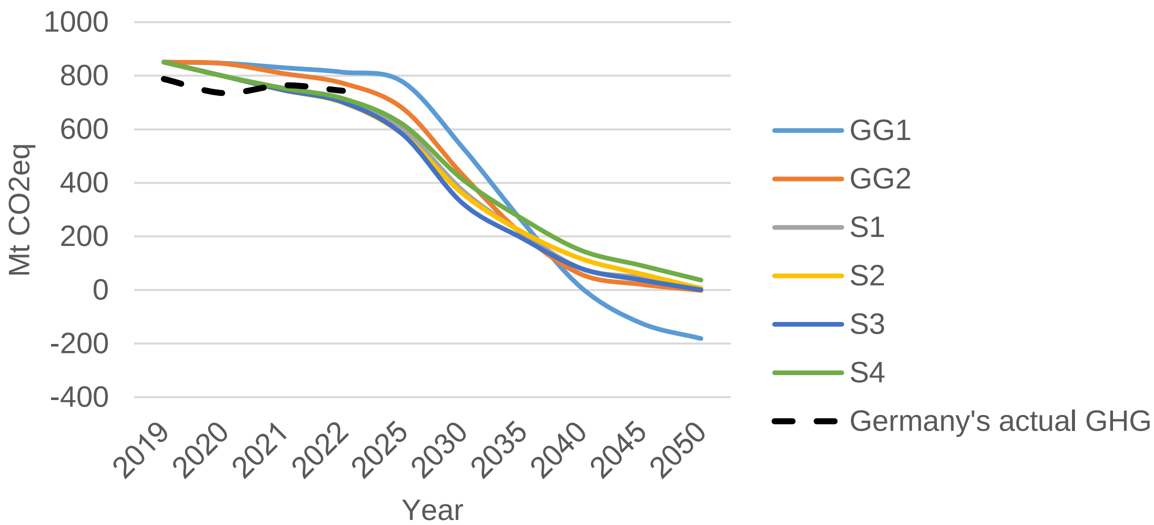

Figure 4. GHG emissions in Mt CO_2eq between 2019 and 2050 for all the EnSu scenarios in the second optimized modeling run. The dotted line indicates Germany's actual emissions by UBA, 2023b.

The following Table 8 illustrates the optimized scenarios sectoral emission for 2050 in detail. In the *Land-Use* sector, GG1 presents the least natural sink potential, while GG2 has the most, standing at -82.50 Mt CO_2eq. The remaining scenarios range between -55.69 to -68.66 Mt CO_2eq. Furthermore, in GG1's *Building* sector stands out, with fairly high emissions, followed by S4 and S2. The *Building* emissions of GG2, S1 and S3 are the equally low (0.01 Mt CO_2eq). For the *Transport* sector the emission range diverges. Here, GG1 presents the lowest, followed by S3, while S2 presents the highest emissions followed by GG2. In the agricultural sector, GG1 has the highest residual emissions and S3 in contrast, the lowest, standing at 18.74 Mt CO_2eq. This is more or less repeated in the *Industry* sector, since GG1 again presents the highest emissions. S3 on the other hand, has the second lowest sectoral emissions, while S1 stands lowest in *Industry*. In the *Energy supply* sector GG1 stand out as an outlier. Its emissions are negative, standing at -318.15 Mt CO_2eq. Furthermore, S3 presents the highest emissions in this sector with a huge difference to the other scenarios. For the *Waste* sector, scenarios S1, S2 and S3 present the same emissions. The emissions of GG1 are the highest, standing at 15.82 Mt CO_2eq.

Table 8. Comparison of all scenarios sectoral and total GHG emissions (in Mt CO_2eq) in 2050 for all EnSu scenarios in the optimized modeling round.

Scenario	Year	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
GG1	2050	-17.36	4.90	0.04	61.49	72.06	-318.15	15.82	-181.20
GG2	2050	-82.50	0.01	3.87	35.41	30.87	0.55	10.55	-1.24
S1	2050	-55.69	0.01	2.49	22.55	25.44	5.54	6.59	6.92
S2	2050	-68.11	3.54	4.73	23.26	35.31	1.12	6.59	6.44
S3	2050	-68.66	0.01	1.15	18.74	28.92	13.91	6.59	0.66
S4	2050	-57.98	4.41	2.86	36.54	34.47	6.22	10.55	37.06

5.1.2 GG1 – Energy imports and fast shift

Figure 5 depicts the decarbonization trajectory of GG1 from 2000 to 2050, while Table 9 provides the corresponding data from 2019 onward. As described previously, GG1 is an outlier due its high portion of negative emissions. Substantial emission reductions start in 2025 but slows down in 2040. By 2050, an emissions reduction of 117.75 % occurred.

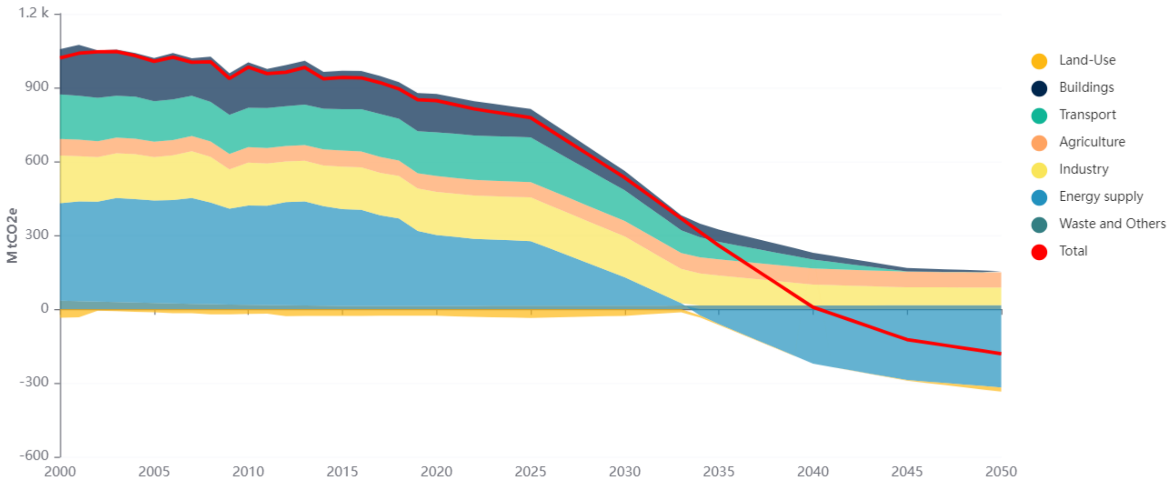

Figure 5. GHG emissions in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others for scenario GG1. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

Climate neutrality is nearly reached in 2040 with only 7.9 Mt CO_2eq left. The emissions from the *Transport* and *Buildings* sectors phase out by 2045. In 2050, negative emissions of -181.20 Mt CO_2eq are mainly attributed by the *Energy supply* sector (-318.15 Mt CO_2eq). The emissions in the *Land-Use*, *Buildings*, *Transport*, and *Energy supply* sectors are either below or close to 0 Mt CO_2eq (see Table 9). Residual emissions in 2050 are present only in the *Agriculture*, *Industry*, and *Waste* sectors.

Table 9. Total and sectoral GHG emissions in Mt CO_2eq from 2019 to 2050 of GG1 for Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others.

	2019	2020	2021	2022	2025	2030	2035	2040	2045	2050
Land-Use	-26.93	-27.20	-29.65	-31.69	-35.55	-27.27	-3.98	0.46	-2.18	-17.36
Buildings	154.62	155.80	147.53	139.38	115.49	78.79	49.45	27.97	13.49	4.90
Transport	170.96	177.58	179.33	180.74	181.34	124.34	71.25	35.74	1.38	0.04
Agriculture	61.86	64.66	64.08	63.55	62.38	62.97	65.81	65.46	63.57	61.49
Industry	172.65	174.94	175.57	176.16	177.44	165.37	121.66	85.06	72.96	72.06
Energy supply	304.42	287.79	279.93	271.71	262.74	115.63	-60.76	-221.73	-288.43	-318.15
Waste and Others	13.18	13.18	13.27	13.36	13.62	14.06	14.50	14.94	15.38	15.82
Total	850.76	846.74	830.05	813.21	777.46	533.89	257.95	7.90	-123.81	-181.20

5.1.3 Comparison GG2 – Renewables all over Germany

Figure 6 presents the GHG emissions of GG2 in the further optimized modeling run. Emissions already decrease 2020, following a continues downward trend. This decline intensifies in 2025 but slowly decreases in 2035 and 2040. The *Land-Use* sector increases continuously form 2020, reaching its peak in 2050. By 2050 an emission reduction of 100.12 % occurred.

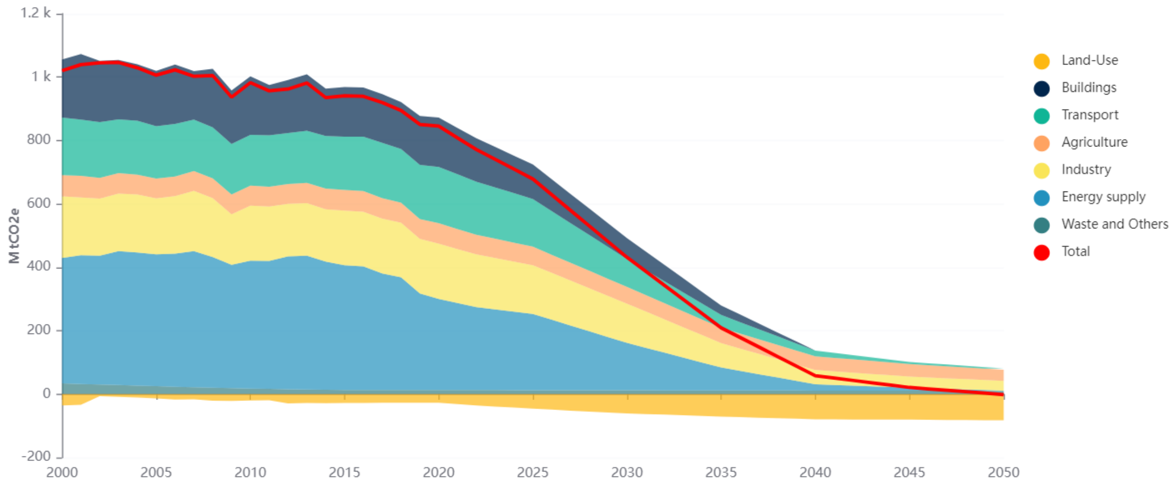

Figure 6. GHG emissions in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others for scenario GG2 in the optimized setting. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

Table 10 depicts the sectoral emissions pathway. The first phase out occurred in *Building* sector by 2040. Apart from the *Building* sector, only the *Transport* and *Energy supply* sectors drop below the 10 Mt CO_2eq in 2045. Although total climate neutrality is reached by 2050, this outcome is mainly due to the negative emissions from the *Land-Use* sector.

Table 10. Total and sectoral GHG emissions in Mt CO_2eq from 2019 to 2050 of GG2 for Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others in its optimized setting.

	2019	**2020**	**2021**	**2022**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Land-Use	-26.93	-27.22	-31.46	-35.34	-45.94	-60.58	-70.52	-79.30	-80.42	-82.50
Buildings	154.62	155.80	146.26	136.87	108.94	66.27	29.89	0.20	0.09	0.01
Transport	170.96	177.58	172.57	167.44	150.34	87.43	40.73	17.53	6.42	3.87
Agriculture	61.86	64.66	63.36	62.09	58.47	52.92	48.11	43.69	39.42	35.41
Industry	172.65	174.18	170.13	166.08	153.78	123.79	77.12	44.62	34.96	30.87
Energy supply	304.42	287.28	274.51	261.72	240.39	149.45	72.09	20.03	9.69	0.55
Waste and Others	13.18	13.18	13.10	13.01	12.74	12.30	11.87	11.43	10.99	10.55
Total	850.76	845.45	808.46	771.87	678.73	431.57	209.29	58.19	21.16	-1.24

To achieve these values, a total of 24 levers were modified to reach -1.24 Mt CO_2eq in 2050. For more info refer to Appendix Chapter 8.9. The following Table 11 compares the 2050 GHG emissions of the former and the optimized setting. The most adjustment happened in the lever groups *Industry* and *Transport*. However, severe change is visible in the *Land-Use* sector, where additional land was allocated to serve as natural sink. The modifications in the *Transport* sector had a negative effect on the emission balance. Although many levers were altered in *Industry*, the overall impact is low. The modifications in *Agriculture* and *Energy supply* were relatively small, causing a corresponding limited impact on both sectoral and total emissions.

Table 11. Sectoral and total GHG emissions comparison (Mt CO_2eq) in 2050 for GG2. Former Setting, Optimized Setting and respective Difference. Values in red picture a comparatively detrimental effect on the emissions.

	Land-Use	**Buildings**	**Transport**	**Agriculture**	**Industry**	**Energy supply**	**Waste and Others**	**Total**
former setting	-38.92	0.01	0.02	38.09	34.15	0.65	10.55	44.55
optimized setting	-82.50	0.01	3.87	35.41	30.87	0.55	10.55	-1.24
Difference	-43.58	0.00	3.84	-2.68	-3.28	-0.10	0.00	-45.79

5.1.4 Comparison S1 – Middle of the Road

The presented emission trajectory of Figure 7 follows a fast decline starting in 2020 already. This decline weakens in 2045. Negative emissions of the *Land-Use* fluctuate between 2020 and 2035, from where they continuously increase and peak in 2050 at -55.69 Mt CO_2eq as shown in Table 12. However, S1's emissions don't reach below zero Mt CO_2eq, with an emission reduction of 99.32 % by 2050.

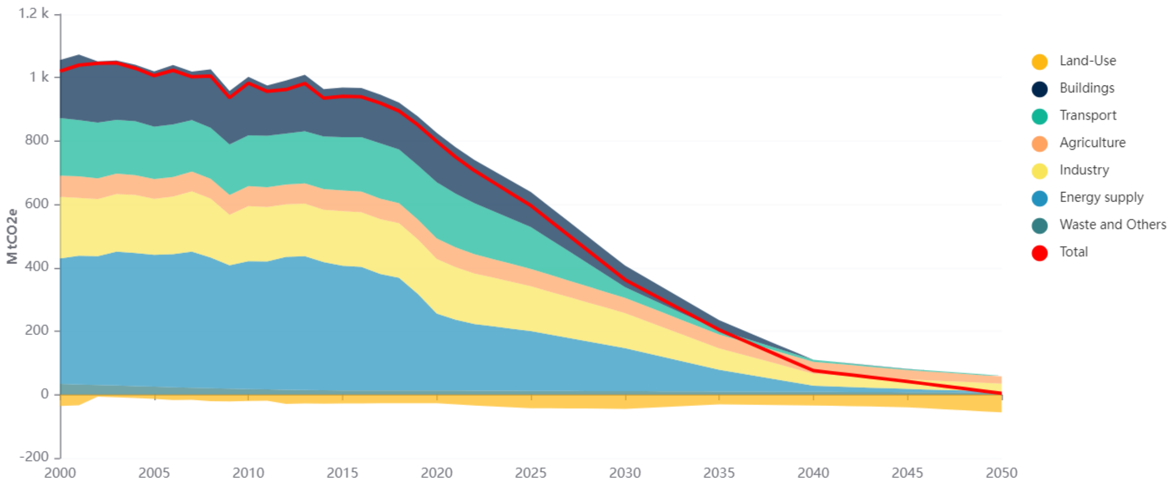

Figure 7. GHG emissions in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others for scenario S1 in the optimized setting. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

A sectoral phase-out only occurs in the *Building* sector in 2040 as depicted in Table 12. Moreover, the sectors *Transport* and *Waste* undercut the 10 Mt CO_2eq mark in 2035 and 2040. In 2050 the final emissions stand at 6.92 Mt CO_2eq, while the largest contributions are from *Agriculture* and *Industry* (46.99 Mt CO_2eq in total).

Table 12. Total and sectoral GHG emissions in Mt CO_2eq from 2019 to 2050 of S1 for Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others in its optimized setting.

	2019	2020	2021	2022	2025	2030	2035	2040	2045	2050
Land-Use	-26.93	-27.24	-30.70	-33.97	-42.58	-44.57	-30.62	-33.96	-39.65	-55.69
Buildings	154.62	155.80	146.34	137.04	110.06	68.36	31.74	0.22	0.10	0.01
Transport	170.96	177.58	169.00	160.72	132.19	33.64	13.30	6.22	3.13	2.49
Agriculture	61.86	64.70	62.58	60.52	54.78	47.96	43.79	37.06	29.51	22.55
Industry	172.65	172.44	165.98	159.69	141.63	110.54	67.51	38.42	30.27	25.44
Energy supply	304.42	242.41	224.95	213.01	195.52	145.96	77.84	23.04	15.08	5.54
Waste and Others	13.18	13.18	12.96	12.74	12.09	10.99	9.89	8.79	7.69	6.59
Total	850.76	798.87	751.11	709.75	603.68	372.88	213.45	79.80	46.14	6.92

A total of nine levers were altered to pursuit climate neutrality in 2050. For more info on the optimization refer to Chapter 8.9 (Appendix). The most difference occurred in *Industry* as, where most changes happened (see Table 13). However, changes in *Land-Use*, *Transport*, and *Agriculture* sectors had minor effect. The adjustments in *Energy supply* can be neglected.

Table 13. Sectoral and total GHG emissions comparison (Mt CO_2eq) in 2050 for S1. Former Setting, Optimized Setting and respective Difference. Values in red picture a comparatively detrimental effect on the emissions.

	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
former setting	-53.47	0.01	4.18	22.89	54.98	4.60	6.59	39.78
optimized setting	-55.69	0.01	2.49	22.55	25.44	5.54	6.59	6.92
Difference	-2.22	0.00	-1.69	-0.34	-29.54	0.94	0.00	-32.86

5.1.5 Comparison S2 – Inland transformation

The following Figure 8 illustrates the decarbonization trajectory of sufficiency scenario S2. Its emission reduction offsets in 2020 but decreases slightly in 2040. Overall, the negative emissions of the *Land-Use* sector remain fairly stable with a slight dip in 2035, before they peak in 2050 at -68.11 Mt CO_2eq. Although climate neutrality is visible, 6.2 Mt CO_2eq remain in 2050 (see Table 14). Yet, the emission reduction by 2050 stands at 99.37 %.

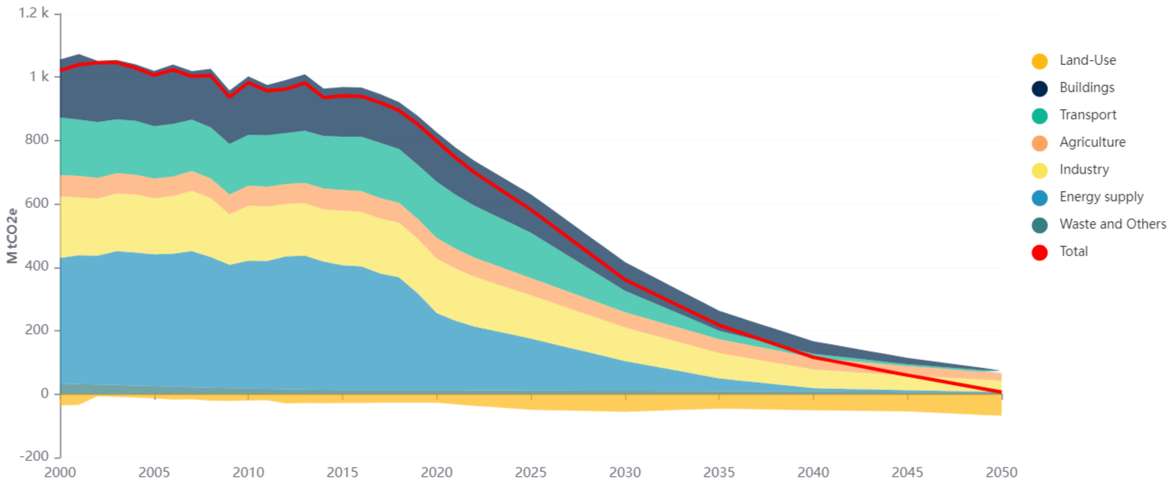

Figure 8. GHG emissions in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others for scenario S2 in the optimized setting. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

In total, three levers were altered to decrease the emissions further. For more info on the optimization process refer to Chapter 8.9 of the Appendix. However, it was not possible to achieve net-zero in 2050. Moreover, no sectoral phase-out happens, as no sector decreases to < 0 Mt CO_2eq by 2050. However, four sectors reach emissions < 10 Mt CO_2eq: *Waste* in 2035, followed by *Transport* and *Energy supply* in 2040, and finally *Buildings* in 2050. The main contributors to the 2050 GHG emissions are *Industry* and *Agriculture*.

Table 14. Total and sectoral GHG emissions in Mt CO_2eq from 2019 to 2050 of S2 for Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others in its optimized setting.

	2019	2020	2021	2022	2025	2030	2035	2040	2045	2050
Land-Use	-26.93	-27.24	-32.16	-36.80	-48.98	-55.64	-45.49	-50.85	-54.59	-68.11

Buildings	154.62	155.80	148.65	141.65	121.38	90.11	62.85	39.63	19.99	3.54
Transport	170.96	177.58	170.50	163.58	143.16	68.08	26.70	12.28	6.01	4.73
Agriculture	61.86	64.70	62.53	60.43	54.64	47.87	43.77	37.25	29.97	23.26
Industry	172.65	172.24	164.56	157.14	136.35	105.93	79.76	59.11	46.06	35.31
Energy supply	304.42	242.39	218.82	200.75	163.28	93.69	40.02	10.11	4.83	1.12
Waste and Others	13.18	13.18	12.96	12.74	12.09	10.99	9.89	8.79	7.69	6.59
Total	850.76	798.65	745.87	699.50	581.92	361.02	217.50	116.33	59.96	6.44

The changed levers mainly affected the *Land-Use* sector. Effects on the *Agriculture* and *Industry* sectors were minor (see Table 15).

Table 15. Sectoral and total GHG emissions comparison (Mt CO_2eq) in 2050 for S2. Former Setting, Optimized Setting and respective Difference.

	Land-Use	**Buildings**	**Transport**	**Agriculture**	**Industry**	**Energy supply**	**Waste and Others**	**Total**
former setting	-59.08	3.54	4.73	23.85	36.61	1.12	6.59	17.37
optimized setting	-68.11	3.54	4.73	23.26	35.31	1.12	6.59	6.44
Difference	-9.04	0.00	0.00	-0.59	-1.30	0.00	0.00	-10.93

5.1.6 Comparison S3 – Urbanized conviviality

As Figure 9 illustrates, total emissions decrease from 2020 onward to almost reach (almost) net-zero in 2050 (0.66 Mt CO_2eq, see Table 16). Generally, the negative emissions of the *Land-Use* sector increase from 2020, with a small recess in 2025. Between 2000 and 2050 an emission reduction of 99.94 % happened.

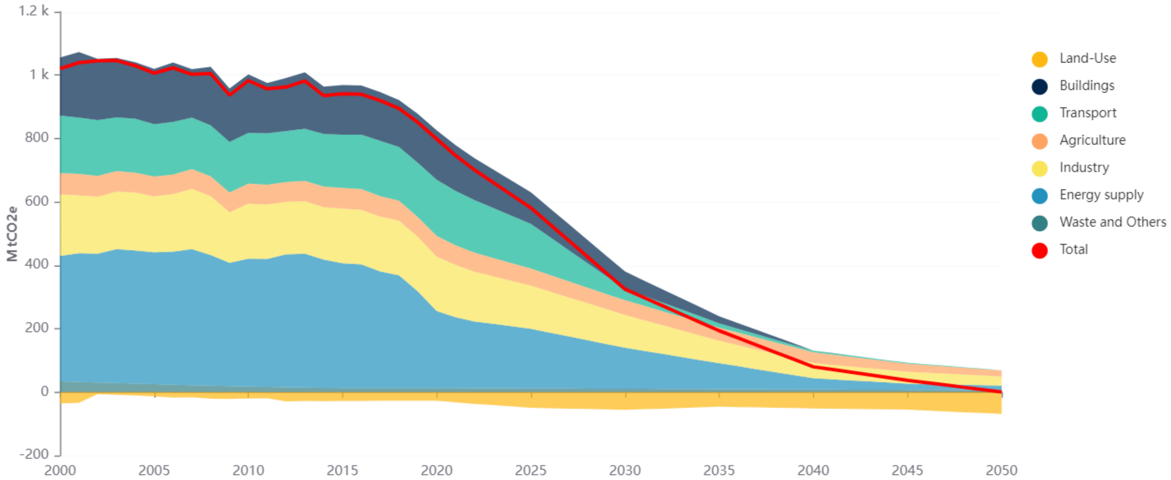

Figure 9. GHG emissions in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others for scenario S3 in the optimized setting. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

To decrease S3's emissions even more, two levers changed to optimize the GHG emissions for climate neutrality in 2050. Both levers referred to a higher ambition level for electrification in the transport and industry sectors (refer to Chapter 8.9). The first sectoral phase-out occurs in 2040 in the *Buildings* sector. The decarbonization trajectory in the *Industry* is relatively constant from 2020 onwards, yet it contributes most to the final GHG in 2050.

Table 16. Total and sectoral GHG emissions in Mt CO_2eq from 2019 to 2050 of S3 for Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others in its optimized setting.

	2019	**2020**	**2021**	**2022**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Land-Use	-26.93	-27.24	-32.19	-36.84	-49.09	-55.86	-45.81	-51.29	-55.08	-68.66
Buildings	154.62	155.80	143.76	132.18	99.97	55.01	22.24	0.13	0.05	0.01
Transport	170.96	177.58	171.60	165.79	140.60	35.57	13.77	5.23	2.19	1.15
Agriculture	61.86	64.70	62.37	60.11	53.88	46.34	41.27	33.90	25.98	18.74
Industry	172.65	172.24	164.54	157.09	136.09	103.74	70.90	48.24	37.36	28.92
Energy supply	304.42	242.39	223.80	210.31	187.92	129.01	81.54	34.98	19.36	13.91
Waste and Others	13.18	13.18	12.96	12.74	12.09	10.99	9.89	8.79	7.69	6.59
Total	850.76	798.65	746.84	701.37	581.45	324.80	193.79	79.99	37.55	0.66

The total emissions of the former and the optimized setting differ only by 7.86 Mt CO_2eq. As Table 17 depicts, small alterations happened in the sectors *Industry* and *Energy supply*.

Table 17. Sectoral and total GHG emissions comparison (Mt CO_2eq) in 2050 for S3. Former Setting, Optimized Setting and respective Difference.

	Land-Use	**Buildings**	**Transport**	**Agriculture**	**Industry**	**Energy supply**	**Waste and Others**	**Total**
former setting	-68.66	0.01	1.15	18.74	36.54	14.16	6.59	8.52
optimized setting	-68.66	0.01	1.15	18.74	28.92	13.91	6.59	0.66
Difference	0.00	0.00	0.00	0.00	-7.61	-0.25	0.00	-7.86

5.1.7 Comparison S4 – Individualized & degrowth society

Since the emissions in the first modeling setting round were relatively high, many adjustments were required to decrease the GHG emissions of S4 (in total 28 levers, refer to Chapter 8.9 of the Appendix). However, it was not possible to alter the levers too much, in order to not deviate too far from the actual S4 Descriptors. Consequently, climate neutrality was barely reached as visible in Figure 10. Total emissions stand at 37.06 Mt CO_2eq in 2050 (see Table 18). The total emissions reduce from 2020 onwards and pursuit a relatively constant trend. The negative emissions of the *Land-Use* sector stand at -57.98 Mt CO2eq in 2050 following some fluctuations in 2025. The emission reduction from 2000 stands at 96.37 %.

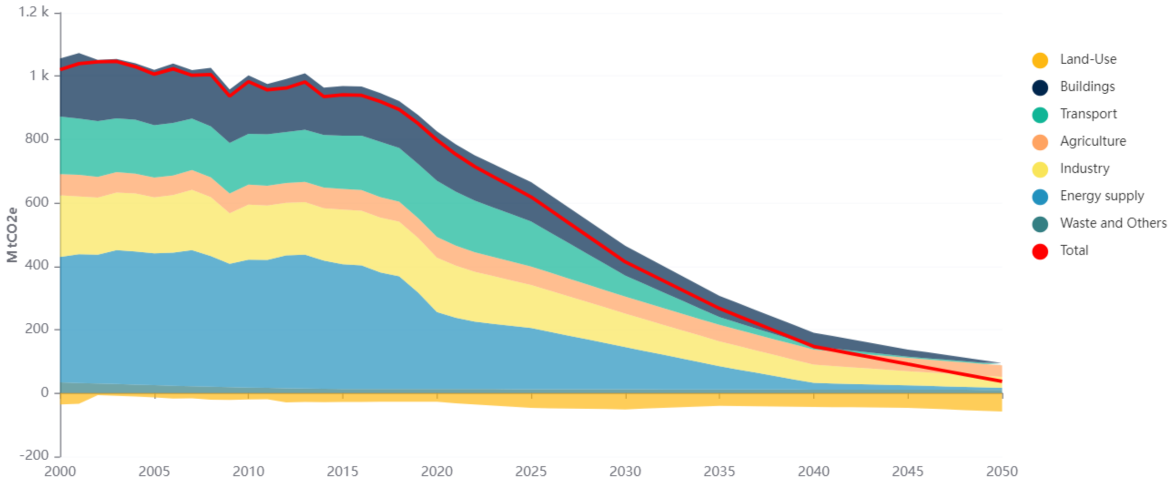

Figure 10. GHG emissions in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others for scenario S4 in the optimized setting. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

Due to the high total emissions in 2050, sectoral emissions are expected to be higher, as depicted in Table 18. Overall, no sectoral phase-out happened. In 2050 only three sectors, *Energy supply*, *Buildings* and *Transport* undercut 10 Mt CO_2eq. Within the 2050 emissions, the *Agriculture* and *Industry* sectors account for the majority of residuals (71 Mt CO_2eq in total).

Table 18. Total and sectoral GHG emissions in Mt CO_2eq from 2019 to 2050 of S4 for Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others in its optimized setting.

	2019	2020	2021	2022	2025	2030	2035	2040	2045	2050
Land-Use	-26.93	-27.24	-31.70	-35.85	-46.56	-51.03	-39.67	-43.53	-46.02	-57.98
Buildings	154.62	155.80	149.31	142.89	124.01	93.99	66.91	43.10	22.32	4.41
Transport	170.96	177.58	170.46	163.47	142.19	66.27	24.55	10.34	4.16	2.86
Agriculture	61.86	64.70	63.19	61.72	57.74	53.68	52.04	47.59	41.96	36.54
Industry	172.65	172.24	164.56	157.13	136.30	105.55	78.31	57.48	44.83	34.47
Energy supply	304.42	242.39	224.73	212.54	192.61	133.28	73.13	20.90	13.50	6.22
Waste and Others	13.18	13.18	13.10	13.01	12.74	12.30	11.87	11.43	10.99	10.55
Total	850.76	798.65	753.64	714.92	619.04	414.04	267.15	147.30	91.73	37.06

Many adjustments were required in the optimized modeling of S4. Consequently, the difference in the total GHG emissions is higher (see Table 19). Most modifications happened in the *Industry* lever group (20 in total) and the difference in *Industry* is relatively high (51.97 Mt CO_2eq). However, the changes in the lever group *Buildings* had the most influence, although only two levers were altered (62.11 Mt CO_2eq). Of the remaining sectors, *Energy supply* stands out, with a difference of 18 Mt CO_2eq.

Table 19. Sectoral and total GHG emissions comparison (Mt CO2eq) in 2050 for S4. Former Setting, Optimized Setting and respective Difference.

	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
former setting	-57.98	66.52	8.74	36.54	86.43	24.36	10.55	175.15
optimized setting	-57.98	4.41	2.86	36.54	34.47	6.22	10.55	37.06
Difference	0.00	-62.11	-5.88	0.00	-51.97	-18.14	0.00	-138.10

5.2 Final energy demand

The following Chapters explore the final energy demand (FED) of the six modeled scenarios. Since the modeling optimization rather focused on the emission reduction than of the FED, the second modeling run is focused. The data of the first modeling run is compiled in Chapter 8.8.2. The following Figures start in 2019, when first variations of the scenarios occurred. However, since the historic data was not matched to actual sectoral data, the focus lays on data from 2025 onwards. This also applies for the scenario specific Chapters.

Figure 11 illustrates the development of FED of all scenarios. The scenarios GG1 and GG2 have the highest FED in 2025. They decrease significantly less until 2050. Further, the FED is initially lower in 2025 and decrease more rapidly, compared to the GG scenarios. Scenario S4 has the lowest FED in 2050, while the FED of S2 and S3 fist decline until 2040 and 2045, it slightly increases afterwards.

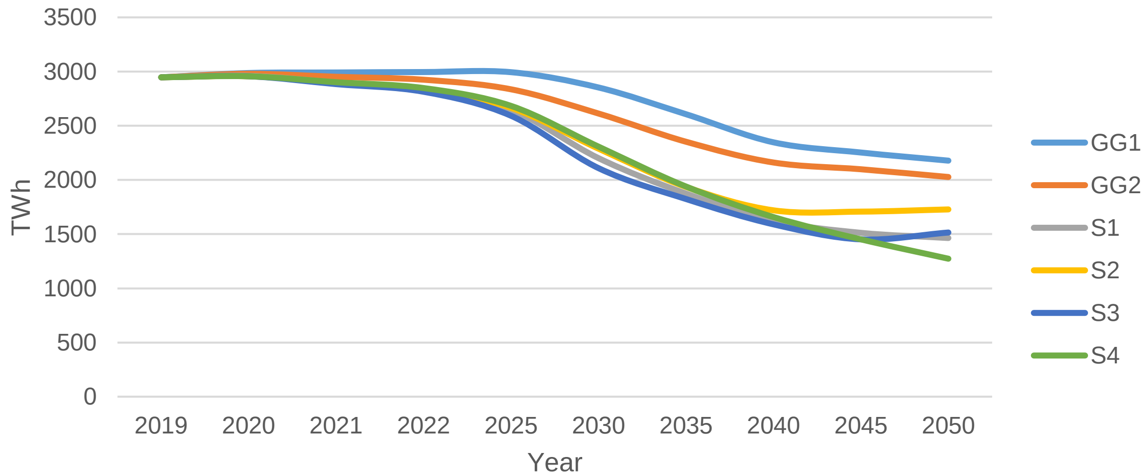

Figure 11. Final energy demand in TWh of all scenarios modeled in its optimized setting between 2019 and 2050.

The following Table compares the FED of the second modeling run for 2050. GG1 uses the least energy for electricity production, while S3 relies the heavily on it. In the *Industry* and

Transport sector (incl. *bunkers*) both GG scenarios have a relatively high FED, compared to the sufficiency scenarios. However, in the *Building* sector the values diverge across all scenarios but the GG1 FED is effectively higher. Noticeable are the *Exports* values of scenarios GG1 and S4 which are zero, while the remaining scenario's FED is higher.

Table 20. Comparison of all scenarios sectoral and total FED in TWh in 2050 for all EnSu scenarios in the optimized modeling run.

Scenario	Energy use for electricity production	Transport	Industry	Buildings	Agriculture	Transport (bunkers)	Exports	Total
GG1	41.17	556.12	710.93	587.58	15.40	267.00	0	2178.20
GG2	105.19	361.42	633.47	494.46	11.72	227.74	193.12	2027.10
S1	145.04	213.61	439.25	424.86	13.00	154.13	74.21	1464.09
S2	77.70	264.46	381.40	388.15	13.29	163.73	439.23	1727.96
S3	169.65	203.84	341.43	422.26	13.29	137.96	226.34	1514.78
S4	82.31	237.80	361.13	422.12	12.38	157.53	0	1273.26

5.2.1 FED of Scenario GG1

According to the data shown in Figure 12, FED remains relatively stable between 2019 and 2025, but decreases slightly from until 2040, from where it stabilizes again. The FED reduction from 2025 to 2050 is relatively minor (-815.99 TWh). The sector with the largest share of energy demand is *Industry*, followed by *Building* and *Transport* (including *bunkers*). *Agriculture* and *Energy use for electricity production* account for the smallest share (56.57 TWh in total).

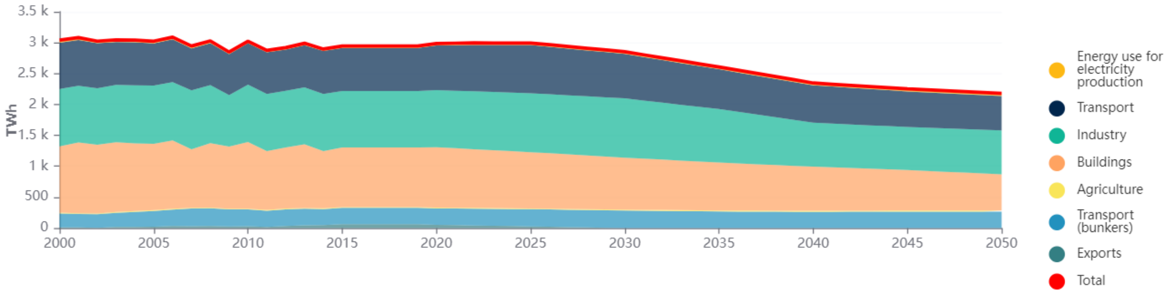

Figure 12. Final energy demand in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports for scenario GG1. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

5.2.2 FED of Scenario GG2

In GG2 the FED already declines from 2020. This trend continues until 2040, from where the rate decreases. The FED in 2050 stands at 2027 TWh. From 2030 onwards, there is an increasing share of FED allocated to *Exports*. In 2050, the largest share of FED is attributed to *Industry*, *Buildings*, *Transport* (including *bunkers*). Only a minor share of Energy is used for electricity production. *Agriculture* holds the smallest almost invisible share.

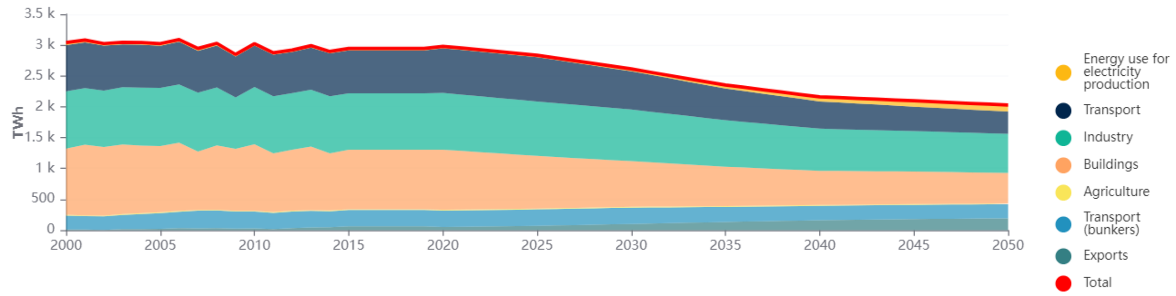

Figure 13. Final energy demand in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports for scenario GG2 in its optimized setting. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

When comparing the two modeling runs some notable observations ariseFigure 17. In the optimized setting, a deterioration occurred in *Agriculture* and *Energy use for electricity production*. Furthermore, the optimization process resulted in only minor reductions in the *Transport* and *Industry* sectors. The highest reduction occurred in the *Exports*, with a decrease of 19.97 TWh.

Table 21. Sectoral and total FED comparison (in TWh) in 2050 for GG2. Former Setting, Optimized Setting and respective Difference.

	Energy use for electricity production	**Transport**	**Industry**	**Buildings**	**Agriculture**	**Transport (bunkers)**	**Exports**	**Total**
former setting	87.74	364.44	633.58	494.46	10.36	227.74	213.08	2031.39
optimized setting	105.19	361.42	633.47	494.46	11.72	227.74	193.12	2027.10
Difference	17.45	-3.02	-0.11	0.00	1.36	0.00	-19.97	-4.28

5.2.3 FED of Scenario S1

Scenario S1 depicts a significant decrease in FED, starting from 2020 (see Figure 14). This downward trend continues until 2040, where it stabilizes. In 2050, total FED stands at 1464.09 TWh. The sectors with the highest shares in 2050 are *Buildings* and *Industry*, followed by *Transport* and its resp. *bunkers*. The share *Transport* and *Transport bunkers* remains fairly constant from 2040 onwards, while the share of *Energy use for electricity production* increases. *Agriculture* and *Exports* hold the smallest shares among the sectors.

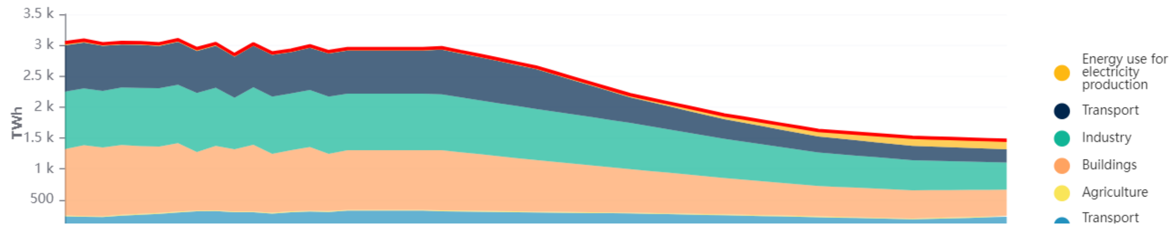

Figure 14. Final energy demand in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports for scenario S1 in its optimized setting. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

The comparison of Table 22Table 22 results reveal a reduction of FED in the most sectors. Hence, during optimization, a deterioration in the *Transport* sector and *Energy use for electricity production* occured. The optimization efforts resulted in a significant reduction of 64.17 TWh in the *Industry* sector and a substantial decrease of 71.93 TWh in the *Export*.

Table 22. Sectoral and total FED comparison (in TWh) in 2050 for S1. Former Setting, Optimized Setting and respective Difference.

	Energy use for electricity production	**Transport**	**Industry**	**Buildings**	**Agriculture**	**Transport (bunkers)**	**Exports**	**Total**
former setting	113.62	210.85	503.43	424.86	13.19	156.66	146.14	1568.74
optimized setting	145.04	213.61	439.25	424.86	13.00	154.13	74.21	1464.09
Difference	31.42	2.76	-64.17	0.00	-0.19	-2.53	-71.93	-104.65

5.2.4 FED of Scenario S2

In Scenario S2 a reduction of FED appears from 2020 onwards. This trend continues until 2040 from where FED stabilizes and finally reaches 1727.96 TWh by 2050. Notably, there is a significant share attributed to *Exports* from 2040 onwards and actually accounts for a large share of FED in 2050. In the remaining sectoral contributing in 2050 are *Industry* and *Building,* followed by *Transport* (including *bunkers*). The share of *Energy use for electricity production* and *Agriculture* are both below 100 TWh.

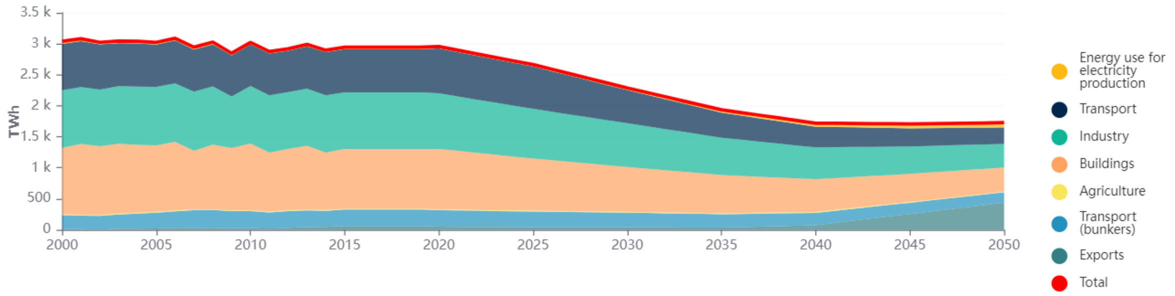

Figure 15. Final energy demand in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports for scenario S2 in its optimized setting. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

Table 23 reveals only minimal changes from the optimization process. Either no changes or minor decreases across the sectors occurred. *Agriculture* had the most decrease, of -1.31 TWh. Overall, the difference between the two scenario settings is exceptionally small. However, the FED increased by 0.33 TWh by the optimization process.

Table 23. Sectoral and total FED comparison (in TWh) in 2050 for S2. Former Setting, Optimized Setting and respective Difference.

	Energy use for electricity production	**Transport**	**Industry**	**Buildings**	**Agriculture**	**Transport (bunkers)**	**Exports**	**Total**

former setting	77.70	264.46	380.62	388.15	14.61	163.73	438.36	1727.63
optimized setting	77.70	264.46	381.40	388.15	13.29	163.73	439.23	1727.96
Difference	0.00	0.00	0.78	0.00	-1.31	0.00	0.87	0.33

5.2.5 FED of Scenario S3

Figure 16 illustrates the FED reduction for scenario S3, which starts in 2020. It decreases consistently until 2045, but again increases afterwards. This development is primarily driven by the *Export*. The sectors, which decrease the most are *Industry* and *Transport*. From 2030 onwards, the share of *Energy use for electricity production* demonstrates an upward trend, reaching 169.65 TWh by 2050. The final total energy demand stands at 1514 TWh.

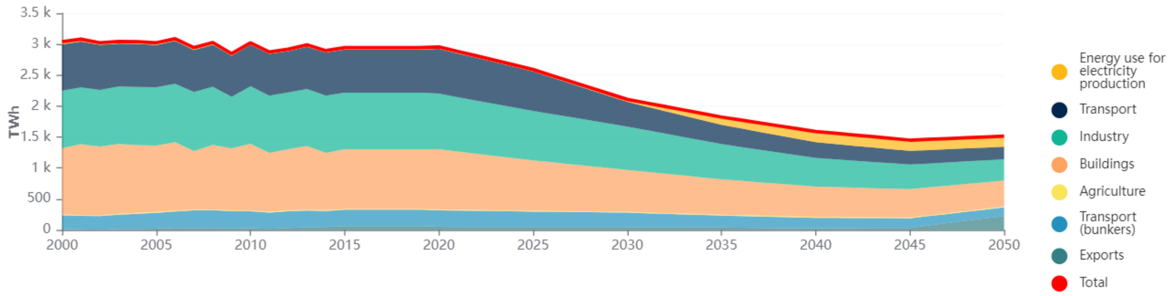

Figure 16. Final energy demand in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports for scenario S3 in its optimized setting. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

Table 24 presents the primarily reductive effects on FED by the optimization process. The highest reduction occurs in the *Exports*, totaling at a decrease of 47.74 TWh. The remaining sectors, experienced either no or only minor changes of less than 1 TWh, with *Energy use for electricity production* being the exception.

Table 24. Sectoral and total FED comparison (in TWh) in 2050 for S3. Former Setting, Optimized Setting and respective Difference.

	Energy use for electricity production	**Transport**	**Industry**	**Buildings**	**Agriculture**	**Transport (bunkers)**	**Exports**	**Total**
former setting	171.49	203.85	342.12	422.26	13.29	138.78	274.08	1565.88
optimized setting	169.65	203.84	341.43	422.26	13.29	137.96	226.34	1514.78
Difference	-1.84	0.01	-0.70	0.00	0.00	-0.82	-47.74	-51.11

5.2.6 FED of Scenario S4

In Figure 17 the continuous FED reduction of S4 is illustrated. From 2020 all sectors experience a consistent decline until 2050 of 1683.11 TWh. Notably, the share of *Transport (bunkers)* remains relatively constant throughout the years. In 2050, the largest shares of FED are attributed to *Buildings* and *Industry*. *Energy use for electricity production* increases to a minor extend from 2035 onwards.

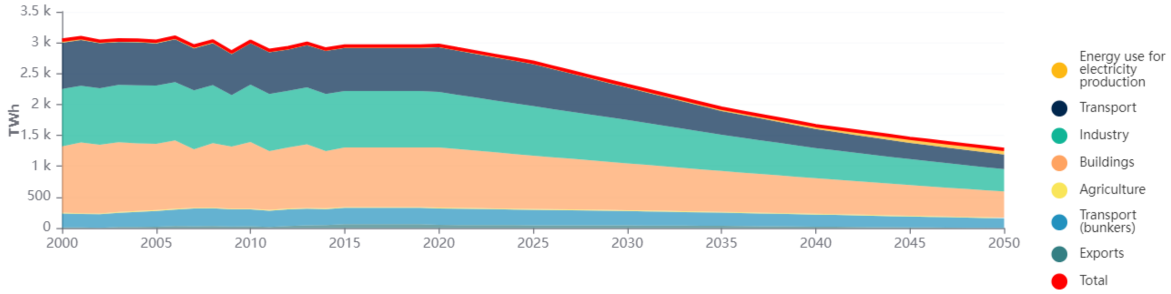

Figure 17. Final energy demand in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports for scenario S4 in its optimized setting. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

Table 25 illustrates a huge difference in the total FED. However, the optimization efforts yielded contrasting results across the sectors. While there were significant reductions in *Energy use for electricity production*, *Industry* and *Buildings*, in the transport sector (both *Transport* and *Transport bunkers*) an increase in FED occurred.

Table 25. Sectoral and total FED comparison (in TWh) in 2050 for S4. Former Setting, Optimized Setting and respective Difference.

	Energy use for electricity production	**Transport**	**Industry**	**Buildings**	**Agriculture**	**Transport (bunkers)**	**Exports**	**Total**
former setting	127.33	231.45	603.65	588.25	12.38	153.14	0.00	1716.21
optimized setting	82.31	237.80	361.13	422.12	12.38	157.53	0.00	1273.26
Difference	-45.03	6.35	-242.52	-166.13	0.00	4.39	0.00	-442.94

5.3 CO_2 budget

The following Chapter examines the scenario's 1.5°C compatibility. While, the second modeling run is focused, the first is provided for completeness in Chapter 8.8.3.

As explained in Chapter 4.5.2, the modeled GHG emissions (in CO_2eq) of the six scenarios were calibrated to match Germany's actual historical CO_2 emissions from 2022. Further, the portion of pure CO_2 emissions was excluded proportionately from the total GHG emission. Since the CO_2 share was excluded respectively from the CO_2eq, the development in Figure 18 is comparable to the emission paths of the scenarios total GHG emissions (in CO_2eq) shown in Figure 4 of Chapter 5.1.1.

First, the dashed line indicates why it was necessary to calibrate the scenarios to the real values for 2020-2022 to avoid misinterpretations. The CO_2 emission of GG1 experiences the sharpest decline, while the remaining scenarios follow a slower emission reduction. The emissions pathways of all scenarios are relatively similar. Only GG1 stands out with its high negative emissions from 2040 onwards.

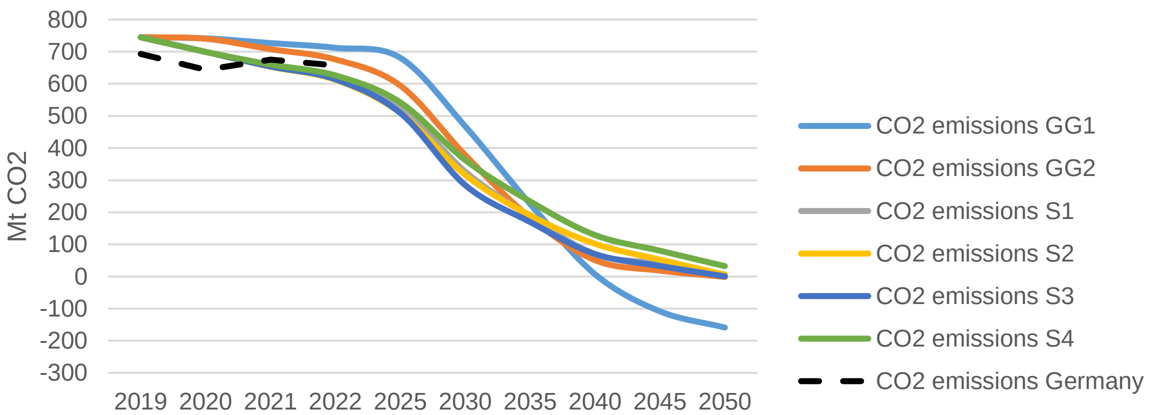

Figure 18. CO_2 emissions of the 6 modeled scenarios from 2019 to 2050 in Mt CO_2 in the optimized setting i.e., for climate neutrality and the historical real CO_2 emissions for Germany in 2019 to 2022.

Table 26 presents the total CO_2 emissions between 2022 and 2050 for each scenario in the second modeling run. As the column *Difference to remaining CO_2 budget* indicates, all scenarios stay below 3.1 Gt CO_2. Scenario S3 has the most difference to the 3.1 Gt CO_2 budget, while Scenario S4 is closest to this mark. This implies a 50 % chance of 1.5°C compatibility to the German CO_2 budget calculated by SRU (2022) in this modeling run for all scenarios. Yet, the margin to the CO_2 budget is minor, with only 1-1.3 Gt CO_2 left.

Table 26. Comparison of the cumulated CO_2 emissions in the period of 2022 to 2050 of each of the 6 scenarios in the optimized setting. Further the difference to the available CO_2 budget of 3.1 Gt CO_2 is shown. The historical actual values for Germany in 2022 are used in the cumulated CO_2 emissions.

	modeled for climate neutrality	
Scenario	cumulated CO_2 emissions (Gt) 2022-2050	difference to remaining CO_2 budget (Gt) (SRU, 2022)
GG1	1.771	1.329
GG2	1.881	1.219
S1	1.815	1.285
S2	1.833	1.267
S3	1.724	1.376
S4	2.037	1.063

5.4 Comparative Analysis

5.4.1 Comparison to the 2030 KSG objective

The passage presents an evaluation of two GG scenarios and four sufficiency scenarios in comparison to the German government's emission reduction targets for 2030. to evaluate their plausibility. The corresponding Tables are provided in Chapter 8.10. In scenario GG1, the projected emissions for 2030 fall short by 119 $MtCO_2eq$, indicating a lack of ambition compared to the German target. GG1 achieves only a 45 % reduction compared to 2000 levels, falling far below the desired goal of 65 % reduction, especially in the *Industry* and *Transport* sectors. However, in the long run, GG1 shows promise, surpassing the 2045 target by 11 %. In contrast, scenario GG2 faces notable challenges, with only the *Land-Use* and *Agriculture* sectors meeting the 2030 emission targets. Overall, GG2 achieves a 52 % reduction, which is considered less ambitious than the government's objectives. The long-term emission reduction for GG2, similar to GG1, exceeds the German target for 2040.

Moving on to the four sufficiency scenarios, scenario S1 demonstrates a slightly lower ambition compared to the German target, achieving a total reduction of 63 %. The most significant difference is observed in the *Transport* sector, while other sectors show varying levels of ambition compared to the government's objectives. Scenario S2 presents a more ambitious trajectory than S1 but still falls short of the 2030 objective by one percent point, with the *Land-Use* and *Building* sectors exhibiting the highest disparities. In contrast, scenario S3 stands out as the most ambitious scenario, surpassing the 2030 objective by 89.72 $MtCO_2eq$, achieving a total reduction of 68 %. The significant divergence is particularly apparent in the *Transport* and Energy production sectors. However, scenario S4 is considered an outlier, with an emission reduction of only 59 %, and emissions from *Energy production*, *Building*, and *Waste* sectors higher than the 2030 government objective.

The analysis highlights potential trade-offs and challenges associated with emission reduction across various sectors in Germany. Overall, the sufficiency scenarios do not fully achieve the necessary reduction in emissions by 2030, but they show promise for exceeding the 88 % emission reduction goal by 2040, except for scenario S4.

In conclusion, the study emphasizes the importance of assessing the plausibility and broader societal and environmental implications of the various scenarios. The long-term perspective is vital in determining the ultimate effectiveness of the strategies in meeting Germany's emission reduction targets.

5.4.2 Comparison to German Climate Neutrality studies

In the following, the modeled scenario results of 2050 are compared to an selection of climate neutrality studies compiled by Wiese et al. (2021). Figure 19 compares the installed Wind and Solar capacity to the scenario specific FED, for the year when climate neutrality is reached. Studies that assume a rapid energy demand reduction, like the most studies by the Umweltbundesamt, have a moderate RE expansion. Scenario S4 aligns with the Umweltbundesamt scenarios, with a slightly higher installed capacity. However, the other sufficiency scenarios contradict this assumption. For instance, S2 presents the most installed capacity with an increased FED. Scenarios S1 and S3 are more in the midfield with regards to the FED, but have an installed capacity that is at the upper end of the range. While scenario GG2 is in a cohort with Fraunhofer ISE scenarios, GG1 presents an outlier as its FED is the second highest, while the installed capacity is the lowest. An extensive and more holistic evaluation on the scenarios results happens in Chapter 6.1.

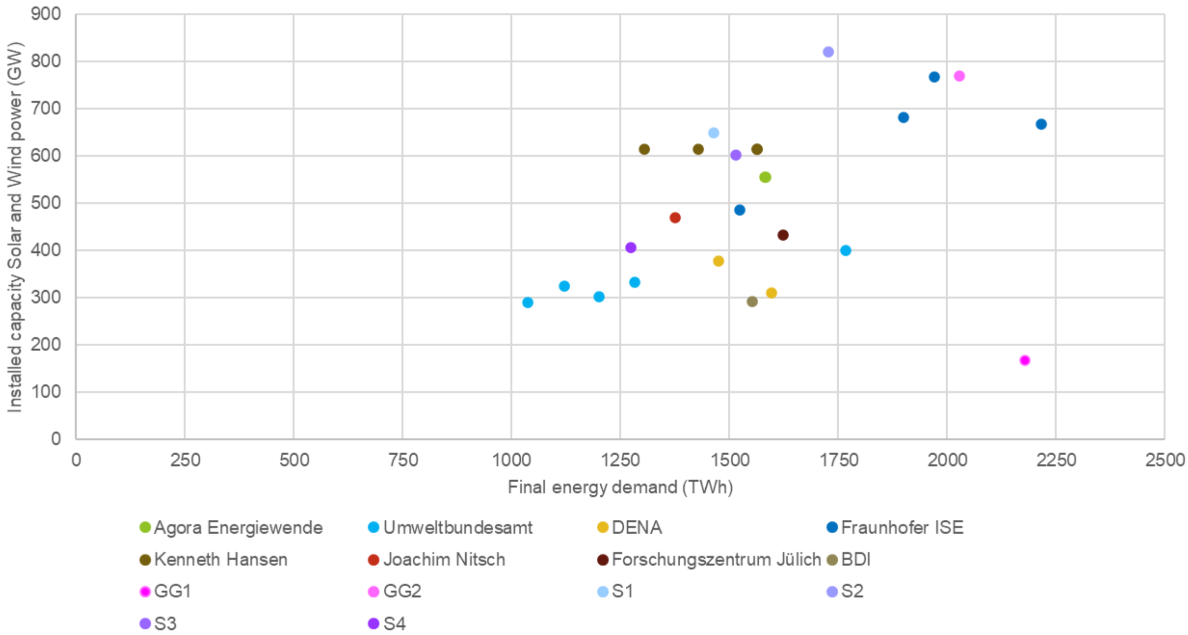

Figure 19. Comparison of installed capacity of RE (GW) and final energy demand (TWh). The dots mark a scenario by the respective institutions when climate neutrality is reached. The data on these climate neutrality studies is provided by Wiese et al. (2021).

Figure 20 compares the utilization of biomass, synfuels, fossil fuels and electricity imports with the FED of each climate neutral scenario. The low energy demand scenarios, such as those presented by Umweltbundesamt and scenarios S1, S2, S3 and S4, reveal that a decrease in FED results in reduced dependency on the analyzed energy carriers and substantial electricity imports. GG2 confirms this assumption, as it shows a slightly higher dependency on the aforementioned factors compared to sufficiency scenarios, but with a significantly higher FED.

Additionally, GG1 relies even more on these factors, with a notably increased FED. These results are discussed further in Chapter 6.3.

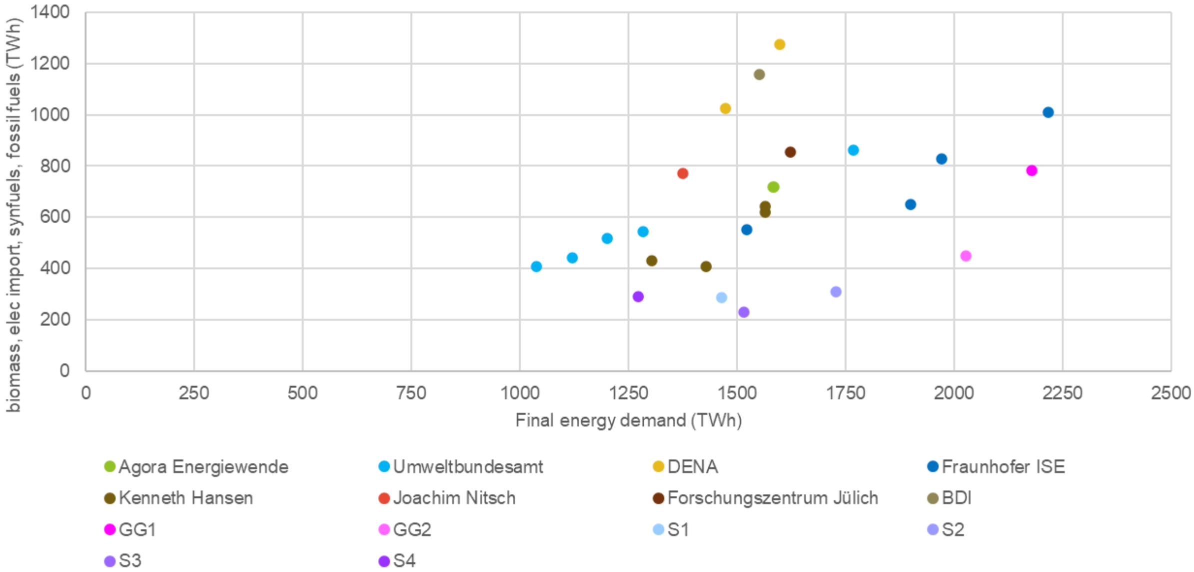

Figure 20. Comparison of the biomass, electricity import, synfuels, fossil fuels demand (TWh) and final energy demand (TWh). The dots mark a scenario by the respective institutions when climate neutrality is reached. The data on these climate neutrality studies is provided by Wiese et al. (2021).

5.5 Sensitivity analysis

The next Chapters provide the local and modified global sensitivity analysis of GHG and FED.

5.5.1 Greenhouse gas emissions

The following tornado chart provides insights on the specific influences, which the five selected input parameters have on results. While the yellow bar represents the reference value, the green bar represents the modeled output results. It is obvious, that *Transport_Technology_e-fuel switch_road*, has a rather negative impact on the GHG emissions exceeding the reference value by 875 Mt CO_2eq. On the other hand, *Energy-prod_RES_Solar-PV* has a slight positive effect on the GHG emissions, lowering them by 79 Mt CO_2eq. The remaining three input parameters show a deviation from the reference value of around 41.6 Mt CO_2eq. To determine their impact on the modeling output is challenging.

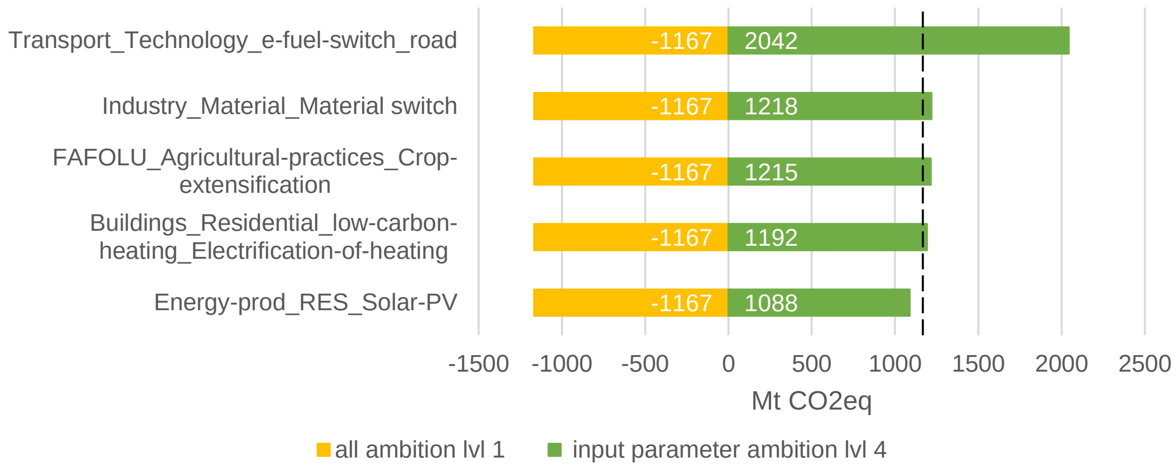

Figure 21. Local sensitivity analysis of GHG emissions in 2050 (Mt CO_2eq). The dashed line represents the baseline value for 'all ambition lvl 1' of ~1167 CO_2eq and is added to enhance comparability.

The global sensitivity analysis results are less conclusive compared to the local sensitivity analysis. The first parameter combination of *Crop extensification* and *Freed-up lands* allocated to *afforestation* exceeds the reference value by 24 Mt CO_2eq. Yet, in the local sensitivity analysis, *Crop extensification* has more impact on increasing emissions, compared to the mentioned lever combination of the FAFOLU sector. The remaining input parameters fall below the reference value of ~1167 Mt CO_2eq. The most significant emission reduction is attributed to the industrial *Material production* (-167 Mt CO_2eq), followed by industrial carbon capture (-78 Mt CO_2eq). Further, the *Transport_Technology evolution – Passenger* parameter and the

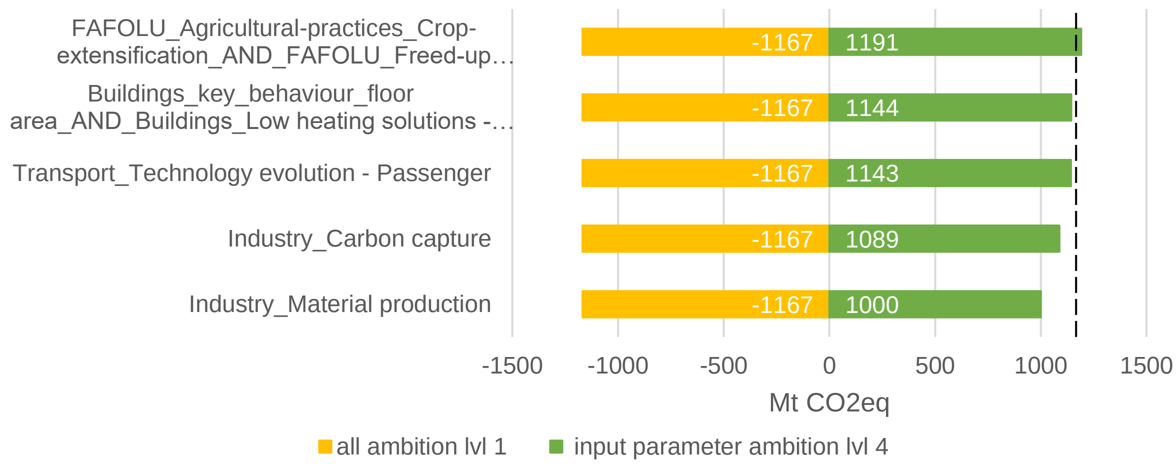

Figure 22. Modified global sensitivity analysis of GHG emissions in 2050 (MtCO_2eq). The dashed line represents the baseline value for 'all ambition lvl 1' of ~1167 CO_2eq and is added to enhance comparability.

Building lever combination of *floor area* and *low-carbon heating solutions* of the *Residential* sector deviate by only 23/24 Mt CO_2eq from the reference. However, the *Buildings* lever combination provides some modeling insights. While in the local sensitivity analysis, only the impact of *Electrification of heating* as a *low-carbon heating solutions* was examined, showing a slight negative impact on emissions, in the global analysis the *Buildings* lever combination decreased below the reference, indicating a positive emission impact.

5.5.2 Final energy demand

The analysis of local sensitivity for FED, as shown in Figure 23, illustrates that all input parameters have a positive impact on FED. Specially, they contribute to lowering the FED below the reference value (~5710 TWh). While the *Residential renovation rate* had the least lowering potential (-76 TWh), *passenger distance* in *Transport* has the most impact (-673 TWh). The input parameters industrial *energy efficiency*, *living space per person*, and *Residential space heating and cooling behavior* have small impacts in lowering the FED.

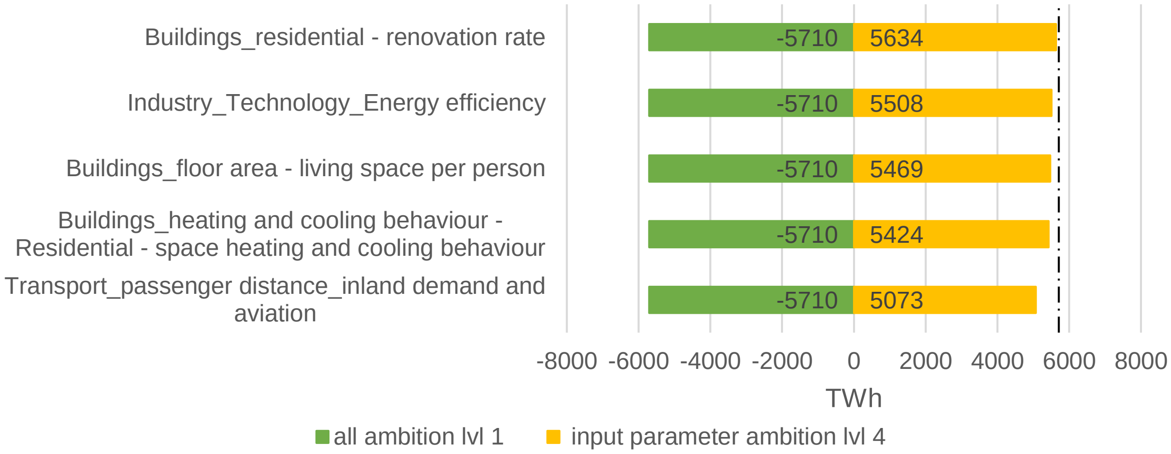

Figure 23. Local sensitivity analysis of final energy demand in 2050 (in TWh). The dashed line represents the baseline value for 'all ambition lvl 1' of ~5710 TWh and is added to enhance comparability.

The global sensitivity analysis reveals significant impacts, contrasting with the local sensitivity analysis. Specifically, the input parameter *Buildings_key behaviours* alone led to a remarkable reduction in FED of 1054 TWh. Furthermore, both the input parameters *Industry_Material production* and the *Transport* lever combination of *passenger distance* and *passenger transport technology evolution* exhibit comparable impact reductions. The lowering potential of the input parameter in the *Residential building envelope* is only slightly lower than the two previous parameters. Finally, an industrial technology switch has the least reductive potential in FED with deviating only -215 TWh from the reference value of 5710 TWh.

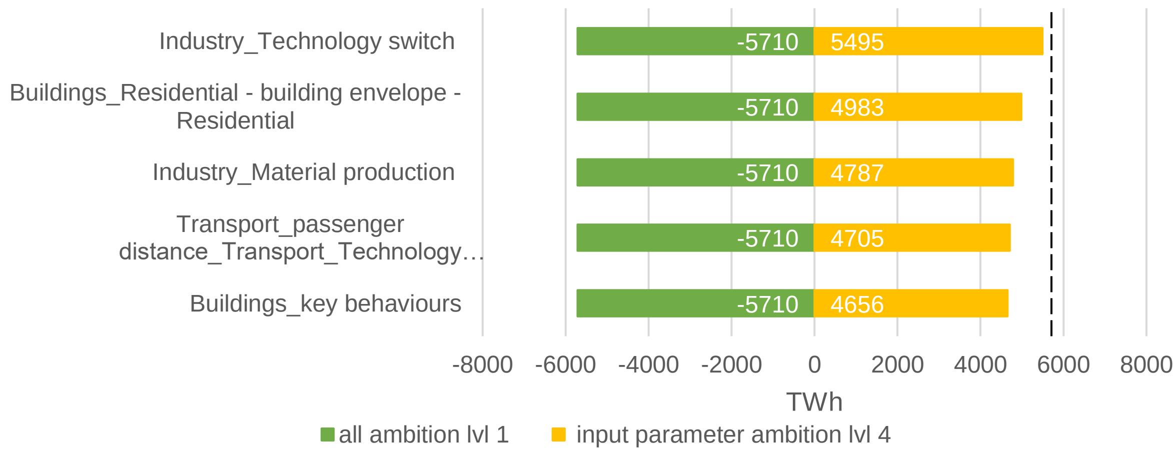

Figure 24. Modified global sensitivity analysis of final energy demand in 2050 (in TWh). The dashed line represents the baseline value for 'all ambition lvl 1' of ~5710 TWh and is added to enhance comparability.

6 Discussion

6.1 Scenarios Decarbonization Trajectory

The following Chapter presents the scenarios decarbonization trajectory, in order to answer the research question: *What are the possible decarbonization trajectories that Germany can follow by 2050 based on modeled scenarios?*

6.1.1 Green Growth Scenarios

Both scenarios GG1 and GG2 rely on greening growth. They differ in almost all Descriptors except for Descriptor *2a Green Growth* and *8b Fast* technology uptake. The following Chapters focus on the differences of both scenarios.

6.1.1.1 GG1 – Energy imports and fast shift

GG1 represents a technology-driven scenario with a continuous increase of sectoral energy service demand and a political focus on economic growth. Individualization and high living standards drive product consumption, diet and transportation patterns (see Descriptors *1a*, *2a*, *3a*). The scenario relies on importing and exporting materials and products to ensures its position as a global player (see Descriptor 6a). Because of limited domestic RE potentials, Germany is dependent on energy imports. Climate protection measures are weighed against economic prosperity. This results in technology-driven emission mitigation (see Descriptor *9a*).

Due to the highly optimistic technological development in efficiency gains and fuel switches driven by Descriptor *7d,* the energy service demand decreased marginally (see Figure 12). Further, Germany's decarbonization strategy focuses on novel negative emissions technologies (NET) like Carbon Capture and Storage (CCS) in the *Industry* sector (see Figure 38), as well as Direct Air Capture (DAC) and localized Carbon Capture in the *Energy* sector (see Table 8). Negative emissions from the *Land-Use* sector contribute only marginally to the emissions mitigation in 2050. Due to the novel technology uptake, natural solutions like afforestation are obsolete. The NETs experience an extensive use and rapid uptake from 2035 onward due to the technology optimism of Descriptor *7d* (see Figure 4). As a result, the *Energy* sector followed the most extreme emission reduction and became climate neutral in 2035, while the *Industry's* emissions experienced the least emission reduction out of all sectors (see Table 9). It contributes most to the final emissions in 2050. Without the amount of negative emissions in the *Energy supply* sector, GG1's final emissions in 2050 would stand at 136 Mt CO_2eq and miss the climate neutrality goal.

When examining the industrial sector in more detail, the high shares of used fossil fuels stand out (see Table 45). Even though a fossil fuel phase-out until 2050 was selected, this phase-out only applies to electricity production and not to other sectoral demands. To meet the high material production demand, there is still a need for fossil fuels and a demand for NET in the *Industry* to compensate the reliance of fossil fuels. Moreover, the *Industry* sector requires Hydrogen (H_2; see Table 45). Generally, the share of secondary energy carriers like H_2 and efuels is exceptionally high in GG1 due to a preferable fuel switch which aligns with the ambitious adoption of advanced technologies stated in the Descriptors *7d* and *8b* (see Table 47). While H_2 is mainly used in the industrial sector, the efuels go mainly to the *Transport* sector (see Table 45 and Table 52). Consequently, the consumption of secondary energy carriers is higher compared to the remaining scenarios (see Figure 20 and Table 39ff). However, the secondary energy carriers are not produced local, as visible in Table 48. Due to the limited domestic RE production, no electricity is used for synfuel synthesis, and it is imported. Consequently, no carbon capture, utilization and storage (CCUS) is applied. The captured carbon by CCS is stored exclusively.

The adoption of secondary energy carriers and NET significantly influence the final energy demand. Yet, they are not the reason for the high total FED, which is mainly driven by the high consumption and production patterns in the *Industry*, *Transport* and *Building* sectors, set by Descriptors *1a* and *3a* (see Table 20, Table 46 and Table 48). This reflects the growth-as-usual mentality of Descriptor *2a* and is further reflected in the energy system configuration of e.g., *living space per capita* and *average distance travelled per capita* which are generally higher (see Table 39ff.). To meet this comparably high FED of scenario GG1, a lot of electricity is imported, since the low domestic RE potential is limited by Descriptor *5a* (see Table 39 and Table 46). These RE capacity limitations lead to the high use of biomass in electricity production visible in Figure 19, which affects the *Land-Use* sector by lowering its potential for natural sinks (see Table 50 and Table 8).

In summary, the focus on green growth and technology-fixated configurations led to CCS as primary decarbonization strategy. No energy demand reduction is focused resulting in both, high energy consumption and residual emissions, although efficiency gains led to some FED declines. The reliance on high-risk NET for decarbonization is controversial, while the import dependency is risky, which is further discussed in Chapter 6.3.1.1.

6.1.1.2 GG2 – Renewables all over Germany

Scenario GG2 is a moderate green growth (GG) scenario, with less focus on technology development, especially when compared to GG1 (see Descriptor *7c*). Furthermore, the priority for climate protection is higher as in GG1, as well as the inland RE potential (see Descriptors *9b* and *5c)*. The energy service demand partially decreased (see Descriptor *3b*) and *Individualization* and *Community* keep its balance (see Descriptor *1b*). By Descriptor *6b* resource availability and trades aim to respect planetary boundaries.

GG2 achieves sectoral climate neutrality in the *Building* sector by 2040 and in the *Energy* sector by 2050. The decarbonization of the *Industry* sector is less ambitious than in the remaining sectors. To reach GG2's climate neutrality, many levers were adjusted in the optimization to achieve -1.24 Mt CO_2eq in 2050 (see Table 10). However, GG2's main climate neutrality strategy is to strengthen the natural sinks of the *Land-Use* sector. They are noticeably lower, than of the other scenarios (see Table 8). Without these conventional negative emissions, 2050 GHG would stand at 81 Mt CO_2eq and miss the climate neutrality target.

When examining the *Land allocation* data in Table 49, the share of *Forests* is the highest across all scenarios. On the other hand, the shares of *Crop*- and *Grassland* are comparably low. It is necessary to keep in mind, that Descriptor *5c* actually would prevent such a land allocation, since a large area of land would be reserved for RE and *Agriculture*. However, the natural sink potential was adjusted in the optimization process to reach climate neutrality in the second modeling run. Yet, this is inconsistent with the GG2 Descriptors. According to the RE capacity setting of Descriptor *5c*, the electricity production by *RES* is respectively high, but the share of utilized *Biomass* is small (see Table 46). Furthermore, 193 TWh of electricity are exported (see Table 48). If such high quantities of wind and solar energy are installed, it should be reflected in the *Land allocation* data. However, there is no column for this regard. Since very little land is available for the production of agricultural goods, a relatively large amount of food has to be imported to meet local needs.

Although GG2 is a GG scenario, Descriptor *3b* should result in a slight reduction of energy demand. Yet, the FED of GG2 is only slightly lower than GG1's. (see Table 20). Apparently, the difference between the set ambition levels of e.g., industrial *Material production* or transportation patterns have less impact than expected. Similar to GG1, the *Industry* sector contributes the most to the FED of GG2 in 2050. Overall, a fairly high share of fossil fuels is still used in the *Industry* sector and no sufficient defossilization happened. While the context of Descriptor *7c* adopts high ambition levels for technology and fuel switch, these apparently did not reduce the dependence on fossil fuels. Furthermore, there is a demand for H_2 and efuels in the *Industry* sector, although the reliance on these technologies is lower than in GG1 (see Table 39 and Table 40). As a result, the final emissions of the industrial sector can only be this low because CCUS is in place.

Ultimately, scenario GG2's high afforestation rate in the *Land-Use* sector is the main reason for the scenarios overall climate neutrality performance. However, they are actually not in compliance with the EnSu context scenario configuration. The *Industry* sector still heavily relies on fossil fuels, compensated by CCUS and the further use of H_2 and efuels. Implications resulting from this setting is elaborated more closely in Chapter 6.3.1.2.

6.1.1.3 Interim Summary Green Growth Scenarios

The decarbonization trajectory of both GG scenarios is growth-driven and focused on technological solutions, aligning with the findings of Keyßer and Lenzen (2021) for scenarios with increased energy demand. GG1 aims to achieve climate neutrality by heavily relying on NETs. In contrast, GG2 adopts a seemingly more balanced approach, primarily focusing on afforestation. Both scenarios have challenges related to fossil fuel dependence and indicate the scenarios' lock-in in the industrial sector. Furthermore, they heavily rely on secondary energy carriers. GG1's approach raises concerns regarding sustainability and effectiveness due to its extensive use of NETs. On the other hand, GG2's reliance on afforestation, questions the feasibility of achieving the required afforestation rate. In summary, both scenarios have their benefits and drawbacks, requiring careful evaluation of socio-ecological implications to determine the most viable and effective path towards decarbonization in Chapter 6.3.1.

6.1.2 Sufficiency Scenarios

The four sufficiency scenarios are characterized by a profound shift towards low levels of energy services consumed, driven by a collective commitment to address pressing global challenges such as climate change, environmental justice (EJ), social inequality and prosperity. It is generally challenging to compare the scenarios since their descriptor configuration is unique. However, the sufficiency scenarios share a substantial amount of descriptor combinations and a vision for a sustainable and just future.

At the heart of these scenarios lies Descriptor *3c Sufficiency-oriented reduction in service demand*. The disastrous consequences of climate change prompt fundamental transformations in public discourse and policymaking (see Descriptor *9c*). The focus shifts from pursuing excessive material consumption to valuing a "good life" that prioritizes health, accessibility, and inclusivity within living environments. This shift translates into reduced average living space per person, more sustainable transport patterns, all aimed at lowering energy demand. Concurrently, a shift towards durable products, the reduction of food waste, and the adoption of plant-based diets contribute to decreased livestock farming intensity and fertilizer use, further aligning consumption patterns with sustainability goals. Levers like used floor area, transport behavior, agricultural practices, diet and industrial material production are considered to be sufficiency indicators, which is why they are used in the scenarios' energy system configuration of Chapter 8.9. Additionally, all sufficiency scenarios share Descriptor *2c Degrowth/shrinking production & consumption* which facilitate the implementation of Descriptor *3c3c Sufficiency-oriented reduction in service demand*. Scenario S1 is the exception, since *2b Independence of growth* i.e., a-growth is considered to be the economic trajectory. These descriptor combinations influenced the scenarios most and distinguished them fundamentally from the green growth scenarios. The remaining Descriptor expressions and their differentiations are addressed in the respective Chapters.

6.1.2.1 S1 – Middle of the road

Scenario S1 is a growth-independent scenario, with a medium RE capacity (see Descriptor 5b). Descriptor *2b Independence of growth* i.e., a-growth has a huge influence on the energy service demand reductions determined in Descriptor *3c.* The moderately promoting influence of *2b* had to result in lower ambition levels than a *2c/3c* combination like in the other sufficiency scenarios (refer to Chapter 8.5). This is for instance expressed in the industrial material production, where ambition level 3 instead of 4 was assumed. But this is also reflected in levers like living space, travelled distance or dietary choices (see Chapter 8.9).

In the first modeling run, the emissions of S1 were relatively high. In total, nine levers were adjusted to reach the final 2050 emissions in the optimized modeling run. At first, levers were chosen that align with the S1 Descriptor expressions, but the emissions lowered only marginally. Finally, the application of DAC was assumed to lower the emissions to less than 10 Mt CO_2eq in 2050. Furthermore, only the *Building* sector reaches climate neutrality in 2040. Yet, the decarbonization rate of the *Industry* sector is outstanding, but still contributes most to the final emissions in 2050. Further, the *Transport* sector follows a great decarbonization trajectory from 2025 onward (see Figure 7). Unfortunately, it cannot be determined why the energy demand in *Transport* is generally lower than in the other sufficiency scenarios. One reason might be the exclusion of *Kerosene* from the demand account (see Table 52).

As the most sufficiency scenarios, S1's technology development is driven by Descriptor *7b Convivial technologies*, which excludes such high-risk technologies like DAC. Yet the DAC uptake was considered to be absolutely necessary, to achieve the climate neutrality target. The DAC share is only increased by 0.33 % in 2050 leading to -4.7 Mt CO_2eq in CCUS, which is exceptionally low, when compared to the CCUS of GG1 (refer to Chapter 8.9). However, the chosen compromise was necessary, since the natural sink potentials from S1's *Land-Use* sector are minor, and the share of forests in the *Land allocation* data are lower (see Table 49).

However, this chosen compromise affects the S1 GHG and FED data significantly, due to the increased FED caused by DAC. For instance, when comparing *Energy supply* emissions with S2 and S4 data, S1 exhibits relatively high emissions (see Table 8). Additionally, Table 20 indicates that the share of *Energy use for electricity production* of S1 is exceptionally high. This share is attributed to the production of efuels, where the captured CO_2 from DAC is utilized (see Table 47). Consequently, this influences the electricity demand of S1. Notably, Figure 20 and Table 47 reveal higher H_2 demand, despite Descriptor *7b* limits on efuels and H_2.

Surprisingly, the *Industry* sectors emissions are the lowest of all sufficiency scenarios. Although, S1 requires a high share of *Liquid Oil* and *Natural Gas* in 2050 as they are both used in the *Industry* sector (see Table 47 and Table 45). However, these shares are only possible in a decarbonization context through the implemented NET. Otherwise, the emissions of *Industry* would be exceptionally higher. Here the question arises if a lock-in effect is visible in S1, since the reliance on fossil fuel is still quite high for a sufficiency scenario.

In conclusion, S1's decarbonization strategies encompass a combination of energy demand reduction and NET use. These approaches aim to counterbalance the elevated FED resulting from the Descriptor *2b* context and its corresponding higher GHG emissions. However, it is difficult to say how accurately S1 represents an a-growth scenario, since many necessary levers were not available in the tool. This issue is further discussed in Chapter 6.6.2.

6.1.2.2 S2 – Inland transformation

Scenario S2 is mainly driven by a skepticism towards novel technology (see Descriptor *7a*) The local energy production potentials are at the highest level possible (see Descriptor *5c).* Overall, the technology skepticism was mainly manifested in levers regarding efficiency. Technologies like H_2, efuels or CCUS were generally assumed in the lowest ambition level possible. This is also reflected in Table 41 and Table 47, were the share of H_2 and efuels are comparably low to non-existent, same as the share of CCUS.

However, technology skepticism is likely the reason for comparatively high residual emissions in the *Transport* and *Building* sectors in 2050. In general, the decarbonization trajectory of S2 is highly influenced by high decarbonization rate of the *Energy supply* sector, while the emissions reduced the least in the *Industry* sector. The *Energy* and *Transport* sector both undercut 10 Mt CO_2eq in 2040.

In the *Transport* sector, the adoption of battery-driven electric vehicles (BEV) is decreased due to Descriptor *8a*. Additionally, decarbonizing the freight sector faces slightly more resistance due to Descriptor *7a*. Nevertheless, where considered feasible the electrification was maximized, taking advantage of the available local RE electricity production capacity. However, it’s acknowledged that complete electrification of the freight sector is not attainable, leading to a greater reliance on *Biofuels*. This switch is evident in Table 50 and Table 52, where the share of *Biofuels* is comparably high. The aforementioned interactions Descriptors *7a* and *8a* are also reason for the low performance of the *Building* sector’s emission reduction, since insulation and renovation rate were highly influenced by those. Due to the high availability of electricity, heat pumps would be the heating and cooling option of choice. However, Table 48 indicates that only a small amount of electricity goes to the *Building* sector. When examining heating in more detail, it’s actually ambiguous how buildings are heated in S2. Table 50 indicates, that only a low share of *Bioenergy* goes to heat production. One possibility could be a reliance on *Natural Gas*, as the residual share in 2050 is fairly high, when industrial demands are subtracted (see Table 45 and Table 47). While this would explain the high residual emissions, it does not clarify the low *Building*'s FED (see Table 20).

Generally, S2's emission reduction performance is exceptionally good in the *Energy* sector. However, without the negative emissions in the *Land-Use* sector, S2 wouldn't reach climate neutrality in 2050. It is necessary to keep in mind, that the *Land allocation* data is not affected by the massive RE uptake, as visible in Table 49. This weakens the robustness of the negative emissions of the *Land-Use* sector significantly and is revisited in Chapter 6.6.3. While the first impression of S2 indicates a general good performance in the remaining sectors based on the high RE capacity of 839 GW, a fairly high share of the *Electricity* demand is actually exported (see Table 48). This export rate is not in line with the Descriptor *6c* which limits imports and exports and aims for self-sufficiency. When excluding *Exports* of the total FED of Table 20, scenario S2 has no longer the highest FED of the sufficiency scenarios but shares a similar low FED. This leads to the question if the emissions' performance of S2 could be enhanced if no electricity *Exports* happened, and the available energy is used in the sectors to the full potential. This would also eradicate the misleading results in Figure 19. For example, the electricity share in the *Building* sector could be higher, as heat pumps exceed any heating and cooling options selected in S2 and no *Natural Gas* would be required.

The results of S2 suggest that a robust decarbonization performance can be achieved through a combination of reduced energy demand (if the inaccuracy of *Export* is excluded) and high domestic RE production. Moreover, the reliance for high-risk technologies is significantly reduced, as visible in Figure 20. In case of a re-modeling the inaccuracies of *Exports* should be adapted enhance S2's performance.

6.1.2.3 S3 – Urbanized conviviality

Scenario S3 is a sufficiency based degrowth scenario with a fast technology switch (see Descriptor *8b*). The housing and supply structure is centralized (see Descriptor *10a*).

In comparison S3 has the best total performance of all sufficiency scenarios, since its emissions stand at 0.66 Mt CO_2eq. In the first modeling run the emissions of S3 were extremely low already and only the electrification degree in the *Transport* and *Industry* sector were increased to reduce the residual emissions (see Chapter 8.9). However, without the negative emissions from the natural sinks in the *Land-Use* sector, the scenario would not achieve its climate neutrality target. The only sectoral phase-out that happens, is the *Building* sector in 2040. While the *Transport* emissions experience the fastest emission reduction, *Industry* decarbonizes the least, and further contributes the most to the total GHG in 2050.

While the sectoral performance of S3 is generally great, the *Energy* sector sticks out due to its comparably high emissions (see Table 8). When examining the vectoral energy demand in more detail, the share of *liquid and gaseous efuels* is notably higher than in the other sufficiency scenarios. This also reflected in the FED, where the *Energy use for electricity production* is really high, due to the increased demand for secondary energy carriers, synthesized from RES (see Table 20). An inconsistency with the EnSu context data is present, as Descriptor *7b Convivial technologies* limits the use of H_2 and synfuels, i.e., efuels in general. However, the fast tech uptake of Descriptor *8b* influences Descriptor *7b* negatively (refer to Chapter 8.5). Nevertheless, the share of synfuels is too high in the degrowth context. Unfortunately, the extensive dataset does not provide an explanation of the source of the efuels demand. Neither the *Industry*, *Building*, *Energy production* sector uses them nor are they exported. The *Transport* sector relies on 2.6 TWh, which still leaves 50 TWh vacant. However, in the electricity production data, there is no column on 'electricity production from secondary energy carriers', which could be the receiving sector (see Table 46).

When further examining S3's FED, the high share of electricity *Exports* becomes evident (see Table 48). However, due to the setting of Descriptor *6c*, no *Exports* should be possible, since the set ambition level aims for self-sufficiency. Perhaps the supply somehow exceeded the demand. This should be adapted, in case of a re-modeling.

Overall, the influence of Descriptor *10a Centralized living and supply structures* on the modeling isn't clear. The *Land allocation* data indicates no significant difference between scenarios with Descriptor *10a* or *10c* (see Table 49). Other effects on demand dynamics cannot be reconstructed from the available data. It would be advisable to model scenario S3 in the decentralized setting of Descriptor *10c* to explore its influence.

The decarbonization trajectory of S3 is mainly driven by energy demand reduction and a fast technology uptake. This combination made a great sectoral performance in the *Industry* possible. However, the *Export* rate and the share of efuels in the *Energy production* sector is too high and presents an unintentional inconsistency to the S3 descriptors. It is more than unfortunate that the efuels demand cannot be detected.

6.1.2.4 S4 – Individualized & degrowth society

Scenario S4 is a degrowth scenario with a high individualization rate. This significantly reduces the scale of Descriptor *2c Degrowth* and the impact of Descriptor *3c* on the energy service demand reduction (refer to Chapter 8.5). The domestic RE potential is low (see Descriptor *5a*).

Overall, S4 presents an outlier scenario. Since it also focuses on sufficiency, the emissions should align with the remaining sufficiency scenarios (see Table 8). S4 has the highest total emissions standing as 37.06 Mt CO_2eq. Reducing its emissions for 2050 was extremely challenging (refer to Chapter 8.9). The decarbonization performance of S4 is primarily influenced by the slow emission reduction of all sectors, with the worst decrease observed in the *Industry* sector. Additionally, no sectoral phase-out occurred and the sectors *Transport*, *Building* and *Energy* undercut 10 Mt CO_2eq relatively late in 2045 and 2050.

The most problematic factor in the emission reduction is the influence of the Descriptor *1a Individualization*. This becomes especially obvious when examining the first modeling run's settings, such as industrial material production. Due to the combination of *1a*, *2c* and *3c*, the material production had to be higher than in the other sufficiency scenarios. However, in the second modeling run, the ambition level of this lever group was increased to level 4 in order to reduce the residual emissions. Here, a balancing act was performed, to balance the importance of *Individualization* and the energy demand reduction of Descriptor *3c*. This issue is also the reason for the high *Building* sector emissions (see Table 8). For instance, is the *living space area* higher than in the remaining sufficiency scenarios (refer to Chapter 8.9). Among other parameters, this also applies to the *renovation rate* or the electrification rate of the room temperature regulation. Furthermore, only a mediterranean diet was chosen in the *FAFOLU* sector, as in scenario GG2, which is one of the explanations for higher emissions in the S4 agricultural sector. However, these settings weren't altered in the second modeling run to keep the influence of Descriptor *1a* on the modeling results. Consequently, the results allow the interpretation that degrowth and a high degree of individualism are difficult to reconcile, or, in this specific case, actually hinder decarbonization.

Another inconsistency to the S4 Descriptors appears due to the settings influenced by Descriptor *5a.* Since the domestic energy production is limited, both RE capacity and electricity production of S4 are comparably low (see Table 46). This made it apparently difficult to meet the scenarios energy supply demands. Furthermore, the share of *Solid Coal* and *Natural Gas* is higher in S4 (see Table 47). While Descriptor *6c* limits the import and export behavior, and 'self-sufficiency' was selected, energy imports occurred in the energy production breakdown of Table 46. Since these were supposed to be excluded, this clearly results from undersupplied domestic demand, requiring imports. Furthermore, a substantial share of biomass is used in electricity production. Although the use of 38 TWh biomass is in compliance with Descriptor *5a*, 89.96 TWh exceed this by far. Consequently, the performance of the natural sinks in the *Land-Use* sector is affected. It's comparably low, similar to the share of *Forests* in the *Land allocation* data (see Table 8 and Table 49). As the natural sink share was adjusted equally across the sufficiency scenarios, the high biomass utilization rate is results in low natural sink potential.

Another reason why S4 is considered to be an outlier is its high emissions, while the FED is the lowest compared to the other scenarios. When examining the S4 FED, the low demand in *Energy use for electricity production* and *Export* are the only obvious difference to the remaining scenarios (see Table 20). The low demand in the first mentioned sector comes from the actual low electricity production and is supported by the low demand for secondary energy carriers' synthesis (see Table 46 and Table 47). However, the 0 TWh in *Exports* should actually apply to the other sufficiency scenarios as well. As already mentioned, Descriptor *6c* should result in a self-sufficient management of resources. Apparently, this chosen lever setting only manifested in S4, since the scenarios energy production and supply is really low and the scenarios demands barely met, which resulted to no exports. Consequently, the high energy demand in *Exports* is an inaccuracy in the other sufficiency scenarios. If the *Export* values are adapted in all sufficiency scenarios to match the desired 0 TWh, the values converge. Accordingly, S4 isn't an outlier here, since this is an inaccuracy of the other scenarios.

As mentioned in the beginning, the low decarbonization performance of S4 comes mainly from the negative influence of the *Individualization* rate. Additionally, the low domestic RE production decreases the decarbonization performance further, since an electrification uptake couldn't happen in many regards. Moreover, biomass is used for electricity production since the other RE capacities are too low to meet the domestic demand. This has a severe negative effect on the negative emissions from the *Land-Use* sector.

6.1.2.5 Interim Summary Sufficiency Scenarios

The sufficiency scenario's decarbonization trajectories present diverse approaches to achieve the overarching climate neutrality target. While each scenario exhibits strengths and weaknesses, all demonstrate great ambitions in compliance to the German government's objectives for 2030, and especially for 2045 (see Chapter 5.4.1). The German government's ambitions face the challenge of achieving a similar level of decarbonization performance while relying to less ambitious and less far-reaching targets. Although none of the sufficiency scenarios reach below zero Mt CO_2eq, they still outperform the German objectives. Consequently, the question arises about how the German government intends to achieve a similarly good performance while adhering to less ambitious targets. This concern is also issued in ERK (2022). In their biennial report, the achievement of the 2030 ambitions is questionable without a paradigm shift. Currently, an almost continuous activity increase can be observed in all sectors, including the rebound effect. This counteracts possible technical reductions in emissions. Efficiency gains are coarse-grained by (economic) growth, larger living spaces or increased transportation pattern. Without a trend reversal towards a rapid transformation of capital flow, the achievement of the climate targets will only be possible if other parameters are addressed more intensely, and activity patterns and the consumption behavior change. These findings are especially reflected in S4, which maintains a high individualization rate. This expression impedes decarbonization efforts, highlighting the importance behavior and preferences in the transition to a low-carbon future (SRU, 2023).

In conclusion, the four scenarios exemplify different decarbonization approaches, highlighting the need for a rapid RE uptake, yet balanced integration of technological advancements, severe energy demand reduction, and sustainable *Land-use* change to effectively achieve emission reduction objectives (Keyßer & Lenzen, 2021). Yet the findings of Figure 19 and Figure 20 confirm the statement by Wiese et al. (2021), that a lower energy demand reduces the dependency on factors like extreme RE uptake and high-risk energy carriers. It is important to consider these factors in a holistic manner as well as misleading errors and inconsistencies present in the sufficiency scenarios. Moreover, all sufficiency scenarios still rely on fossil fuels in the *Industry* sector, emphasizing the urgent defossilization need and substantial investments required to transform this sector. As the German government strives to meet its climate goals, these scenarios serve as valuable references for understanding the complexities and challenges involved in the journey towards a more sustainable and climate neutral future.

6.2 Scenarios CO_2 budget

In order to evaluate the EnSu narratives 1.5°C Paris compatibility, the scenarios emissions were compared to the German carbon budget of 3.1 Gt CO_2, calculated by SRU (2022). The research question *Which scenarios are in compliance with the German CO2 budget?* is answered in the following. The results in Chapter 5.3 reveal that the CO_2 budget is met across all scenarios in the second modeling run. The mean difference of 1 Gt CO_2 to 1.3 Gt CO_2 is minor. This margin appears even smaller when considering the fact, that the SRU adapted the CO_2 budget for Germany in their actualization in 2022 by 0.8-1.1 Gt CO_2.

Out of all scenarios, S3 has the most difference to the residual budget of 1.37 Gt CO_2, followed by GG1 with a difference of 1.32 Gt CO_2. Solely considering the residual margin, both S3 and GG1 would offer objectively safe decarbonization pathway. However, the scenarios socio-ecological implications and their plausibility is elaborated closely in the following Chapter 6.3. Nevertheless, the residual margin is quite small, particularly when considering the uncertainties entailed in the CO_2 budget. This also applies for the other scenarios.

Moreover, the results should be interpreted with care, since the CO_2 shares were extracted from the GHG emissions by an average value to serve as a proxy. While the calculations outlined in Chapter 4.5.3 base on an average percentage of 87.57 % (by UBA, 2023c), UBA (2023b) assumes a share of 89.3 % of CO_2 in the total GHG emissions. Although the difference is only 1.73 percentage points, altered CO2 shares would have an enormous impact on the 1.5°C compatibility, precisely because the difference to the CO2 budget is very small.

Therefore, CO_2 shares in this calculation do not represent the actual CO_2 values of each scenario, especially since minor fluctuations in the share of CO_2 occurred, as the actual German data shows (see Figure 18 and Figure 36). This can come from changed patterns of fossil fuels use or e.g., volcanic events (UBA, 2023b). Although the 2022 data was calibrated to match Germany's actual CO_2 emission share, the deviation to the German history data may understate the CO_2 budgets of both GG scenarios. Moreover, the discussion outlined in Chapter 6.1 highlights that the decarbonization pathways presented in these scenarios are exceptionally ambitious, requiring rapid technological advancements, significant alterations in individual behaviors, and substantial changes within the political system. These aspects are further covered in the following Chapter 6.3.

As already outlined in Chapter 2.2 the national carbon budget allocation is subject to criticism, especially when considering climate justice aspects. Right now, Germany's budget is allocated by the equal-per-capita approach. Germany's carbon debt i.e., historic contributions to the climate change, are estimated at approximately 12 Gt CO_2 (Matthews, 2016). Consequently, this leaves Germany, along with other Global North countries, with an extremely limited or potentially non-existent CO_2 budget. If the carbon budget of Williges et al. (2022) was applied, Germany would have been allocated -3.9 Gt CO_2, implying that Germany has already exceeded its budget. However, decarbonization is crucial for these early industrialized countries and to achieve the 1.5° target. Therefore, the focus has shifted towards deliberations on compensatory measures and remedies in light of these constraints (IPCC, 2023).

In addition to the challenges related to climate justice, criticisms of the CO_2 budget arise from its exclusive focus on CO_2 emissions, neglecting other potent GHG with shorter atmospheric lifetimes but higher climate impacts (Matthews et al., 2020; Matthews et al., 2021). As the calculations of Chapter 4.5.3 imply, the total GHG emissions of all scenarios are actually 12.7 % higher, than the pure CO_2 emissions since their share was extracted respectively from GHG. When calculating with the GHG CO_2eq values, the available carbon budget would be exceeded in all scenarios, due to the small available headroom. Furthermore, this gap between CO_2 and total GHG emissions could potentially lead to an even lower available carbon budget. For instance Saunois et al. (2020) call for a stronger consideration of the CH_4 budget to assess realistic climate mitigation pathways. Similar uncertainties are highlighted by Matthews et al. in 2020 and 2021, where they discussed various factors contributing to the uncertainties associated with the carbon budget. These factors include such non-CO_2 scenarios i.e., CH_4 or N_2O, uncertainties in historical emissions, the influence of aerosols, and feedback mechanisms within the carbon cycle and the broader Earth system, such as permafrost degradation.

In summary, the CO_2 budget is a solid decision-making tool for defining decarbonization paths in systems and sectors in a target-oriented framework. However, it should be considered critically and calculated with a generous buffer due to the uncertainties described above. Exceeding the budget is not advisable for several reasons. In the context of this work, and also generally speaking, the period after 2050 is crucial. Emissions must continue to decrease and remaining GHG emissions in the atmosphere must be sequestered in order to provide a livable planet for all. Moreover, the CO_2 budget is not only influenced by Germany but by global emission contributions. Moreover, are the consequences of a carbon budget exceedance not distributed equally. To guarantee climate justice, stronger global efforts are urgently needed by the early industrialized countries to reduce the global consequences of climate change (IPCC, 2022a).

6.3 Unraveling Socio-Ecological Implications

The following Chapters aim to explore the socio-ecological implications of the modeled scenarios. By that, the final research question on how these implications vary based on the conditions required for the different scenario trajectories, is answered.

While a statistical analysis or a feasibility analysis, as conducted by Keyßer and Lenzen (2021) would result in a robust and satisfying statements on the occurrence likelihood of the six modeled scenarios, such would beyond the scope of this work. Hence, the scenarios results are discussed in a qualitative manner to address their socio-ecological implications and by that their plausibility i.e., their occurrence likelihood.

6.3.1 Green Growth Scenarios

In the following Chapters the socio-ecological implications of the GG scenarios are explored.

6.3.1.1 GG1 – Energy imports and fast shift

Scenario GG1 stands out mainly due to its extreme decarbonization trajectory, especially in the *Industry* and *Energy supply* sector. It relies heavily on energy imports, which are risky, as the energy crisis resulting from the Russian invasion of Ukraine revealed (Best & Zell-Ziegler, 2022). Moreover, the high use of biomass for electricity production neglects conservation aspects and is also considered to be controversial (Hennenberg & Böttcher, 2023). However, the main concerns come from the assumed amount of negative emissions, since they are questionable due to various reasons. While the CCS technologies applied have always been assigned the highest ambition level, there is great uncertainty if the technology will be accessible in 2030, like assumed in the tool and if the necessary operational scale is reached in general. Like GG1, most scenario that aim for the 1.5°C or 2°C limit of the Paris Agreement, heavily rely on some NET in the second half of the 21^{st} century (Kuhnhenn, 2018). The cumulated global amount of CDR deployment needed to achieve this goal ranges between 450-1100 Gt CO_2. Although CDR is already partially implemented, only 2 Gt CO_2 are extracted currently and come mainly from conventional CDR on land i.e., afforestation and land-use management. Novel CDR methods, such as Direct Air Carbon Capture and Storage (DACCS) or Bioenergy with Carbon Capture and Sequestration (BECCS) offer higher mitigation potentials. However, their technology readiness level (TRL) is currently too low for an imminent market uptake. Additionally, they come with immense costs per scale. Consequently, the necessary ramp-up is uncertain and controversial in the long term (Smith et al., 2023).

Furthermore, there is a reasonable chance that the adopted ambition levels are far above what is theoretically possible in Germany. Not only are the technology switches and CCS deployments in the German *Industry* sector often way above what is currently considered possible by Agora Energiewende and Wuppertal-Institut (2019), CDR in Germany could only compensate for a fairly small share. The practical CDR potential for Germany can only compensate 36-63 Mt CO_2 (Borchers et al., 2022; Mengis et al., 2022). In the case of GG1, the necessary CCS deployment stands at 401 Mt CO_2 in 2050 (see Table 39). Since this exceeds Germany's potential, CDR should not be the most feasible emission reduction option.

Moreover, NETs come with severe environmental and social implications often not considered enough when focusing on its mitigation potential. For example, the high energy demand of DACCS could lead to an increase in RE capacity, since the CDR options should not be powered with fossil fuels. This could lead to severe competition for RE use or an increase of GHG emission, if no RE is used. In the case of GG1, a huge amount of energy is imported, which poses high risks of energy dependencies. Furthermore, importing energy to power domestic CDR is highly controversial from an EJ perspective. Additionally, BECCS compete for land and water resources, if used on purpose grown biomass feedstocks. As a result, the uptake of BECCS compete with food production, soil fertility and conservation of biodiversity, as land is frequently disturbed (Smith et al., 2023). Certainly, there are further challenges, that arise from the long-term storage. The captured carbon can be stored in a deep underground geological suitable rock formation which act as a reservoir. Deep saline aquifers possess the hugest potential for Germany, especially in the North East German Basin (Borchers et al., 2022). However, CCS is only effective when the inserted carbon is permanently captured. Even though potential leakage is considered to be low when closely monitored and adequately managed, there are still mayor uncertainties of the long-term behavior and bio-interaction of stored carbon (Alcalde et al., 2018). Furthermore, installation of (transport) infrastructure is necessary for these NETs. This could lead to lock-in effects, as the provided infrastructure has a single purpose. These implications are not included in the tool, distorting GG1's impression.

These implications act as severe trade-offs also for other societal goals and can affect energy and food security, health issues or land-use conflicts. CDR has, similar to other large-scale project, often a societal acceptance problem. These are reinforced by the fact that the theoretical possibilities for CDR does not exist equally throughout the federal states and offshore storage in the North Sea offers particularly high potentials. In general, conflicts are dependent on the scale of CDR implementation. If the local community can participate in the implication process or even benefit from it, resistance is lower. While public decision making is crucial, public acceptance is currently low for NETs, since it is not widely known yet. For an socially sustainable NET upscale, building trust and implementing participatory governance processes is crucial, which is not deployed yet (Borchers et al., 2022; Ragwitz et al., 2023).

Consequently, NET is not considered to be a silver bullet but should act as an addition for hard abatable residual emissions. This further applies to the overly ambitious uptake of H_2 and efuels in the *Industry* sector come with similar socio-ecological implications as CDR (Ueckerdt et al., 2021). Given the uncertainties and challenges about a possible CDR and synfuel scale up, its dependence can be reduced by mitigating emissions faster and efficiently enhance energy use (Borchers et al., 2022; Smith et al., 2023). But the dependency on respective technologies is huge, since it is the main mitigation option choice (see Chapter 6.1.1.1). This clearly reveals the prioritization of growth instead of climate protection. The emissions of the *Industry* sector, which can be seen as a proxy for the GG Descriptor *2a,* are reduced the least and contribute most to the 2050 GHG. This results from the continuous high production and consumption demand in *Industry* and other sectors. By relying on high-risk technologies like NET or synfuels, time to take action is pushed back further, due of the perception of technology taking care of it in the end. Consequently, path dependencies and lock-ins are likely, if no other emission reduction deployed and the technologies not available at the required scale. Ultimately, this would further affect GG1's 1.5°C compatibility, as the budget could be exceeded if the NET technologies are not in place. As Table 26 depicts, the margin of GG1 is small.

Finally, following the depicted path of GG1 is not recommendable after reflecting its social and ecological implications. Consequently, the occurrence likelihood of GG1's uptake is low. The necessary assumptions on CDR technologies in GG1 are way above what is possible in Germany (Borchers et al., 2022; Smith et al., 2023). The actual available TRL is not in line with what is assumed in the used modeling tool and the social and ecological implications that follow NETs are not reflected. A reliance on NET and synfuels is risky and not the most feasible option to reduce emissions, as e.g. Keyßer and Lenzen (2021) concluded. Energy demand reduction and non-technology driven emission reduction present a much safer way to align emission with the 1.5° objective.

6.3.1.2 GG2 – Renewables all over Germany

Although GG2 is considered to be a more moderate green growth scenario, it still relies heavily on growth, as the decarbonization trajectory of 6.1.1.2 indicates. Furthermore, net-zero emissions are only achieved because of the high number of negative emissions from the *Land-Use* sector. Yet, this presents an inconsistency to the EnSu context scenario, as Descriptor *5c* would influence natural sinks potentials negatively due to high pressure on land. However, the question remains, if this amount of negative emissions from the *Land-Use* sector is even possible in GG2 and generally in Germany.

To achieve afforestation rates this high, a lot of croplands needs relocation to forests as visible in Table 49. Since this indicates low shares of domestic food production, major compensation by imports of agricultural products is required. While this was actually set in the *Import/Export* lever group, its magnitude unravels in the context of the high afforestation rate of GG2. To safeguard the domestic climate neutrality objective, GG2 focuses on local natural sinks and by that externalizes food production to achieve this goal. These natural sinks are only available to this extend because of the freed-up land from crop- and grassland. This results in Germany being extremely dependent on food imports, which poses high risks in supply chain disturbances and price fluctuations on the global market. Moreover, the exporting countries agricultural areas are under high pressure to meet German import demands. Generally, this externalization is an expression of GG mentality and reinforces an imperial way of living (I.L.A. Kollektiv, 2019). However, this is not considered aspirational from an EJ perspective. Resources like land, water, soil and biodiversity are severely pressured due to the German externalization strategy. While this fits to GG2 Descriptor *2a*, both Descriptors *6b* and *9b* would limit the import behavior and the respective externalization rate. However, these circumstances result from the low technical carbon mitigation option potential of GG2 set by Descriptor *7c* and the high afforestation rate to achieve climate neutrality in the optimization process.

After determining the cause of the high levels of afforestation, it is relevant to verify whether the low emissions from the *Land-use* sector are possible in the first place. The last forest report by BMEL (2023) pictures the devastating state of the German forests. Their ability to bind CO_2 is massively disturbed due to bark beetle infestation and its advanced age structure (Vass & Elofsson, 2016). The German forest sink potential is expected to deteriorate further to less than 51 Mt CO_2, because of heat waves and droughts caused by climate change (Hennenberg & Böttcher, 2023). Additionally, the *forest management* lever in the modeling is considered to be dead and cannot influence the afforestation rate. Moreover, values for German forest sinks diverge extremely due to methodical disharmony and sometimes even assume a linear increase, which is unlikely to happen (Hennenberg & Böttcher, 2023). While the carbon-binding potential per hectares increase over the forest’s lifespan, the management intensity highly influences the sinking potential. Multiple authors suggest that biomass use from forests should be reduced to a minimum in order to enhance the forest sink potential (Hennenberg & Böttcher, 2023; Ragwitz et al., 2023; Selivanov et al., 2023; Vass & Elofsson, 2016). Selivanov et al. (2023) suggest a highly conscious use of forests biomass and a focus on binding potentials. However, in GG2 some solid biomass from forests is used for electricity production and biofuels (see Table 46 and Table 47). While the majority of biofuels comes from other sources, solids contribute a third. Even though the shares are minor, they should be as low as zero for the negative emissions of the *Land-Use* sector to be that high. This further indicates an overestimation of the carbon-binding potential of forests in the modeling tool. Finally, the estimates are much higher than the values of Hennenberg & Böttcher (2023).

Certainly, there are other natural sink options for reducing atmospheric carbon like enhanced weathering and bio-charcoal. Yet, their TRL is not high enough for a market uptake. Options like carbon sequestration in soil through agroforestry or rewetting of cropland offer high potentials in Germany too, with a ready-to-use-TRL. The *2050 Pathways Explorer* neglects such options for now and focuses solely on afforestation in the *Land-Use* sector. Although there is the option on adjusting the BECCS share though the uptake of biofuels, its implementation is controversial, same as the 'climate-neutral' usage of biomass (Selivanov et al., 2023). Since no other nature based sinking options are considered in the tool the compensation of the *Land-Use* sector comes solely from forests. These further highlights the overestimates of the potential forest sinks by the tool, since the available German forest sinks could not compensate the residual emissions of GG2 (Hennenberg & Böttcher, 2023). When comparing the German KSG objective of the *Land-Use* sector for 2030 and 2045 to GG2, both times the GG2 values are way higher (see Chapter 8.10). This underlines the aforementioned interpretation, that the *2050 Pathway Explorer* values are overestimated for *Land-Use*.

Consequently, a reliance on afforestation as major mitigation strategy is really risky, while pursuing growth-driven behavior. Since the natural sink potentials are not realistic, a higher reliance on NET could be necessary, to achieve emissions' reduction and comply with the German CO_2 budget. However, an uptake of CCS comes with severe socio-ecological implications as the discussion of GG1 in the previous Chapter 6.3.1.1 showed. Consequently, the reliance on NETs no matter if conventional or novel, cannot compensate the high residual emissions coming from an energy demand this high. An reduction of energy demand presents the safer emission mitigation option in the end (Keyßer & Lenzen, 2021).

6.3.1.3 Conclusion of the Green growth scenarios

The socio-ecological implications of both GG scenarios, reveal the intricate trade-offs between economic growth, technological innovation and climate protection in the pursuit of decarbonization. Both scenarios adopt different approaches, leading to distinct socio-economic and ecological outcomes.

GG1's priority on economic growth and technology may yield short-term economic gains, but raises concerns about the heavy reliance on synfuels and NETs. While these technologies offer potential solutions for mitigating climate change, their large-scale implementation comes with severe ecological risks, such as biodiversity concerns, geological storage hazards and potential impacts on ecosystems. Furthermore, GG1's focus on NET and efficiency gains from fuel switches in pursuit of economic prosperity may overlook the potential risk of not-reaching the necessary TRL within the expected time frame. On the other hand, GG2 tries to balance economic growth and climate protection more, but probably fails to do so. The modeling tool's mistaken high afforestation rate in GG2 raises concerns about the feasibility of the 1.5°C objective. Moreover, the externalization of food production to safeguard local natural sinks neglects ecological implications like land-use changes, implications for local food production and local communities' livelihoods elsewhere and promotes an imperial way of living (I.L.A. Kollektiv, 2019). However, without the reliance on both unrealistic emission reduction approaches, the 1.5°C budget is depleted quickly. Accordingly, following the respective scenario pathways is associated with high risks and overall has a low occurrence likelihood.

Both scenarios face challenges in reducing emissions in the *Industry*, with GG1's relying on carbon capture technologies and GG2's moderate yet ineffective reduction efforts. Furthermore, the import dependence on energy and secondary energy carriers in both scenarios as well as on agricultural goods in GG2 has implications for energy and food security and economic stability, exposing Germany to supply chain disruptions and price fluctuations on the global market.

In conclusion, the socio-ecological implications of the GG scenarios highlight the need for a holistic and thoughtful approach to address climate change. Considering the trade-offs and complexities involved, policymakers and stakeholders must carefully evaluate the potential impacts of different strategies and prioritize solutions that promote long-term environmental sustainability, social well-being and stability, without prioritizing economic growth. To ensure sustainable socio-ecological outcomes, it is crucial to balance technological advancements and behavioral changes. Emphasizing sufficiency principles, along with adopting advanced technologies in a cautious and responsible manner, can lead to more environmentally sustainable and equitable decarbonization trajectories like in the sufficiency scenarios.

6.3.2 Sufficiency Scenarios

The following Chapters explore the socio-ecological implications of the sufficiency scenarios.

6.3.2.1 S1 – Middle of the road

The modeling of the sufficiency scenarios in the *2050 Pathways Explorer* came with severe challenges. However, the Descriptor expression *2b* presented a special issue. As illustrated in Chapter 3.2.3 growth is viewed to be agnostic and consequently, economic growth is no longer focused in the political agenda and only be pursuit in growth-worthy sectors, like the social system or education. However, both were no setting option in the modeling tool. Moreover, there is no option on setting GDP. Subsequently, industrial production is seen as a proxy towards economic growth and set to ambition level 3 to reflect the agnostic attitude. Additionally, this proxy does not give a holistic view of a-growth in an energy system.

The ambition level 3-setting is one of the reasons for the higher FED of the *Industry* sector, since the sufficiency measures and energy service demand reduction cannot unravel like in the other sufficiency scenarios (see Table 20). Yet, the *Industry* emissions of S1 are the lowest compared to the other scenarios. An uptake of DAC compensates for the reliance on fossil fuels, which are required to meet the higher industrial production rates (see Chapter 6.1.2.1).

However, DAC deployment is inconsistent with Descriptor *7b Convivial technologies* and highly controversial. Generally, DAC is only considered beneficial for decarbonization, if the used electricity comes from RES (Block & Viebahn, 2022; Smith et al., 2023). While there are options to use the captured carbon in efuels for the *Transport* sector, their climate neutrality balance should be considered carefully. The efuels emissions in *Transport* are calculated as 'climate neutral', because their carbon was previously removed from the atmosphere (Block & Viebahn, 2022). However, this balancing method neglects negative effects of the production process and its resource demands (Kasten, 2020; Ueckerdt et al., 2021). In the context of the modeling tool the balancing method is not clear. Furthermore, it is not comprehensible which sector relies on the high shares of efuels in S1. The *Transport* sector only uses on a minor share and no efuels are exported (see Table 51 and Table 52).

To remove the captured carbon permanently, storage opportunities are required. As already issued in the CCS technology uptake discussion of scenario GG1 of Chapter 6.3.1.1, storage is not available to the necessary extend in Germany. However, if DACCS only has a low deployment rate, storage options may sufficiently compensate low residual emissions (Borchers et al., 2022). According to Block and Viebahn (2022) DAC plants should be installed near the German North Sea coast in order to keep the transport infrastructure to the offshore storage facilities small. However, the necessary area allocated to the DAC plant itself is huge. This land-use demand increases, when considering the storage sites. Furthermore, there is a high freshwater and huge energy demand in DAC facilities and processes. While the energy in coastal plants may come from offshore wind energy, the total energy demand is still extremely high. The produced energy is exclusively available to the DAC plant and consequently competes with locals' energy supply. Furthermore, the DAC and DACCS plant can affect biodiversity negatively. However, the relationship of biodiversity, land-use and such plants is complicated and not well studied, since the focus solely lies on the mitigation potential of DAC(CS) (Bysveen et al., 2022). Respectively, the *Land allocation* data does not issue DAC plants or similar infrastructure in their listing (see Table 49).

In comparison to the assumed DAC values in Prognos et al. (2020), energy demand and deployment rate of DAC are comparably low. This also applies to the captured carbon from DAC which is lower than the assumptions by Ragwitz et al. (2023). Yet, Block and Viebahn (2022) conclude that even small DAC plants come with a tremendous resource consumption and bigger plants may be more conceivable due to cost-effectiveness. However, an DAC uptake should not happen carelessly. Besides ecological implications, there are severe social implications from DAC and other NETs. Certainly, these need consideration as Descriptor *9c* focuses on EJ. Communities where such NET projects allocate, should be in the center of the decision-making process, to ensure EJ dimensions. The community engagement should empower the citizens to engage in the decision-making process and to convey ownership through investments and incentives. Both burdens and benefits of the DAC should be distributed fairly among the German federal states or compensated in an adequate manner (Batres et al., 2021). Even though these dimensions would be considered in Germany when pursuing S1, currently no procedure for a deployment of CDR technologies is in place. Further preparatory steps should include not only technical testing and cost reductions, but also a social understanding of the conditions for use and the provision of a political framework that permits it (Ragwitz et al., 2023). Finally, the socio-ecological implications of S1 are mainly influenced by the uptake of DAC. To fulfill the conditions of Descriptor *9c*, monitoring and political frameworks are required, to ensure EJ of such large-scale and high-risk NET projects.

In principle, this debate could be avoided or implementations reduced if there would not be an initial focus on NETs. However, the FED and consequently, final emissions of S1 are too high to neglect DAC as mitigation option in this specific case. As already mentioned in Chapter 6.1.2.1, there could be a lock-in effect entailed in S1, as *Industry* continues to rely heavily on fossil fuels to cover the higher production demands. These dependencies should be deconstructed to achieve more emissions and energy demand reductions. Since these circumstances results from Descriptor *2b*, the aforementioned discussion allows the interpretation, that an agnostic attitude towards growth may not be sufficient to reduce the emissions and energy demand. This confirms concerns Kallis et al. (2018) issued towards van den Bergh (2011) approach on ignoring GDP (refer to Chapter 3.2.3). In S1 the economy clearly continues to growth, although GDP cannot be measured in the modeling tool. This path dependency in the industrial production could be an expression of the deep embedment of growth in the existing institutional and political structures.

However, the modeling tool is no perfect fit for a-growth scenario modeling, since necessary levers are missing. However, this is further elaborated in Chapter 6.6. Therefore, the results and interpretations should be considered with caution. Furthermore, S1 should be re-modeled with another tool to refute or confirm these conclusions.

6.3.2.2 S2 – Inland transformation

The decarbonization trajectory of S2 allows the interpretation that a reduction of energy demand and high local RE production lead to a robust decarbonization performance while significantly decreasing the reliance on high-risk technologies (if the inaccuracy of electricity *Export* is excluded). However, technology skepticism hinders a holistic socio-ecological transformation in the *Transport* and *Industry* sector. To enhance the emission trajectory performance of S2, further optimization in the modeling process is necessary. First, this aims towards adjustments of the RE supply and demand dynamics to avoid *Exports* but still meet local energy demands through self-sufficiency. This would furthermore affect *Transport* and *Industry* energy demands and reduce the actual installed RE capacity, which is really high in S2 (see Table 42). This generates misleading results, that do not fit to the findings by Wiese et al. (2021) of Figure 19. Since this RE uptake is not reflected in the *Land allocation* data of Table 49, it is unclear how the modeling tool accounts for negative effects that can follow such a massive RE uptake. Furthermore, the natural sinks are not affected by the RE uptake.

Solar PV, for example, relies heavily on resource extraction of (rare) metals (IEA, 2022b). Their sourcing can have negative effects on the environment due to pollution and social impacts on workers and the communities near the extraction site (Martin & Iles, 2021). For example, significant social and environmental injustice occurred when cobalt mining in the Democratic Republic of Congo with serious human rights violations, child labor and environmental pollution causing health issues (Florin & Dominish, 2017). Furthermore, mining site and supply chain impacts affect the resource availability. While Australia and Chile are major lithium producers, large deposits in Bolivia remain undeveloped due to justified local concerns about social and environmental impacts (Giurco et al., 2019). In general, negative effects on biodiversity cannot be excluded in the extraction process (Rehbein et al., 2020). Moreover, current technologies available in the PV industry could face resource constraints at the TW size needed to cost-effectively mitigate climate change (Goldschmidt et al., 2021). The resource availability for a high RE uptake may be limited by sustainable manufacturing capacities of existing and future PV technologies. They are fundamentally determined by the resource availability and the possibility of sustainable manufacturing on a multi-TW scale (Zhang et al., 2021). Here, an energy demand reduction would ease the pressure on resources and production. To minimize negative effects on the domestic land-use, pre-polluted areas like landfills, buildings and roofs could be prioritized in PV deployment. Additionally, there are holistic approaches like floating PV or combining ground-mounted PV with the rewetting of peatlands or agricultural areas to enable multipurpose application (Fraunhofer ISE, 2022; NABU, 2021).However, these technologies are not considered in the modeling tool. Furthermore, wind power also entails severe socio-ecological constraints. Both onshore and offshore wind power affect the local ecosystem's biodiversity in the installation phase and during their lifetime if not managed correctly, and the socket of onshore wind is completely sealed (KNE, 2022; NABU, 2023). The deployment of wind power, like all large scale projects, need local participatory decision-making processes and a fair benefits and burdens sharing to lower acceptance problems (Flachsbarth et al., 2021). However, the presented implications do not intend to suggest that RE is not a no-regret action. The socio-ecologic implications of RE uptake are less damaging to EJ and the environment than fossil fuels. Nevertheless, with such an upscaled RE uptake, demand reduction should be considered first, as it is done in S2, rather than replacing the current consumption with RE and by that spiraling towards the aforementioned negative consequences (Keyßer & Lenzen, 2021). However, an RE uptake to this extend is only possible in Germany if the permitting process is revolutionized to facilitate the widespread uptake of both ground-mounted PV and on- and offshore wind energy. Currently, the permitting process and non-incentive payment structures hinder a rapid RE uptake (acatech et al., 2022).

Furthermore, an adjustment of the supply and demand structure would affect the currently high *Biofuel* shares in the *Transport* sector. These come from the tech skepticism of Descriptor *7a*, which assume slightly less direct electrification uptake. However, these too, have severe socio-ecological implications. Both, the production and processing of bioenergy materials can have various environmental impacts throughout their lifetime. Particularly noteworthy are land-use changes for a production intensification. Large-scale use of *Biofuels* requires appropriate sustainable technologies and certification schemes to avoid environmental damage and competition with food production and conservation (Nogueira et al., 2020). The most uncertain and influential factors in the *Biofuels* supply chain are the GHG emissions resulting from direct and indirect land-use and cover changes. It is important to note that *Biofuels* generally have lower lifecycle GHG emissions compared to oil-based fuels, unless there are significant alterations in land-use or cover (Panchuk et al., 2020). However, the direct electrification of the *Transport* sector through BEV represents a much greater decarbonization potential than alternative fuels (Kasten, 2020). BEV have a much better GHG saving potential than the most *Biofuels*. Panchuk et al. (2020) conclude, that the use of carbon-neutral synthetic *Biofuels* should only be used as substitute for hard-abatable *Transport* emissions, like in the long-distance and freight sector. Certainly, biomass use is often misleadingly referred to as ‘climate neutral’, since only the abated fossil emissions are compared. Land-use sinking potentials, if biomass is not used, are neglected in these calculations (Hennenberg & Böttcher, 2023). By increasing the direct electrification share in the *Transport* sector more, less electricity would be exported and further enhance the *Transport* sectors and S2’s overall performance. At this point, a consideration between *Biofuels* and efuels in the *Transport* sector would also be appropriate, yet efuels are categorically excluded by Descriptor *7a* in S2.

Similar action could take place in the *Industry* sector, which still has a high reliance on fossils fuels, namely *Natural Gas*. Consequently, only a slight defossilization of the *Industry* sector happened. Even though it is contradictory to Descriptor *7a*, some industrial processes rely on high heat and in order to phase out fossil fuels in the *Industry* sector, a reliance on H_2 is probably necessary (Agora Energiewende & Wuppertal-Institut, 2019). However, the electrification potential available in the *Industry* sector should be used to the full extend in S2, to minimize the deployment of H_2. As Matthes et al. (2020) frame it, H_2 should be considered as valuable and delicate resource, only applicable if other options are exhausted. This is also due to the negative effects accompanying the synthesis of H_2. Its freshwater and energy demand is huge and could compete with local RE production and land-use due to the facilities space requirements. Local benefits and burdens resulting from the production sites should be shared equally throughout a country to ensure EJ dimensions (Ueckerdt et al., 2021).

In conclusion, S2 shows that reducing energy demand and increasing local RE production can achieve significant decarbonization while minimizing reliance on high-risk technologies. To make this approach plausible in Germany, fundamental changes in permitting and financing are required. Furthermore, addressing socio-ecological implications of RES and resource-intensive technologies is vital for a successful and sustainable energy transition. However, the lack of consideration for land allocation data decreases the robustness of S2.

6.3.2.3 S3 – Urbanized conviviality

As elaborated on in Chapter 6.1.2.3, S3 has a great decarbonization performance and the most headroom to the carbon budget calculated by SRU (2022). The main reason is the reduction of energy demand which is facilitated by the fast technology uptake. Descriptor *8b* reduces conviviality’s constraints’ on the technology development (refer to Chapter 8.5). This is expressed by the renovation rate of *Buildings* or the technology switch of the *Industry*, for which a higher ambition level than in S1 or S4 was assumed (see Table 41ff). The concept of conviviality was particularly characterized by Illich (1973). In the context of degrowth, convivial technologies promote solutions that are relatable, accessible, adaptable, appropriate and have an ecofriendly bio-interaction (Vetter, 2017). While technological advancements can bring many benefits, a fast uptake without careful consideration of their social, environmental and cultural implications can undermine the principles of convivial technologies. Consequently, a fast uptake could lead to a neglect of conviviality standards, like decentralized technology organization, equality dimensions, community engagement and a positive environmental focus. Overall, the definition of convivial technologies is very broad. In principle, the development of technology and innovation is integrated into economic growth as it is one of many opportunities for its generation. However, in an already established degrowth society, economic growth is no longer part of the equation. Consequently, it is possible to guide the design of a fast tech uptake in a way that conviviality principles continue to be upheld or are merely eased for certain sectors, if monitored closely. This could apply e.g., in the *Industry* sector, where it is difficult to decarbonize. This scenario's results could act as a first serve for a fast, yet selected tech uptake. However, in the used modeling tool it was difficult to guide a fast uptake under the conviviality premises, due to the vast, yet limited ambition level options, while sticking the internal continuity of the scenarios.

Consequently, this could have led to the high shares of efuels in S3, illustrated in Chapter 6.1.2.3. The efuels uptake is accompanied by a high demand for H_2, since it's a prerequisite resource for efuels production. Unfortunately, it is not possible to reconstruct where the high efuels demand origin. The *Transport* sector could be a major receiver, but uses efuels only to a minor extend in S3. Furthermore, the efuels uptake is expected to happen from 2040 onward in S3. However, Ueckerdt et al. (2021) doubt a cost-effective development of both efuels and H_2 which would be necessary for an uptake anywhere before 2050. Moreover, Ueckerdt et al. call for a conscious and responsible implementation and usage of both technologies. They possess a huge risk of not being available at a large scale at all. Further, they could result in lock-in effects, since the infrastructure investment is huge, while their TRL is not high enough yet for a large-scale implementation. Consequently, efuels and H_2 should only be used in sectors that have hard abatable residual emissions, like the chemical industry or long-distance freight sector. However, there are calls for a wider replacement of efuels and H_2 to substitute fossil fuel infrastructure e.g., in cooking, heating, or in light-duty vehicles. Although the demand-side transformation would be reduced, this would be accompanied by side severe effects. Especially an uptake to S3' extend would come with negative effects on the local energy system. Both efuels and H_2 have a high energy intensity and compete with local energy production and supply. The synthesis of H_2 requires large amounts of freshwater. This would compete with local freshwater supplies, which will stressed even more in the future due to climate change (Kleijn & van der Voet, 2010; Ueckerdt et al., 2021). Furthermore, the production of efuels relies on carbon capture in the first place. However, in S3 no CCS technology, neither punctual CDR nor DAC was selected. The efuels are not imported. Yet, it is possible, that the captured carbon stems from BECCS technology. Even though there is no BECCS-lever, an implementation of biofuels can imply BECCS in the modeling tool. In this case, BECCS compete with local food production or biodiversity since fertile land is used for energy crops or biomass production. However, in the context of Muraca and Neuber's work on the compatibility of such NET technologies and degrowth, it is questionable whether efuels or H_2 uptake, or the use of BECCS, are at all consistent with degrowth, biodiversity concerns and conviviality in S3 (2018). As already mentioned in the discussion on efuels and DAC of the previous scenarios, benefits and burdens need equal sharing among the German federal states, as well as participatory decision-making standards to guarantee EJ dimensions.

However, in case of a re-modeling, the efuels share should be lowered to avoid potential negative implications not accounted for in the modeling tool and to enhance compliance with the scenarios Descriptor expressions. Moreover, the share of exported electricity requires adjustment (see Table 20 and Table 48). This would lead to a better compliance to the outcomes highlighted in Wiese et al. (2021). An enhancement could be an increased electrification degree of the *Industry* and *Transport*, as already happened in the optimization process of S3. As Table 17 illustrates, this increase led to a severe reduction in *Exports*.

While in S3 the fast tech uptake is clearly in focus and mainly responsible for the great decarbonization performance, it is also necessary in social dimensions to mitigate climate change fast enough. Not only the technology switch requires rapid speed, but also the transformation of the current economic hegemonial principle to degrowth. The energy service demand reduction of Descriptor *3c* is only possible through collective adoption of lifestyle changes and altered consumption patterns. This requires a fundamental system change and political responsibility and commitment to enable respective transformations in lifestyle and an economic re-orientation of Germany (SRU, 2023). The focus on energy sufficiency as guiding principle for the transformation of the energy system would ease the biodiversity crisis, enhance domestic social equity and justice equality and further strengthen Germany's resilience and adaption. Even with the inconsistencies in S3 in mind, the 1.5°C performance is the best of all scenarios and therefore represents the safest decarbonization path, whose socio-ecological implications can be reduced through close planning and monitoring.

6.3.2.4 S4 – Individualized & degrowth society

Scenario S4 is considered to be an outlier. Its emissions do not decline near to zero emissions in 2050. Accordingly, the headroom to the 1.5°C budget is small. As elaborated on in Chapter 6.1.2.4, one issue of S4 is the data output inaccuracies arising from the domestic energy production (see Descriptor *5a Minimal competition for land*). Due to the low RE capacity, S4 relies on energy imports and a high use of biomass for electricity production (see Figure 20,

Table 46), even though it is not intended. This use of biomass is also the particular reason for the low natural sink performance of S4. While the majority of bioenergy is used in energy production, the second largest share is used in the *Transport* sector, which heavily relies on biofuels (see Table 50 and Table 52). While Lauer et al. (2023) highly emphasize the use of bioenergy in long-term energy scenarios for Germany, they neglected the trade-offs accompanied in biodiversity and land-use changes. Furthermore, the definition of climate neutral biomass use is not universal and often calculated incorrectly (Selivanov et al., 2023). Especially the usage of solid i.e., woody biomass is controversial since forests present a huge sinking potential and decrease the negative impacts on the stressed biodiversity (CEPS, 2020; Lafuite et al., 2018). As Hennenberg and Böttcher (2023) elaborated on biomass use in the context of climate protection, it should only be used for material substitution i.e., products that bind carbon in the long term, such as construction timber or wood fiber boards as insulation materials. A reduction in emissions cannot be achieved in energy production sector by using bioenergy from cultivated biomass, due to so-called 'missed sink contributions'. Missed sink services are emission reductions that could take place on an agricultural land if succession to a forest was not prevented. They are currently not taken into account in the GHG balance of bioenergy. This is further confirmed by Selivanov et al. (2023). As already elaborate on in the biofuel discussion of scenario S2 (refer to Chapter 6.3.2.2), the emission mitigation performance of electricity driven vehicles is not only better in general, but also more cost-effective (Nogueira et al., 2020; Panchuk et al., 2020). Consequently, no biomass should be used in the *Energy production* nor *Transport* sector. Especially, since its sinking potential should be considered as more valuable for climate protection. This argument gains particular importance in the sufficiency scenarios where no NETs are applied, except for afforestation.

However, the main issue in decreasing S4's emissions is the influence of Descriptor *1a Significant individualization*. This behavioral expression led to high energy service demand and consequently high residual emissions in 2050. These results indicate, that without addressing individual behavioral patterns and lifestyle changes, achieving the climate targets is highly unlikely. This conclusion is on the one hand supported by the performance of the scenarios S1, S2 and S3, which focus on community-driven behavior and generally perform better. On the other hand this it is further confirmed by the recent publication of SRU (2023), who demand a stronger focus on the citizens' behavior in politics. However, this is not to shift the responsibility solely to the citizens. SRU (2023) further demands a re-organization of industrial production patterns and thereby more responsibility and commitment of politics to guide the socio-ecological transformation.

6.3.2.5 Conclusion of the Sufficiency Scenarios

In conclusion, each sufficiency scenario presents a unique pathway towards decarbonization, with distinct socio-ecological implications. To ensure successful implementation, a holistic approach is necessary, incorporating technological advancements, radical demand reduction strategies flanked with political governance, community engagement and severe political commitment. Moving beyond the hegemony of growth is considered to be the major challenge when addressing the scenarios plausibility i.e., occurrence likelihood due to the necessary radical social change in both society and political setting (Keyßer & Lenzen, 2021). Furthermore, energy demand reduction measures need political action and incentivization. Consideration of ecological consequences, resource availability and social justice dimensions is crucial in guiding the transition to a low-carbon future and achieving emission reduction goals effectively. Generally, key feasibility risks like major reliance on secondary energy carriers and NETs are significantly reduced in the sufficiency scenarios by focusing on energy demand reduction. Scenario S1 is the exception here, since DAC is assumed. The inaccuracy of a high efuels demand in S3 would also present an exception but since the sectoral demand of efuels cannot be determined, an exclusion in case of a re-modeling has a high likelihood, which is why this inaccuracy can be neglected. Furthermore, the general performance of S3 is exceptionally great, which is why it aligns with the assumptions and conclusions on energy demand reduction scenarios of Keyßer and Lenzen (2021).

In general, close planning, monitoring and continuous assessment of policy frameworks are crucial in minimizing negative socio-ecological impacts and achieve emission reduction objectives successfully by emphasizing the reduction of energy and resource consumption through changes in individual and societal lifestyles. This involves promoting and incentivizing conscious and sufficient consumption through effective policy baskets and adopt more sustainable practices in various aspects of life, such as housing, transportation and diet, since they can lead to a shift towards more sustainable and ecologically friendly patterns of citizens, However, not only individuals need altered consumption patterns. The whole German economy and industry requires a core transformation which must be in conjunction with effective legislation and guidance to prevent economic crisis. This requires a regulation of environmental standards, taxation of polluting activities and promotion and subsidies of sustainable products and services. In order to facilitate the transformation of lifestyle patterns, massive investments in public infrastructure are necessary. Furthermore, subsidies should support the sustainable transformations in the building, energy and agricultural sector. The government should support industries, companies and initiatives that are committed to a sustainable economy through targeted investment incentives and funding programs. This can help sustainable technologies and business models to be developed and disseminated quicker. This further reduces the economical ineffectiveness and socio-political low feasibility of degrowth (Keyßer & Lenzen, 2021). Moreover, information programs should provide knowledge on the advantages of transforming Germany according to the degrowth principles, to reduce public concerns and strengthen the collectiveness. Since the whole economy experience core transformation some workforce is relocated. The government needs to ensure social safeguards to mitigate the negative impact on workers and communities. Overall, the state plays a central role in transforming the economy and society and needs to create an enabling environment. Especially, given the pace at which societal transformation is needed. While there are degrowth approaches that rely more on decentralization, bottom-up initiatives, and local communities, creating an enabling environment for this bottom-up to occur and unravel is still necessary.

6.3.3 Conclusion of the Scenarios Socio-Ecological Implications

This Chapter summarizes the aforementioned socio-ecological implications of the scenarios. The GG scenarios demonstrate intricate trade-offs between economic growth, technology adoption, and climate protection. GG1 prioritizes economic growth and technology, leading to potential ecological risks associated with synthetic fuels and NETs. Additionally, reliance on domestically produced synfuels appears unlikely, necessitating careful consideration of energy sources. Concerns about the feasibility of achieving the 1.5°C objective arise due to mistaken assumptions in GG2, along with its reliance on externalized food production. The GG scenarios' success largely depends on fast technology uptake and face risks due to lock-in effects and uncertainties associated with NETs and their future policy and price developments.

Contrarily, the sufficiency scenarios offer unique decarbonization paths focusing on energy demand reduction and EJ perspectives. These scenarios generally present lower risks and higher plausibility, offering a safer route for achieving emission reduction goals without externalizing environmental costs. Emphasizing energy sufficiency strategies reduces reliance on high-risk factors. Yet, its effectiveness depends on sectoral settings and decarbonization strategies. While the presence of high RE capacity does not lower FED in this scenario modeling, these factors should not be considered in isolation and may require remodeling to address potential misunderstandings especially contained in the sufficiency scenarios.

Overall, successful climate change mitigation and a sustainable energy sufficient future require a comprehensive approach, integrating technological advancements, political commitment, social considerations and innovative economic perspectives. Implementing the promising sufficiency scenarios necessitates systemic transformation, cautious monitoring and guided facilitation to depart from perpetual growth-based economic systems emphasizing decoupling GDP from ecological impacts to achieve a sustainable and environmentally just decarbonization.

6.4 Broadening the scope

In a highly globalized world, it is difficult and short-sighted to focus solely on Germany. Since it's part of the EU, it cannot be treated in isolation. Local climate protection targets and measures are always embedded in the EU context, such as the *Fit-for-55* package or the European Green Deal (European Commission, 2023; Presse- und Informationsamt der Bundesregierung, 2023). This creates opportunities to benefit from synergy effects within the EU. However, there are also various concerns about being left out or not supported enough or even paternalized. The uprising of populism and protectionism worsens the initial position. To bridge the gap on climate neutrality, energy security and sustainability, CLEVER (2023) released a groundbreaking report that could guide the EU's trajectory to implement the 2030 Fit for 55 package and its respective climate targets through a distinguished focus on energy sufficiency, efficiency and renewables.

Moreover, climate change is a global phenomenon. There are severe concerns on the global efforts to mitigate climate change. Now, eight years after the globally established Paris Agreement, the outcome does not look promising. If current global trends persist, the projected temperature increase by the end of the decade is estimated to reach 2.7°C. However, if the planned measures scheduled until 2030 are effectively implemented, the temperature rise is expected to be limited to 2.4°C. Furthermore, in a particularly optimistic scenario, where non-binding measures are also put into action, it is possible to achieve a temperature increase of 2°C, or even as low as 1.8°C. The action taken towards the Paris Agreement achievement is at least 'insufficient' in most states (Climate Action Tracker et al., 2022). This also applies to the countries with the highest global emissions, China and the U.S. (IEA, 2022a). Accordingly, it is not enough for Germany or even the EU alone to set more ambitious targets. On the one hand, there is a need for ambitious target tracking and implementation. This implementation must take place under EJ aspects for a socially just transformation, both at domestic and global level. On the other hand, efforts must be stepped up to reduce emissions faster globally. With the historical responsibility of the early industrialized states in mind, they must take a lead and challenge the privileges that have resulted from historic dynamics. With both climate and intergenerational justice in mind, the achievement of the Paris Agreement is non-negotiable. Safeguarding economic activity cannot be the focus when addressing climate change mitigation. Especially since the cost of mitigation is far below of what compensating damages will cost (Köberle et al., 2021). These scenario narratives show, that a system change is overall plausible and possible, if courage and ambitions are stepped up.

6.5 Sensitivity analysis

This sensitivity was mainly performed to identify the Descriptor expressions influence on the GHG and FED results. However, the sensitivity analyses were not able to give satisfactory results, since the differentiation between most input levers is only marginal. Hence it could not be used for determining respective influence of certain levers on the modeling results. Most of the times more than one Descriptor expression influenced the respective ambition level. Consequently, it is impossible to say which Descriptor had the most influence on the modeling.

Nevertheless, the sensitivity data can be interpreted, yet it does not give satisfactory results to determine Descriptor expression's influence on the modeling. When revisiting the data, it is obvious that in the local sensitivity analysis the switch to efuels has a highly negative effect on the GHG as it is increased above the reference value (see Figure 21). While efuels should mitigate emissions since they do not rely on fossil fuels, their beneficial effect is highly influenced by the carbon intensity of the electricity input and by the CO_2 source (Ueckerdt et al., 2021). Since only the input lever changed, the remaining levers have shaped the energy system to a continuity of trends e.g., RE capacity is low and travel demand per capita increases. By that the remaining settings decreased the mitigation potential of efuels as the high travel demand increased the total final energy demand and consumption and probably fossils were used for electricity production. This explanation gives a good example on how ambition level 1 masked the levers effects in the sensitivity analysis. This also applies to the local FED analysis for buildings renovation rate (see Figure 23). In the global sensitivity analysis, the positive effect of the material production on the GHG emissions is outlined (see Figure 22). This could be attributed to the influence of Descriptors *2 Growth independencies* and *3 Demand for energy services*, as they were mainly used to determine the ambition level of the *Material production* levers. However, it is not clear, if the effect on the GHG is coming from the actual reduced production or appears due to the number of levers affected in the material production lever group. This also applies to the global sensitivity analysis of FED, where *Material production* also was analyzed (see Figure 24). This circumstance also applied to the remaining global sensitivity FED results. Here mainly modifications happened on a higher lever group level. Consequently, it is difficult to evaluate if the number of settings altered influenced the results or the actual data behind it. In the local FED analysis only inland passenger demand lowered the FED substantially. While such an effect is expected to happen on the FED, it is noticeable, that another lifestyle changes i.e., *living space per capita* has a less meaningful effect on the FED. Both would be determined by Descriptor *3*, with yet different magnitudes of effects. In conclusion, even though it is possible to reconstruct the tool's dynamics, the Descriptor influences cannot be derived and would require more data analyses.

As already described in Chapter 4.5.4 both implementation and results of the sensitivity analysis are not ideal. For an analysis with higher confidence values, input parameter should be modified by their standard deviation (Hamby, 1994; Iooss & Lemaître, 2015; Saltelli, 1999). However, this was not possible. Moreover, the sampling size of five levers each per analysis may be too small to get a comprehensive overview of the lever's influence. Also, the chosen input variables may not be ideal to reflect the levers influence on GHG and FED. The examination of the GHG and FED data from *Material production* shows that it would have been more useful to query the same levers in the analyses and further analyze these.

The biggest obstacle, however, is that all other levers remained on ambition level 1, since it influences the final modeling output. They masked the input parameters of both sensitivity analyses and cannot be considered isolated. Furthermore, it was assumed that the results of the global sensitivity analysis are more meaningful than those of the local sensitivity analysis, since they should give insights on levers interdependencies. This cannot be confirmed clearly after the analysis in Chapter 5.4. Nevertheless, the performance of a global analysis was necessary, as the local analysis would have fallen short to capture interdependencies.

Given the design of the modeling tool and the high variance in data input, the used method of sensitivity analysis i.e., the alteration of one input parameter, is not ideal to provide satisfactory results. To achieve more reliable results for future modeling alternative approaches may be helpful. First, a broader sensitivity analysis should be done, not only analyzing the same levers in FED and GHG, but also combining different levers in the global analysis, but always in such a way that there is also some comparability through commonalities. Second, a deeper understanding of the background data is advised as well as working with data scientists to analyze the extensive background dataset. Additionally, a statistical analysis is necessary to get robust results. Here, a *Monte Carlos simulation* may be fitting. Generally statistical methods like correlation or multi-variance analysis are advisable to complement an extensive analysis.

6.6 Reflection

The following Chapters reflect the used methods and derives opportunities for improvement.

6.6.1 Obstacles in translating qualitative to quantitative research

The challenges associated with translating qualitative storylines into quantitative data have been discussed previously in Chapter 4.4.2, highlighting both the advantages and drawbacks of the SAS approach by Alcamo (2008), as well as the attempted solutions to deal with the shortcomings. To enhance the research's credibility, consultations were conducted with the EnSu members. To ensure maximum transparency the entire dataset is available as supplementary data, to understand the decision-making process for the levers and resp. ambition levels (see Chapter 8.3). However, inherent uncertainties stemming from subjective interpretations of Descriptors persist. While EnSu members were consulted on this matter, not all levers were thoroughly discussed. In many instances, 'guessumptions' were employed, combining literature-based assumptions with descriptor interpretation-based guesses, to determine the most fitting lever's ambition level. Moreover, the modeling process was consistently guided by a predefined target image, introducing a potential bias due to priming effects. Consequently, it is recommended to consider externally validating as well as repeating the modeling process and compiling the resultant outcomes at this juncture.

Yet it's important to highlight that the used method-chain, combining CIB and SAS, is generally advised. Prehofer et al. (2021) concluded in their research that this hybrid scenario construction provides valid results in energy system modeling. This is mainly due to close interaction and consistent knowledge transfer between both storyline and simulation group. Yet, both processes, first the creation the storylines and second, the modeling of them, are separate processes with a lot of time in between. Even though close interaction was possible, the loss of knowledge wasn't fully preventable. However, the challenges apparent in this methodology appear mainly from the selected tool, covered in the following Chapters.

6.6.2 Limitations of the EnSu Narratives and Descriptors

As already mentioned in Chapter 4.5.1, the actual EnSu narrative texts were not used for the translation into the *2050 Pathways Explorer*, but rather the text modules of the Descriptors and their expressions (see Chapter 8.4). The reason for this is that the narratives serve the purpose of depicting the future in 2050 and represent the Descriptors as well as the expressions in a compressed and highly simplified way. Consequently, the Descriptor texts can be incorporated in the tool more accurately, especially when using CIB matrices which represent the scenario-specific expressions in relations (see Chapter 8.5).

Moreover, some general challenges appeared, adding to those presented in Chapter 4.5.1. For example, the tool's levers are small-scaled, while the Descriptor texts are more superficial. Consequently, consultation of the EnSu members was necessary, to provide the context scenarios and narratives consistency for aspects not covered by EnSu originally (see Table 27). It is generally advisable to extend the narratives created by EnSu with further sector-specific quantitative objectives. The tool levers could act as guidance.

However, the most severe limitation in translating the narratives in quantitative data was the lacking integration possibility of social dimensions such as Descriptor *4 Wealth distribution and property relationships*. This challenge rather appeared due to the selected tool, since none of the available levers addressed such equity dimensions specifically. Descriptor *4* expressions were only considered implicitly in e.g., in per capita floor area, vehicle occupancy and flight distance. Aspects like ownership of infrastructure, tax fraud or unfair cost distribution in the energy transition, all mentioned in Descriptor *4* were impossible to include. Yet, the explicit integration of such equity or EJ aspects are important to include in energy system modeling, especially when modeling in the degrowth context (Keyßer & Lenzen, 2021). In this tool, the integration of the lever group *Costs* could allow its usage as a proxy, as done by Kuhnhenn et al. (2020). However, this wasn't possible as explained in Chapter 4.5.1.2.

Similar issues appeared in the translation of Descriptor *2b Independence of growth*, which differentiates S1 from the remaining sufficiency scenarios. Since the expression of a-growth is only marginal from degrowth, the integration of the social and well-being dimensions, and effects on workforce would be necessary to provide further consistency between the scenarios. Yet, no social-specific levers are included in the tool as well as no proxy was available. Generally, in many cases it was difficult to integrate Descriptor expression's aspects in the tool. Further tool-based limitations are covered in the following chapter.

6.6.3 Obstacles Arising from the *2050 Pathways Explorer*

Some tool-based limitations were already covered in the Chapter 4.5.1.2 of the data collection. Not only did some levers had ambiguous or none apparent effect on the results (see Table 28 and Table 29), the whole lever group *Costs* could not be included in the modeling due to severe uncertainties. This affects the results robustness. Furthermore, historic emission levels were not calibrated to countries actual emission levels, as described in Chapter 4.3. While the actual German emissions reduce in 2019 and 2020 due to COVID-19, they rebounded to their original trend in following years (UBA, 2023a). Consequently, calibration would be necessary for all scenarios as Figure 4 indicates. All the scenarios emission are higher than the real German emissions until 2021. Afterwards the sufficiency scenarios emissions drop below the real German trend. Thus, the interpretation of the results is difficult. Furthermore, the data output like sectoral and vectoral energy consumption and demand is inconsistent in many cases, and sectoral and vectoral demands cannot be reconstructed by referring to the available data. Climact (2023c) mentioned this as a possibility, the extend was underestimated. Even more limitations became apparent when examining the data in more detail.

Generally, simulation tools like the *2050 Pathways Explorer,* offer certain user-based advantages. They facilitate comprehensive system analysis, understanding the systems performance, respond and design and provide a dynamic representation of an energy system and its interactions over time. However, they come with certain drawbacks. For example, one obstacle arose from the ability to take into account the systems complexities, such as dynamics of energy supply and demand. If not met inherently by the chosen levers, import will be adjusted to meet the demand. This e.g., shows in sufficiency scenario S4 where *self-sufficiency* was selected in the lever group *Imports/Exports* and yet electricity imports appeared in the scenarios FED. Since S4 has a low potential for domestic RE (see Descriptor *5b*), local demand exceeded domestic supply, causing the unexpected energy imports. Consequently, these explicit results for S4 are considered to be false, in the sense of that the outcomes of S4 are not matching its underlying assumptions and operational framework created by the context scenarios. Similar inaccuracies appeared in the other scenarios like in S3. Yet, it is not said, that the underlying simulation model is not providing robust results in general, and that an optimization model would lead to no such issues. Logically, a predefined model cannot address the existing scenario specific conditions perfectly. Only a model created specifically for this modeling could have accomplished this. As Zeng et al. (2011) covered, uncertainties and model-based limitations also appeared in their research on optimization models in energy system planning. Hence, the combination of both modeling approaches could be considered when re-modeling (Barton & Meckesheimer, 2006).

Although the *2050 Pathways Explorer* is open-source and more intuitive than, e.g., IAM's, the exact impact modes could not be understood in detail i.e., which lever settings are responsible for which results. This is also evident in the sensitivity analysis, which does not deliver satisfactory results, but this is mainly due to the general functionality of the tool and the resulting modified analyses (see Chapter 4.3 and 4.5.4). Furthermore, it is not clear how the so-called rebound effect, which refers to the phenomenon where energy efficiency improvements can lead to an energy consumption increase, is reflected in the tool. While it is possible to analyze the background data provided (see Climact, 2023d, 2023e), to validate the data and reconstruct input data and lever dynamics would have been beyond the scope of this paper. Resulting uncertainties became obvious e.g., in the selection of endo- or exogenous modeling of *Industrial material production* or *Oil production capacities*. Such a decision is also possible for the lever group *Cost*, but can be neglected since it is not included in the modeling. Both lever groups relevant were adjusted for exogenous modeling. While the decision on the *Oil production capacities* is literature-based (see Prognos et al., 2020, 2021), the decision for industrial *Material production* is based on information by the Descriptor expressions of *2a* and *2c*, *3a* and *3c*, *6a* and *9a* (see Chapter 8.4). The information of the respective Descriptors is considered to be sufficient to interpret the general *Material production* levels even though the resp. passages are vague and general. They do not provide detailed information of material specific production levels and just describe production level in general, as "[...] the production in the industry sector stays the same as today [...]" (Descriptor *3a*) or "[...] the number of products has decreased substantially and thus also the volumes of materials and products that are produced in the industrial sector" (Descriptor *3c*). An alignment of production levels with sectoral demands would have been advisable, but did not happen. The narratives do not address *Industry* at all and the Descriptor expressions are vague in this regard. Consequently, it would have been well beyond the scope of this thesis to perform a deeper sectoral analysis. Finally, the question remains whether endogenous modeling would be advisable based on the sole availability of general statements. Since knowledge on the dynamics of endogenous modeling in the *2050 Pathways Explorer* is not provided, relying on exogenous modeling was chosen, to guarantee consistent results with the EnSu data input.

Yet, most of the apparent modeling challenges resulted from the levers not included in the tool. Already in the tool selection process, one missing basic lever was really evident: the exclusion of GDP as an input lever. Since it is not considered as a suitable measure for well-being, growth, and prosperity within the concept of degrowth (as discussed in Chapter X), both the EnSu context scenario and the narratives did not make any assumptions regarding GDP. Consequently, the *2050 Pathways Explorer* was chosen as a fundamentally suitable tool, since the absence of the GDP lever was not considered problematic given the context of the focus on sufficiency scenarios. The tool does not make any assumptions on economic growth, since the modeling is mainly driven by behavioral, societal, technological chances and decision-making expressed through the decarbonization levers. However, Samadi et al. (2017) advise the integration of modeling impact on economic activity when modeling energy sufficiency. These economic effects should be provided by supplementary models and integrated in further analysis, to provide a holistic impact chain of energy sufficient lifestyles.

For most levers it was difficult if not impossible to integrate the Descriptor's expression in its entirety. For example, the actual pace of technology uptake of Descriptor *8* could not always be reflected comprehensively. Reason is that the overarching target achievement e.g., the switch to alternative climate-friendly energy sources by 2050, could only be achieved with ambition level 4. This means that in some cases a higher ambition level had to be assumed than the context scenario specified. This applies e.g., to the energy carrier switch in the lever group *Energy production* for S1, S2 and S4. Where possible, gradations were included.

This issue of not appropriately including Descriptor's expressions further applied for the integration of the potential natural sinks, i.e., negative emissions from natural sources. The tools only possibility is namely afforestation coupled to the availability of freed-up land from e.g., agriculture. This limitation arose particularly for the sufficiency scenarios which refuse novel CDR technologies and referred exclusively to 'CO_2 sequestration' and natural solutions, like 'greening of cities' (see Descriptor *7b*). Since afforestation was the only possibility for natural sinks, the highest ambition level was assumed, although the setting of Descriptor *5c* assigned freed-up land to cropland for bioenergy or food production instead of forests. As explained in Chapter 6.3, the forest sinks assumed in the *2050 Pathways Explorer* are overestimated, and the absence of other natural sinks, like rewetting of peatlands disturbs the natural sink potential for Germany in the tool (see BMEL, 2023; Borchers et al., 2022; Hennenberg & Böttcher, 2023; Vass & Elofsson, 2016).

Generally, the results of the *Land-Use* sector should be interpreted with caution. This is also due to the underrepresentation in the *Land allocation* data. For example, the installed capacity of onshore wind power or ground-mounted PV does not seem to have an impact on such data. The *Land allocation* data represents no column for 'land allocated to RE production' (see Table 49). Furthermore, it is not clear how the effects from CCS on land-use and biodiversity are taken into account. There is also no column representing CCS in the *Land allocation* data. As Bysveen et al. (2022) conclude, the relationship between CCS, like BECCS and DACCS, and land-use and biodiversity is complicated. While a reduction of GHG is beneficial for climate change mitigation and in the long run also to prevent biodiversity loss, the life cycle assessments of such technologies are often neglecting negative impacts on nature. The focus on emission reduction seems to outweigh land and water use implications as well as ecotoxicities and environmental stressors leading to pollution. These excluded effects need consideration when analyzing the scenarios in the following chapters.

Furthermore, it was difficult to integrate biodiversity dimensions in the FAFOLU lever group in general. Biodiversity is addressed in Descriptor *9c High priority for climate and environmental justice*, yet there is no appropriate lever to adjust e.g., protected areas for biodiversity gains. Generally, positive changes in the *Land-Use* sector, like extensive agriculture and freed-up land for afforestation can be used as a proxy for biodiversity gains (Lafuite et al., 2018). Since the *Land-Use* results contain high uncertainties weakening their robustness, no final statement can be made regarding the scenarios biodiversity development.

While the *2050 Pathways Explorer* provides a fairly comprehensive picture of the energy system, there are some severe limitations. Consequently, the respective results should be interpreted with caution. Nevertheless, it provides robust results which are further enhanced after re-modeling and eliminating tool-based errors. Even now, the results give a great insight on the modeling of low energy demand scenarios and their potentials in contrast to green growth scenarios.

7 Prospects and Conclusion

This master's thesis investigates climate neutrality trajectories for Germany by 2050 using emission pathway modeling and assesses their implications for climate change mitigation. The research focuses on possible decarbonization trajectories for Germany by 2050 based on modeled scenarios, their compliance with the German CO_2 budget and their socio-ecological implications based on different scenario trajectories.

The results outline the scenarios distinct decarbonization trajectories for Germany. While the GG scenarios rely on advanced technology uptakes and externalization of environmental cost, the sufficiency scenarios performance is driven by energy demand reduction and scenario specific energy system settings. Comparing the sufficiency scenarios to the government's objectives, it becomes evident that the sufficiency scenarios demonstrate greater ambition and optimized pathways for emission reduction. This highlights the need for a paradigm shift in addressing activity patterns, consumption and production behavior to meet the climate targets. Furthermore, the modeled scenarios are in compliance with the German carbon budget. However, their residual margin is very small. Furthermore, these results should be interpreted cautiously due to uncertainties in CO_2 shares and the focus solely on CO_2 emissions while neglecting other potent GHGs. This could lead to misjudgment in policy drafting. To avoid exceeding the budget, a generous buffer and effective, sustainable emission reduction actions are recommended to account for these uncertainties.

The analyzed the socio-ecological implications of the different scenario trajectories underline the generally better socio-ecological performance of the sufficiency scenarios, indicating their safer decarbonization path. The socio-ecological implications reveal the complexity of trade-offs between economic growth, technological innovation and climate protection. Energy demand reduction scenarios help to reduce reliance on high-risk factors like synfuels and imported energy, as well as the deployment of NETs significantly. Further, they account for EJ perspectives and minimize the externalization of environmental costs. The sufficiency scenarios highlight the importance of considering individual behavior adoption and an integration of energy sufficiency strategies in the transition to a climate neutral society. Moreover, the results align current beyond growth trajectory research, emphasizing the reduction of material production and consumption and changes in activity patterns to stay within safe carbon budgets for high-income countries. To achieve the ambitious decarbonization performance, a fundamental shift from growth to degrowth is required.

The thesis acknowledges certain limitations, such as the isolated consideration of the German energy system without considering the broader EU and global context. Furthermore, the results are influenced by shortcomings in the modeling tool, which can be mitigated by re-modeling.

Since the used modeling tool is updated frequently, this would already provide improvements to the scenarios energy system modeling.

Overall, the modeled scenarios serve as a valuable first draft for deriving policy implications and shaping sufficiency indicators for monitoring the socio-ecological transition Germany. The development of energy sufficiency boundaries provide guidelines for a just social-ecological transformation and support a complementary approach for a sufficiency-based systemic transition, beyond conventional efficiency efforts to a more holistic approach.

Further research should aim to highlight the integration of equality aspects and explore GDP development in sufficiency scenarios. By conducting an optimized sensitivity analysis, the influence of descriptors on the modeling can be determined, leading to actionable insights for implementing energy sufficiency policy packages aimed at reducing energy demand at both individual and sectoral levels. Moreover, it is recommended to continue and complete the SAS approach to enhance modeling credibility. Additionally, uncertainties and inconsistencies to the underlying narratives need further consideration, dealt with by re-modeling the scenarios.

In light of climate urgency and the importance of climate justice, early industrialized countries like Germany should take stronger global efforts in reducing emissions. Policymakers and stakeholders must consider the complexities and challenges involved, striving for a balanced integration of technological advancements, behavioral changes and decarbonization efforts to achieve an effective and equitable climate neutral future. Energy sufficiency principles need further consideration in the adoption of decarbonization strategies as they minimize risks and promote environmental sustainability, while targeting multiple crisis at once. Overcoming growth, choosing energy sufficiency and implementing it in climate protection action is highly recommended. Especially, since the sufficiency scenarios clearly outperformed the green growth scenarios. Finally, choosing energy sufficiency is a no-regret option to comply to the emission reduction trajectory of Germany, and safeguard Earth’s livability for all human beings.

8 Appendices

8.1 List of Tables

8.2 List of Figures

8.3 Note on external data sets

This master's thesis relies heavily on data i.e., tables and graphs not shown in this paper. The reason is, that it would have expanded the work artificially. The external data set consists of the full EnSu narrative dataset, all downloaded data in the first and second modeling run. They are structured in modeled scenarios in both modeling runs plus sectoral and total datasets. A selection necessary for clarifying the modeling results is presented in Chapter 8.11. To provide maximum transparency an extensive table on the assumptions for each scenario in both modeling runs i.e., the chosen ambition levels in the 2050 Pathways Explorer, is provided. Here, further explanation on the decision-making process is included (see *Pathway_Ex_assumptions_final.xlsx*).

This full data set is handed to the University of Freiburg on a hard drive, but is also available and happily shared on request. Contact: kayafiorella@googlemail.com

8.4 EnSu descriptors for context scenarios

The following Chapters provide a condensed summary of the respective EnSu descriptors. The original EnSu descriptors and narrative texts are provided as external data.

1 Individualization

Individualization is the trend towards self-determination, as individuals internalize previous social constraints as norms and values. This sociological megatrend is analyzed and discussed, alongside counter movements like a return to traditional gender roles. Industrialized societies display regressive aspects, including gender-unequal mobility, consumption norms, and exploitation in precarious wage labor. Consumption norms shape individual socialization and serve as markers of social distinction, including sustainable consumption and voluntary sufficiency. Historical individualization is linked to Fordist production, mass production, and mass consumption, intensifying the exchange between nature and society.

1a Significant individualization

Consumption patterns, culture, and lifestyles vary in today's society. Flexible biographies and evolving care and wage labor dynamics contribute to increased mobility and smaller households. This offers diverse options for travel, living, and work but also brings insecurity. Liberalism is associated with legal consumption freedom, while sustainability allows the affluent to differentiate themselves but places responsibility on individuals. This reflects the current state.

1b Keep the balance

Individualization and communities share a mutually beneficial bond. Sharing economies like co-housing, repair cafés, community gardens, energy communities, car sharing, and public transport flourish at micro and meso levels. These initiatives provide important spaces for socialization, driven by shared interests and conviviality. They help address social challenges arising from demographic changes and resource limitations. The trend towards personal freedom and self-determined lifestyles continues, gradually eroding traditional familial and national ties. The state actively supports these communities while respecting their self-governing capacities.

1c Community

Communities and the state take precedence over individual interests, utilizing collective decision-making to set consumption boundaries. This societal shift emphasizes stronger family and social ties, aiming to enhance security through local structures. These collective frameworks heavily influence individuals' socialization, surpassing the pursuit of personal and self-determined lifestyles. The family, as the smallest societal unit, promotes cohesion and security.

2 Growth independencies

Since the Club of Rome report in 1972, the link between climate/environmental protection and economic growth has been a subject of debate. The possibility of decoupling economic growth from nature/resource consumption is a controversial question. Relative decoupling refers to efficiency improvements, resulting in reduced nature consumption per GDP. However, emissions can still rise with increasing GDP. Absolute decoupling involves increasing economic output while decreasing nature consumption. Relative decoupling is widely accepted and observable, but there is an ongoing academic debate about the feasibility of absolute decoupling and potential displacement effects. Regardless, it is clear that absolute decoupling alone may not sufficiently and rapidly reduce nature consumption. These indicators reflect the prevailing discourse in policy and society regarding the relationship between economic growth and ecological consumption.

2a Green Growth

Climate change presents significant ecological, economic, and social challenges to our societies. It is evident that the costs of climate protection are outweighed by the damages caused by climate change. However, climate protection technologies also offer opportunities for a new growth market, enabling economic growth and climate protection to align. In fact, they must align, as further economic growth is needed to finance the necessary but costly investments in climate protection. Promoting efficiency improvements, renewable energies, and sustainable goods is thus crucial in this context.

2b Independence of growth

Currently, there is limited solid evidence to support the possibility of achieving an absolute decoupling of economic growth from nature and resource consumption. Concurrently, there is a growing body of evidence suggesting that economic growth is an inadequate measure of prosperity. The political emphasis on economic growth is a relatively recent development, emerging gradually in the postwar era. However, a cultural and institutional reliance on economic growth has become deeply rooted. It is no longer necessary to prioritize economic growth as the primary objective of political action. Instead, efforts should be directed towards achieving independence from growth i.e., a-growth. This approach is crucial for comprehensive climate protection, ensuring that savings are not nullified by rebound effects, and securing prosperity that transcends access to material resources.

2c Degrowth/shrinking production & consumption

Historically, OECD countries in the Global North have witnessed a strong link between economic growth and nature consumption, surpassing the global average. To achieve strong sustainability, reducing overall consumption levels is necessary. It is increasingly clear that further economic growth in these countries does not necessarily lead to increased prosperity and may even result in a decrease. This has sparked critical discussions on consumption, seen in movements like flight shame and degrowth discourse. Degrowth advocates argue that lowering consumption levels can coexist with wealth preservation, aiming to promote human well-being. Achieving this requires a shift towards independence from growth as a fundamental prerequisite.

3 Demand for energy services

This descriptor pertains to the level of demand for energy services provided by energy-consuming technologies. These services encompass various aspects such as comfortable indoor temperatures, good air quality, well-lit workplaces and homes, and the ability to be sufficiently mobile or transport goods. Energy services can extend beyond basic needs, encompassing desires for off-season food, meat-based diets, or overseas leisure trips. The final energy demand resulting from these services depends on the technologies employed, their efficiencies, and the energy sources utilized. However, the service level itself takes precedence over these factors, influenced by available infrastructures, policy frameworks (including regulations and incentives), cultural and social norms, and psychological routines. Affordability may also limit the service level, leading to energy poverty and unsustainability. Nevertheless, technologies, their availability, attractiveness, and social acceptance can still impact energy service demand (for example, the availability and social acceptability of large cars influencing mobility demand).

3a Continuous increase of energy

Public discourse on addressing the climate crisis primarily focuses on technical solutions such as expanding renewable energy, improving energy efficiency, and fuel switching. Service-level approaches are often criticized as over-regulatory or intrusive. In the building sector, the average floor area per capita continues to increase, albeit at a slower rate due to rising costs. High living standards are associated with large living spaces, thermal comfort, and numerous appliances. In transportation, high mobility standards prioritize individual comfort and low costs, resulting in long commuting distances and increased freight transport. Consumption remains high, with limited emphasis on circularity. The average diet, agricultural practices, and livestock numbers remain unchanged. The prevailing social norm is high living standards, characterized by large living spaces averaging 52 m^2 per person in 2050, along with high thermal comfort and a maximum number of appliances. The projected transport demand in 2050 remains at the same level as today, with an estimated 1,200 billion passenger kilometers (pkm). This will require an increase in transport needs from the current 660 billion tonne-kilometers (tkm) to 900 billion tkm, encompassing both national and German parts of international transport.

3b Stabilization and partial decrease of service demands

Scenario studies indicate that relying solely on technology options to meet climate targets would require unsustainable energy imports or biomass use. However, in an alternative future, dedicated policies are enacted to limit drastic increases in service demand levels. This includes slightly reducing living space per person (m^2/person is reduced to the level from the year 2000 (39.5 m^2/person average) in 2050) and shifting focus towards public transportation in the transport sector. While overall product demand remains high, the popularity of the circular economy leads to a slight decrease in the demand for new products. Additionally, there is a trend towards less animal-intensive diets, resulting in a modest reduction in animal livestock and decreased imports of animal feed.

3c Sufficiency-oriented reduction in service demand

In the 2020s, the consequences of climate change prompt a significant shift in public discourse and policy. It is recognized that achieving climate targets requires a profound change in lifestyle and consumption patterns. The vision of a ‘good life’change to prioritize a healthy, accessible, and inclusive living environment. As a result, average living space per person decreases, and there is a decrease in average trip distances. The improved public transport network encourages public modes of transportation, reducing passenger kilometers. Durable products lead to a decrease in the number of items produced, and there is a shift towards reducing food waste and adopting vegan and vegetarian diets, resulting in decreased livestock farming intensity and fertilizer use.

Per-capita floor area stabilizes and decreases to an average of 32 m^2/person. The improved public transport network, with a maximum frequency of 20 minutes, enables widespread use of public modes of transportation in most regions. Pkm decrease to 958 billion, while tkm see a slight increase to 739 billion, as projected by the UBA Green Supreme scenario.

4 Wealth distribution and property relationships

Wealth and property have a complex relationship with sustainability. Germany has high wealth inequality, with the richest decile owning 60% of the total wealth. Ownership of fossil structures creates a vested interest in maintaining them, hindering retrofitting efforts. Rising energy costs disproportionately affect poor households, impacting their budgets. The energy transition brings job changes in sectors like energy, transport, and industry. This descriptor examines the effect of wealth distribution assumptions on other indicators, including occupational positions, education, power, and wealth.

4a Reinforcing Inequality

In Germany, income inequality is increasing, leading to a rise in poverty, social exclusion, and limited opportunities for self-realization, particularly within national borders. Rural areas, in particular, are facing neglect and social conflicts are escalating. Meanwhile, a small class of wealthy individuals benefits from tax evasion and avoids social responsibility. Poor households bear the brunt of the costs associated with the energy transition, lacking financial relief and opportunities for participation. Additionally, rising transport costs make mobility less accessible for many.

4b Greater Equality

Social inequality is greatly reduced, with equal opportunities for all individuals regardless of social class. Basic access and rights are guaranteed, and wealth accumulation is capped. Tax-funded services, like mobility and energy, support energy-poor households. Owner-occupied properties are widespread, and affordable multimodal transportation replaces private vehicle ownership.

5 Domestic potentials of land for renewable energy production

Land is a limited and irreplaceable resource that faces competing uses such as food production, nature conservation, urban and rural development, and energy generation. Renewable energies require relatively large amounts of land per unit of energy capacity, which places constraints on installed capacity. Currently, Germany imports a significant portion of its cropland footprint due to consumption patterns. The issue of competition between food production, energy crops, and resistance to new wind turbines highlights the political nature of defining the available land and its allocation.

Biomass potential: 5a 38 TWh, 5b 200-340 TWh

5a Minimal competition for land

To minimize land competition in Germany, the potential for renewable energies is tightly restricted. As of 2021, a significant portion of the energy consumed in Germany is imported from other regions, particularly northern parts of Africa. Energy crops are not used domestically, limiting biomass potential to waste materials. The potential for onshore wind energy and freestanding solar systems is strictly limited. In order to prevent conflicts, the potential for offshore wind energy is also tightly regulated. The highest potential lies in rooftop solar installations.

5b Medium land consumption

In an effort to strike a balance between minimizing land competition and harnessing the high potential of renewable energies in Germany, a larger share of biomass is utilized for energy production. The potentials of onshore and offshore wind energy, as well as freestanding solar systems, are considered moderate. However, rooftop solar systems still hold a high potential for energy generation. This approach aims to optimize renewable energy sources while mitigating land use conflicts.

5c High inland energy production

To decrease energy imports and fully utilize the potentials of renewable energies, Germany maximizes the use of these resources. Restrictions, such as distancing regulations for wind turbines or nature protection considerations, are minimal, and there is high public acceptance. The promotion of energy crops is encouraged, resulting in a biomass potential that is primarily limited by economic factors. Additionally, the potential for other renewable technologies, such as solar and wind energy, is very high. This approach aims to fully exploit the renewable energy potential in Germany, considering it a land-intensive but necessary endeavor to reduce reliance on energy imports.

6 Resource availability, externalization and international distribution

The transformation of energy systems and activities in various sectors is closely connected to resource consumption. Resources encompass subsurface resources (such as metals, fossil fuels, and minerals), areas above the solid surface (forests, water bodies, natural areas), as well as recyclable and renewable energy resources. These resources are crucial for the energy transition and the sectors' operations, including the production of consumer goods, technologies, and buildings.

However, resources are not infinite, and their availability and exploitation can be limited by environmental, social, financial, and political constraints. Factors influencing resource availability in Germany include the occurrence and accessibility of reserves, technological and financial limitations, and the potential negative effects associated with resource extraction, such as climate impact, ecological consequences, and conflicts over land use and distribution.

The descriptor distinguishes between resources available and used within Germany and resources imported from outside the country, highlighting the ethical and environmental implications of relying on external resources and potentially living at the expense of others.

6a Availability of resources is only limited by techno-economical constraints

The resources used in Germany, including imports and the externalization of impacts, are mainly driven by economic considerations and the price of resources. If there is a demand and economic supply, resources are imported and utilized. The global availability of resources is largely unaffected by social and ecological movements. Technological progress in resource extraction can increase resource availability to some extent. To secure energy imports, Germany may invest in supply infrastructures in exporting countries that lack the necessary facilities.

6b Availability of resources is limited by planetary boundaries

Global resource availability is guided by ecological considerations, such as adhering to planetary boundaries. This recognition serves as a boundary condition for resource usage. However, the distribution of resources is predominantly driven by economic principles. As resources become scarcer, their prices increase, although imports remain higher compared to a future scenario with a "just distribution" of resources. Technological advancements in resource extraction are rapidly evolving to enhance resource availability.

6c Availability of resources is limited by planetary boundaries and just distribution

The quantity of resources utilized in Germany is based on an equitable distribution, considering factors such as per capita allocation and the needs of future generations. These considerations shape the available resources, which are seen as a boundary condition for the transformation of energy systems and sectoral activities. Technological advancements in resource extraction can further contribute to increased resource availability.

7 Technological development

Technological development plays a crucial role in unlocking the potential of renewable energy plants, storage technologies, grid infrastructure, energy-efficient renovations, vehicle technologies, industrial processes, synthetic fuel production, carbon capture, and more. The availability and cost-effectiveness of these technologies depend on global efforts and investments in climate protection technologies, support for their further development, technology transfer options, and access to risk capital for potential game-changing innovations.

The market volume and potential scale effects resulting from widespread adoption heavily influence the potential for cost reductions and technological advancements. Digitalization offers opportunities for resource and energy savings, but it has also been associated with increased resource and energy consumption due to the infrastructure, devices, and services it requires.

The alternative futures described in this context highlight the key areas of focus for technological development and their potential impacts.

7a Technical skepticism

In this scenario, technology is viewed as a tool to achieve societal goals, but it is recognized that technology alone cannot solve socio-ecological problems. Technological development is important and can improve processes, but its effects are always shaped by social conditions. Historical evidence shows that increased technology use has often led to more exploitation of nature. The production of high-tech products raises concerns regarding human rights and global trade systems.

A sensible approach involves considering rebound effects, where increased efficiency may result in higher resource consumption. Social rebound effects can also occur, leading to heightened stress despite technical optimizations. Therefore, technical innovations should not be pursued for their own sake. Instead, they should be integrated back into the social sphere and critically evaluated based on their contribution to human well-being and environmental preservation.

Technologies should serve the common good economy rather than profit motives. This entails a contraction of the techno-sphere, where policymakers prioritize social innovations and system change as solutions to societal challenges like climate change, exceeding planetary boundaries, and growing social inequality. The focus is on reshaping the system rather than relying solely on techno-economic solutions.

7b Convivial technologies

In this scenario, a combination of technical and social approaches is embraced, with a focus on small-scale, open-source technologies that can be modified and repaired by individuals. The ideal is to foster conviviality, where technologies are accessible, flexible, adaptable, and environmentally friendly, minimizing toxicity and harmful interactions.

Households are not just energy consumers but also energy producers, actively participating in energy communities and utilizing small solar and wind power plants. Shared mobility services using electric vehicles are preferred over private cars, and long-distance travel relies on synfuels and hydrogen.

For carbon sequestration, emphasis is placed on practices such as humus build-up in soil through smallholder farming and community-supported agriculture. Carbon management is achieved through composting and circular economy principles. Greening of cities is also important for both carbon sequestration and climate control.

While digitalization continues to exist, its growth is significantly reduced. Efforts are made to improve energy efficiency and promote circularity in the production and use of electronic devices and infrastructure, helping to offset the moderate growth rates of data traffic, storage, and device usage compared to current trends and projections.

7c Steady technology development

Existing technologies that are crucial for the energy transition in Germany undergo incremental development. Sector coupling, connecting different sectors through integrated energy systems, becomes a central element of the transition. Technologies related to electrification, including digitalization, receive extensive support.

From the 2020s onwards, wind and solar energy will be widely implemented, aided by advancements in materials for PV panels and wind turbines, resulting in reduced installation costs. Recycling processes also improve, leading to a significant reduction in primary resource input for these key technological pillars of the energy transition.

Heat pumps become more affordable, and environmentally friendly coolants are developed, supporting the electrification of space and process heating. Efforts are made to lower the required heating temperatures, leading to the use of new sustainable materials for energy-efficient renovations. This simplifies the renovation process and reduces the primary energy input for insulation materials.

In the transport sector, electrification becomes pervasive, with electric motors being utilized in trolley trucks, ships, and even planes. Only long-haul cargo ships and planes still rely on fuels, but efforts are underway to find sustainable alternatives for these modes of transportation as well.

7d Technology optimism

Worldwide, there is a high demand for technologies that contribute to climate-neutrality. Significant research funding is dedicated to improving existing technologies and developing early-stage options. CO_2 is utilized for generating synthetic fuels, and photovoltaic modules are integrated into various applications. Large-scale power plants capable of utilizing hydrogen are available as a backup in the energy system. High-temperature storage systems efficiently store and provide heat and electricity. The efficiency of synthetic energy carrier generation processes, such as hydrogen and methane, improves. While the energy efficiency of electronic devices and digital infrastructure increases, global data traffic, storage, and device usage continue to grow exponentially.

8 Speed of technology uptake

The urgency of achieving climate goals requires a rapid transformation of energy systems. However, this fast-paced implementation comes with challenges. It requires the availability of capacities, materials, land, permits, investment capital, technological advancements, and societal acceptance. Sectors involved in the transition cannot easily scale up or down, as they depend on established resources, successful procurement, and stable economic conditions. Interdependencies between sectors can also impact the pace of transformation, such as the expansion of renewable energy relying on the development of the electrical grid. The speed of grid expansion is influenced by approval procedures and legal actions. Different activities and demands, whether from private individuals or companies, also require specific considerations, such as the installation of rooftop PV systems versus standalone systems or the expansion of railways versus individual vehicle usage.

8a Slow but safely

In this future scenario, expansion rates are carefully managed to maintain stability. The goal is to avoid sharp declines in any sector during the period and the following 10 years. While incremental fluctuations, including downward trends, are acceptable, they should be limited to a few sectors and accompanied by options for retraining. The initial ramp-ups of sectors are assumed to be relatively low, preventing rapid expansion in the early years. This measured approach aims to ensure a balanced and sustainable growth trajectory.

8b Fast

In this scenario, speed is prioritized in order to achieve climate protection goals. Approval procedures for infrastructure and renewable energy projects are expedited, and production capacities in certain sectors are rapidly expanded, even if it leads to sharp declines in other sectors and temporary unemployment. The implementation of central infrastructures like bicycle lanes and large-scale projects, as well as individual actions by citizens such as home insulation and adoption of electric vehicles, happens at an accelerated pace beyond previous expectations. The focus is on swift adoption of new technologies and behavioral changes to accelerate the transition towards a sustainable future.

8c Acceptance problems for large scale projects

This descriptor expression is not used in the EnSu context scenarios.

9 Priority setting for/discourse on climate protection and planetary boundaries

The political importance of climate and environmental protection is strongly influenced by social discourse. Social movements, such as the anti-nuclear movement, Fridays for Future, and climate justice movements, have the power to shape agendas, influence discourses, and exert pressure on decision-makers. The occurrence of catastrophic events like the Fukushima nuclear disaster or severe droughts, as well as new scientific findings, also contribute to shifts in discourse. This descriptor examines the various developments in climate and environmental discourses and their implications for political prioritization.

9a Consistent priority of climate protection

Climate and environmental protection have gained significant priority in political decision-making due to the growing recognition of climate change impacts. Although some social movements struggle to maintain momentum, there is regular media coverage on these issues. However, ensuring Germany's position as an industrial hub and promoting economic prosperity continue to be central political goals. Within the realm of climate and environmental protection, the primary focus is on mitigating climate change and meeting internationally agreed-upon climate targets, with a particular emphasis on national emission levels.

9b High priority for climate protection

Climate and environmental protection take center stage in political debates and decision-making processes. It becomes an unavoidable goal for all political parties, and business leaders also acknowledge the importance of climate protection and advocate for the transition to a green economy. The presence of numerous social movements puts pressure on decision-makers across various sectors related to climate issues. The focus of these debates is primarily on climate protection and meeting national emission targets.

9c High priority for climate and environmental justice

Climate and environmental protection is recognized as a crucial goal in all sectors of society, extending beyond climate change to include other planetary boundaries and sustainability concerns. Biodiversity loss, land use change, and the promotion of a sustainable circular economy are given significant attention in political agendas. The principle of accountability has shifted towards the polluter pays principle, where the responsibility for climate and environmental damage lies with the entities causing it. Thus, the focus is not only on emissions and nature consumption within Germany but also on the embedded damage associated with the consumption of goods. Climate justice movements, interconnected globally, exert considerable pressure on decision-makers in Germany and other countries. The overarching objective is to reduce resource and energy demand to a just and globally applicable level, aligning with the goal of limiting global warming to 1.5 degrees Celsius.

10 Housing and supply structure

This descriptor focuses on the structure and distribution of living spaces and everyday life amenities, such as workplaces, grocery stores, schools, healthcare facilities, and cultural venues. Urbanization, a significant megatrend, offers the advantage of shorter distances to multiple points of interest (POI), enabling sustainable transportation options and reducing road traffic. However, the migration of people from rural to urban areas puts pressure on cities to provide sufficient living space and infrastructure, especially as the average per capita living area continues to increase. Conversely, rural areas experience a trend of increasing living space per person, resulting in vacant properties, deteriorating buildings, and a decline in local amenities. This, in turn, leads to longer distances for daily necessities and reinforces the urbanization trend. These parameters have a significant impact on other factors such as household energy consumption for heating, transportation volume and modes, infrastructure requirements, and residential building demand.

10a Centralized living and supply structures

Market principles primarily drive the development described in this scenario, with limited regulatory and incentive policies in place. Large cities experience substantial growth, while rural areas continue to depopulate. The increasing demand for larger living spaces in urban areas is primarily met through the construction of new residential housing, and to a lesser extent, due to changes in work organization that reduce the demand for office buildings. In rural areas, the decreasing population density leads to a decline in the density of amenities, negatively impacting sustainable transportation options and increasing distances to points of interest (POIs). Additionally, many cities face the challenge of centralization in provisioning structures, which further complicates the shift towards sustainable modes of transportation.

10b Decentralized living structures and centralized supply structures

This descriptor expression is not used in the EnSu context scenarios.

10c Decentralized living and supply structure

Regulatory, fiscal, and incentive policies play a significant role in shaping the described development. Efforts are made to address the "push pressures" that drive people away from rural areas by focusing on decentralized provisioning structures and revitalizing local communities in both urban and rural areas. Fiscal policies and incentive structures are designed to support small businesses and private infrastructures in rural areas, such as care services, medical facilities, food provision, and leisure infrastructure. Public infrastructures, including childcare, educational institutions, and local administrations, are re-localized, resulting in shorter distances to points of interest in rural areas and an overall improvement in quality of life. These measures lead to a significant slowdown in migration from rural to urban areas, reducing the need for extensive construction of new residential buildings. This helps alleviate ecological pressures associated with land and resource consumption while creating capacity for energetic retrofitting.

8.5 EnSu CIB Matrices

The CIB Matrices were provided by EnSu (see Chapter 4.2.2). The respective Table is provided externally: *EnSu_CIB_matrices_15112022.* The reading direction starts in the top-left row.

8.6 Further input of the Data collection

The following Tables provide further input on the data collection and modeling process.

8.6.1 Assigned descriptors for further clarification by EnSu

Table 27. Assigned descriptor for further clarification by the EnSu Group for selected 20 levers.

Lever level 1	**Lever level 2**	**Lever level 3**	**Lever level 4**
Buildings	Key behaviours – Buildings	Appliances use and ownership	Appliance use
Buildings	Key behaviours – Buildings	Heating and cooling behaviours – Service	Hotwater demand
Buildings	Key behaviours – Buildings	Heating and cooling behaviours – Service	Deployment of cooling system (non-residential)

Buildings	Residential	Buildings envelope – Residential	Demolition rate
Buildings	Residential	Low-carbon heating solutions – Residential	Electrification of cooking
Buildings	Services	Building envelope – Service	Demolition rate
Buildings	Services	Low-carbon heating solutions – Services	Electrification of catering
Transport	Passenger Transport	Automation of LDVs	
Transport	Technology and fuels	BioFuel switch	Road
Transport	Technology and fuels	BioFuel switch	Marine
Transport	Technology and fuels	BioFuel switch	Aviation
Food, Agriculture, forestry and land use	Agriculture practices	Alternative Protein Source	
Food, Agriculture, forestry and land use	Land-use	Freed up lands allocation	1. Afforestation
Food, Agriculture, forestry and land use	Land-use	Freed up lands allocation	2. Energy crops or natural praries
Food, Agriculture, forestry and land use	Land-use	Forestry	Forest management
Food, Agriculture, forestry and land use	Bioenergy	Agriculture co-products, waste and co	
Energy production	Combined heat and electricity (CHP) production capacities		
Energy production	Electricity production capacities	Hydro, geo & tidal	
Energy production	Technology – Energy	Carbon capture	Energy production (heat + elec)
Demographic and long term	Population		

8.6.2 List of levers which provided not apparent data

Table 28. List of 8 levers which provided no apparent data or were quantified as '0' and thus marked as 'dead'.

Lever level 1	**Lever level 2**	**Lever level 3**	**Lever level 4**	**Error**
Buildings	Services	Low-carbon heating solutions – Services	Electrification of catering	all ambition levels were quantified as 0
Buildings	Residential – Services	Green Gas	Switch to e-gas	all ambition levels share the same text; no apparent data was provided
Buildings	Residential – Services	Green liquids	Switch to e-liquids	all ambition levels share the same text;

				no apparent data was provided
Food, Agriculture, forestry and land use	Land-use	Forestry	Forest degradation	all ambition levels share the same text; no apparent data was provided
Industry	Carbon Capture	Non-ferrous		all ambition levels share the same text; no apparent data was provided
Industry	Carbon Capture	Ceramic		all ambition levels share the same text; no apparent data was provided
Industry	Carbon Capture	Chemical-Chlorine		all ambition levels were quantified as 0
Imports/exports	Imports/exports – Energy	Heat		all ambition levels were quantified as 0 %

8.6.3 List of levers with ambiguous interpretation

Table 29. List of 17 levers which were considered to be 'ambiguous' and thus contain potential misinterpretations.

Lever level 1	**Lever level 2**	**Lever level 3**	**Lever level 4**	**Ambiguity**
Food, Agriculture, forestry and land use	Land-use	Settlements and other lands		in the ambition levels only the share of 'other land areas' changes while the share of 'settlements area' stays the same
Industry	Technology	Technology switch	Cement	technology switch is broad, so there's a suitable option for each scenario, but cannot be customized exactly
Industry	Technology	Technology switch	Ceramics	only ambition level 4 provides apparent data
Industry	Technology	Technology switch	Chemical-Olefin primary	only ambition level 4 provides apparent data
Industry	Technology	Technology switch	Chemical-Olefin secondary	technology switch is broad, so there's a suitable option for each scenario, but cannot be customized exactly

Industry	Technology	Technology switch	Steel	technology switch is broad, so there's a suitable option for each scenario, but cannot be customized exactly
Industry	Carbon Capture	Aluminium		only ambition level 4 provides apparent data
Industry	Carbon Capture	Wood		only ambition level 4 provides apparent data
Energy production	Electricity production capacities	RES	Biomass & Waste	presented as cumulated capacities, preventing the determination of the optimal share of production capacities
Energy production	Electricity production capacities	RES	Solar PV	no differentiation between centralized and decentralized (rooftop or ground-mounted solar PV systems) as it is usual for Germany
Energy production	Electricity production capacities	non-RES	Nuclear phase out	phase-out data differ visually, but ambition level descriptions remain the same
Energy production	Electricity production capacities	non-RES	Fossil fuel phase out	phase-out data differ visually, but ambition level descriptions remain the same
Energy production	Technology – Energy	Switches across all energy carriers	In electricity production, the energy carrier switch (from natural gas to biogas)	energy carrier switch data differ visually, but ambition level descriptions remain the same
Energy production	Technology – Energy	Efficiency across all energy carriers	Improvement in energy efficiency	data differ visually, but ambition level descriptions remain the same
Energy production	Technology – Energy	Carbon capture	Energy production (heat+elec)	only ambition level 4 provides apparent data
Imports/exports	Imports/exports – Energy	Hydrogen		2021 is assumed as the starting year for import/exports of

				Hydrogen in all ambition levels
Imports/exports	Imports/exports – Energy	Efuels		2021 is assumed as the starting year for import/exports of Efuels in all ambition levels

8.6.4 Local sensitivity analysis parameter

Table 30. Parameter chosen for the local sensitivity analysis of GHG emissions and final energy demand on the lowest resolution level.

Output parameter	Lever level 1	Lever level 2	Lever level 3	Lever level 4
GHG	Buildings	Residential	Low-carbon heating solutions – Residential	Electrification of space and water heating
GHG	Energy production	Electricity production capacities	RES	Solar PV
GHG	FAFOLU	Agriculture practices	Crop extensification degree	
GHG	Industry	Material	Material switch	
GHG	Transport	Technology and fuels	e-Fuel switch	Road
FED	Buildings	Key behaviours	Floor area	Living space per person
FED	Buildings	Key behaviours	Heating and cooling behaviours – Residential	Space heating and cooling behaviour
FED	Buildings	Residential	Buildings envelope – Residential	Renovation rate
FED	Industry	Technology	Energy efficiency	
FED	Transport	Key behaviours	Passenger distance	Inland demand and aviation

8.6.5 Modified global sensitivity analysis parameter

Table 31. Parameter chosen for the modified global sensitivity analysis of GHG emissions and final energy demand. In some cases, multiple levers were combined to explore hidden interdependencies.

Output parameter	Lever level 1	Lever level 2	Lever level 3	Lever level 4
GHG	Buildings	Key behaviours	Floor area	Living space per person
		Residential	Low-carbon heating solutions	

GHG	FAFOLU	Agricultural practices	Crop extensification degree	
		Land-Use	Settlements and other lands	
		Land-Use	Freed up lands allocations	1. Afforestation
GHG	Industry	Material production (if not linked to sector activity)		
GHG	Industry	Carbon capture		
GHG	Transport	Passenger Transport	Technology evolution – Passenger	
FED	Buildings	Key behaviours		
FED	Buildings	Residential	Buildings envelope – Residential	
FED	Industry	Material production (if not linked to sector activity)		
FED	Industry	Technology	Technology switch	
FED	Transport	Key behaviours	Passenger distance	inland demand and aviation
		Passenger transport	Technology evolution – Passenger	

8.7 2050 Pathways Descriptor levers

The complete transcript of the *2050 Pathways Explorer* levers can be found in the externally provided data set. Please refer to *Pathway_Ex_assumptions_final.xlsx*.

8.8 Data of the first modeling run

In the following, data of the first modeling run is compiled for completeness.

8.8.1 GHG

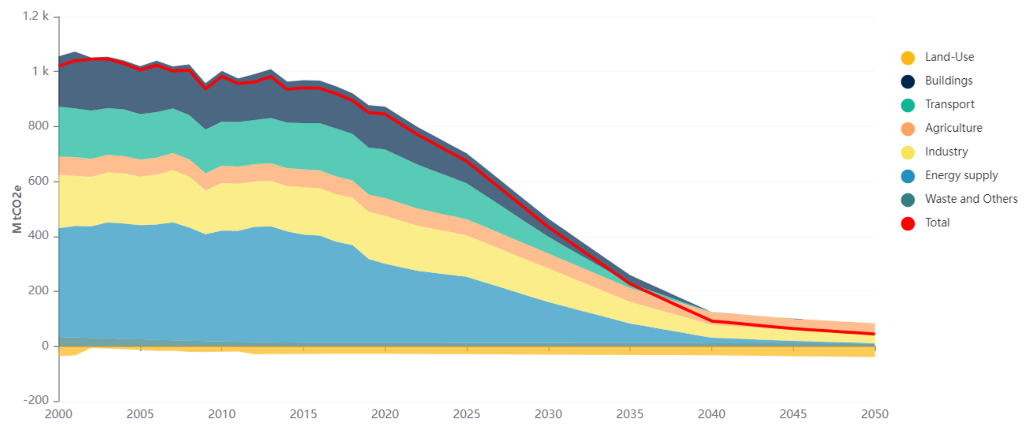

Figure 25. GHG emissions of scenario GG2 in the initial modeling run in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

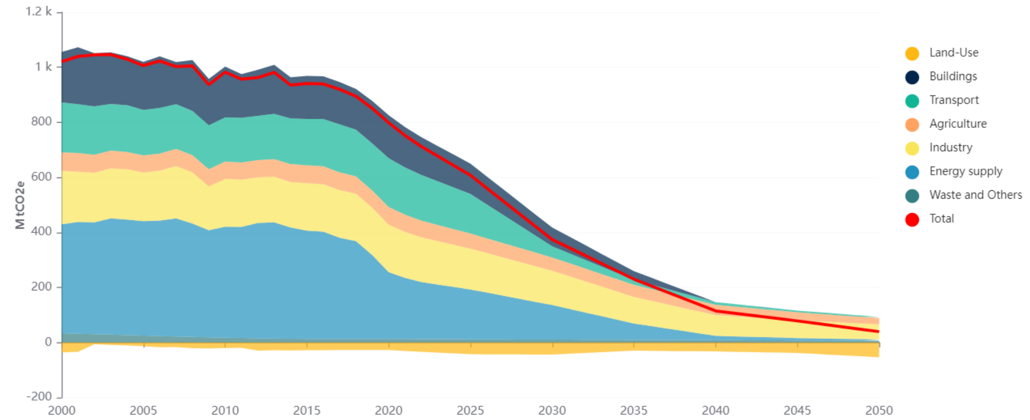

Figure 26. GHG emissions of scenario S1 in the initial modeling run in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

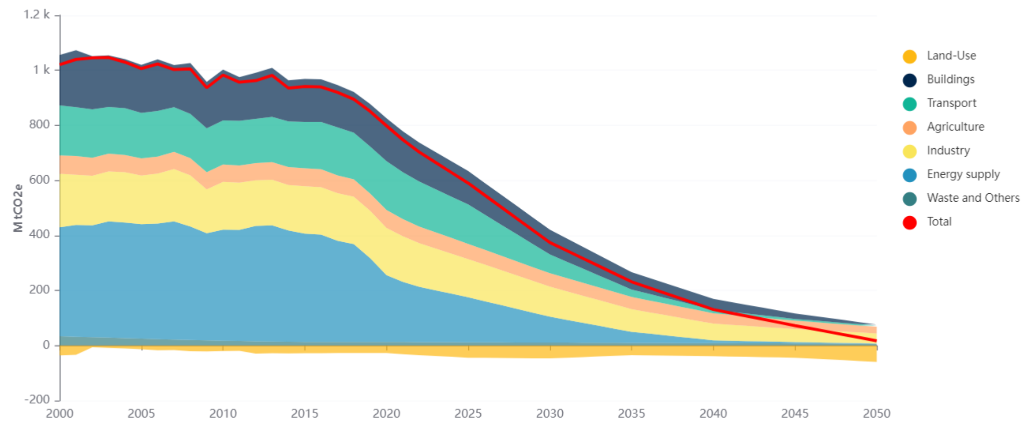

Figure 27. GHG emissions of scenario S2 in the initial modeling run in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

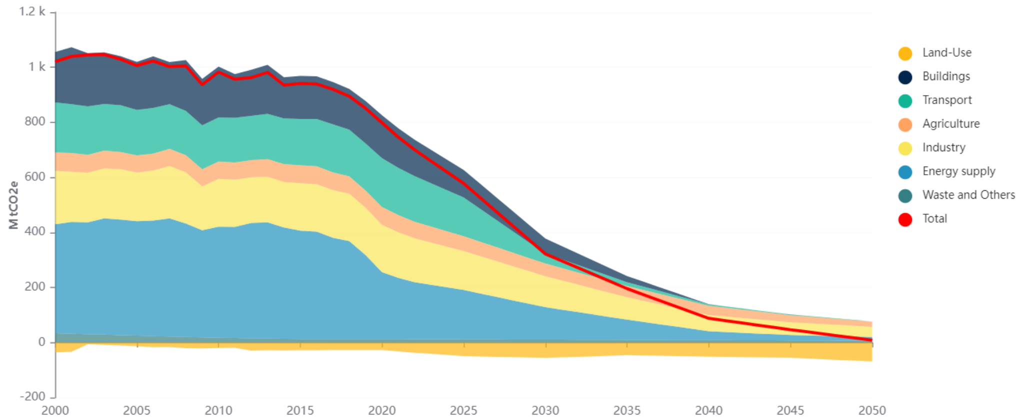

Figure 28. GHG emissions of scenario S3 in the initial modeling run in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

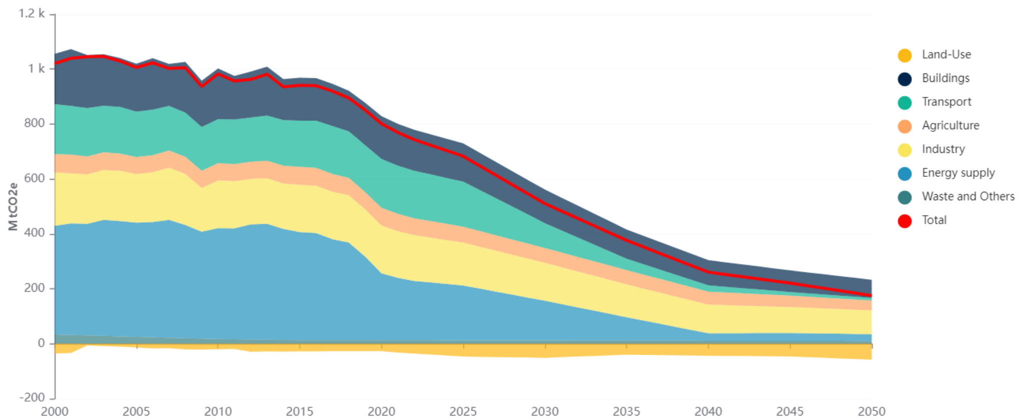

Figure 29. GHG emissions of scenario S4 in the initial modeling run in Mt CO_2eq from 2000 to 2050 for the sectors Land-Use, Buildings, Transport, Agriculture, Industry, Energy supply, Waste and Others. The red line indicates the total GHG emissions. This figure was created by the 2050 Pathways Explorer.

8.8.2 FED

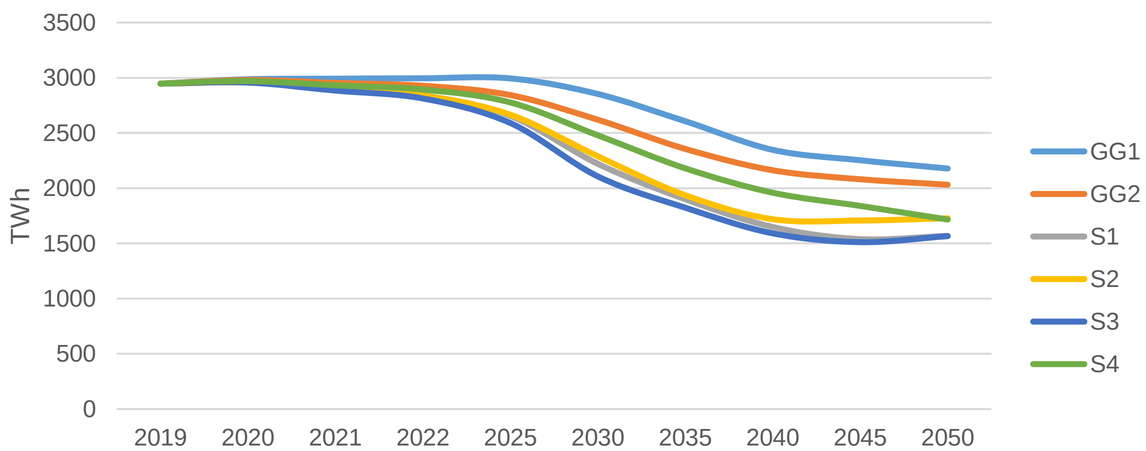

Figure 30. Final energy demand in TWh of all scenarios modeled in its original setting between 2019 and 2050.

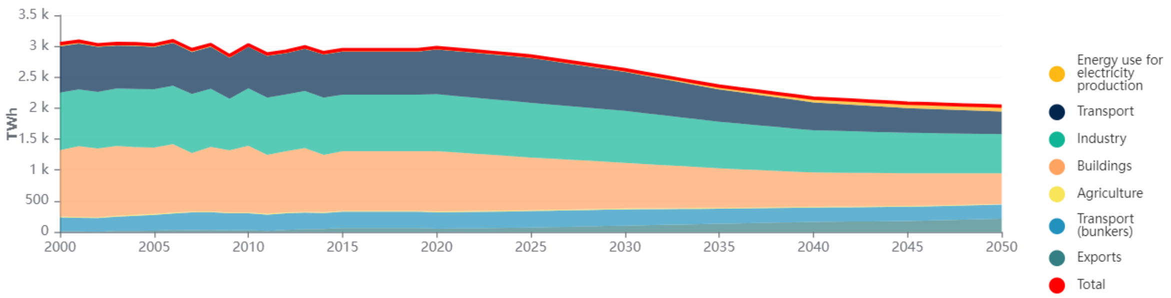

Figure 32. Final energy demand of scenario GG2 in the initial modeling run in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports f. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

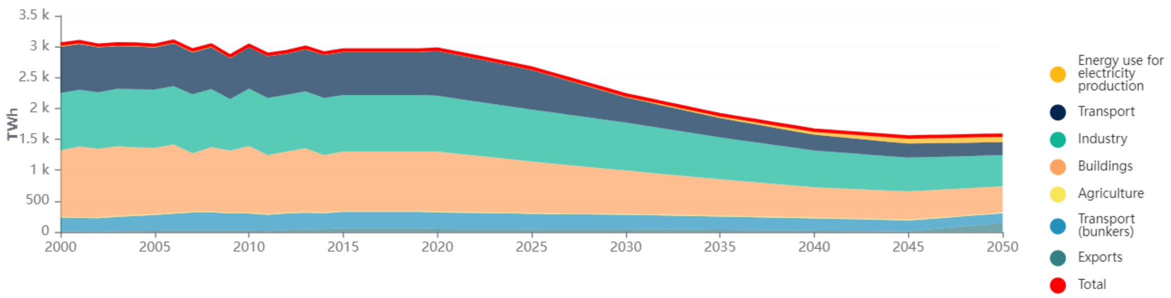

Figure 31. Final energy demand of scenario S1 in the initial modeling run in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

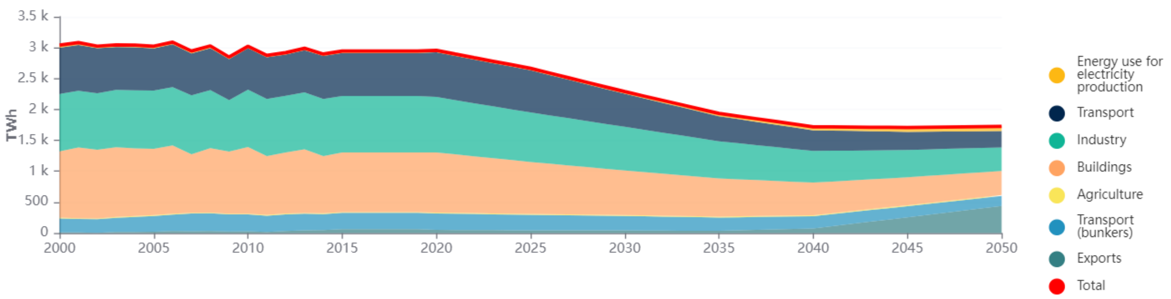

Figure 33. Final energy demand of scenario S2 in the initial modeling run in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

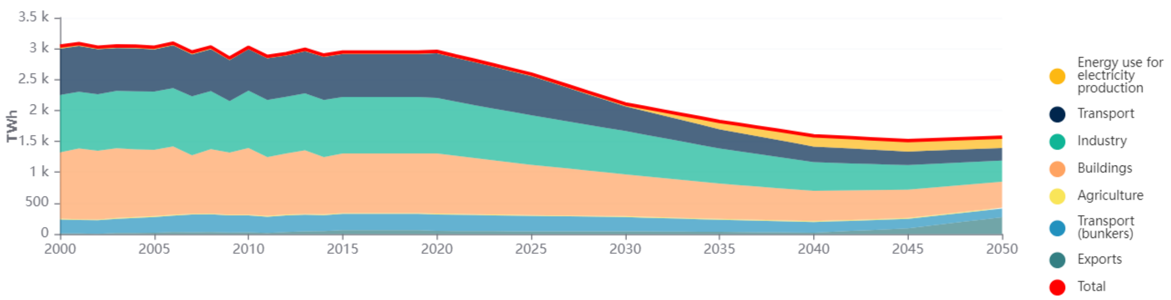

Figure 34. Final energy demand of scenario S3 in the initial modeling run in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

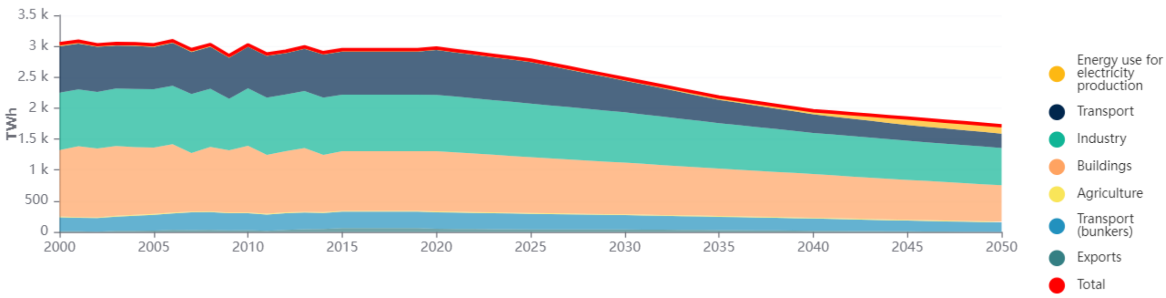

Figure 35. Final energy demand of scenario S4 in its initial modeling run in TWh from 2000 to 2050 for the sectors Energy use for electricity production, Transport, Industry, Buildings, Agriculture, Transport (bunkers) and Exports f. The red line indicates to total FED. This figure was created by the 2050 Pathways Explorer.

8.8.3 CO_2 Budget

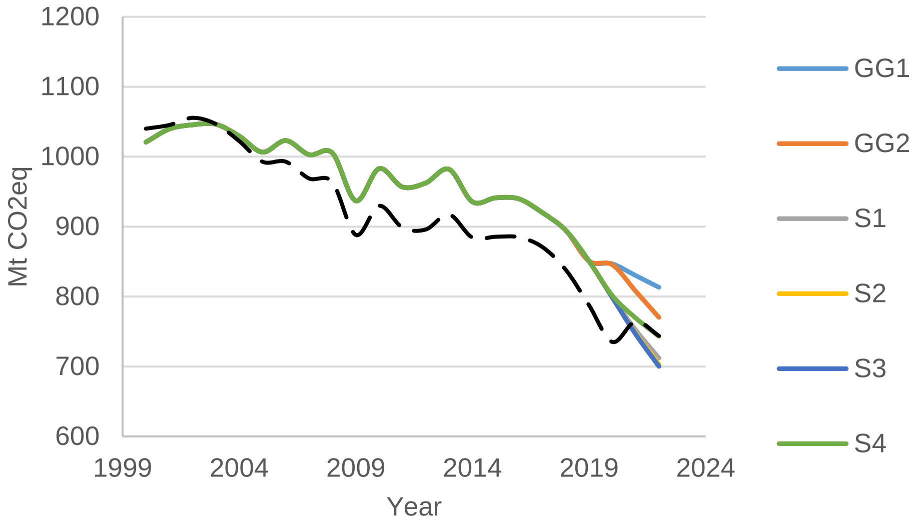

Figure 36. Comparison of historical real GHG emissions for Germany by UBA (2023c) and historical data of the modeled scenarios in the former setting, i.e., not optimized for climate neutrality from 2000 to 2022.

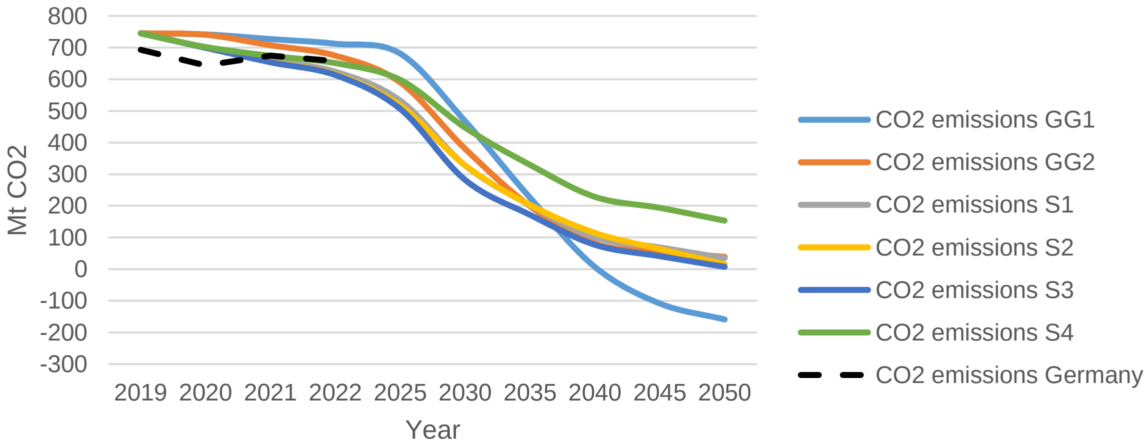

Figure 37. CO_2 emissions of the 6 modeled scenarios from 2019 to 2050 in Mt CO_2 in the original i.e., not optimized setting and the historical real CO_2 emissions for Germany in 2019 to 2022.

Table 32. Comparison of the cumulated CO_2 emissions in the period of 2022 to 2050 of each of the 6 scenarios in the former setting. Further the difference to the available CO_2 budget of 3.1 Gt CO_2 is shown. The historical actual values for Germany in 2022 are used in the cumulated CO_2 emissions.

	former setting	
	cumulated CO_2 emissions (Gt) 2022-2050	difference to remaining CO_2 budget (Gt) (SRU, 2022)
GG1	1.771	1.329
GG2	2.002	1.098
S1	1.923	1.177
S2	1.898	1.202
S3	1.742	1.358
S4	3.282	-0.182

8.9 Scenarios adjustments for net-zero in 2050

As already mentioned in Chapter 4.5.1.1, several adjustments were necessary. Refer to the external dataset (see *Pathway_Ex_assumptions_final.xlsx*) so examine the changed levers.

8.10 Comparison EnSu scenarios 2030 emissions

Table 33. GG1's 2030 sectoral and total emissions in Mt CO_2eq and difference to Germany's sectoral climate neutrality objectives for 2030 based on a 65% emission reduction. Germany's data based on UBA, 2023a, 2023c.

Scenario	**Land-Use**	**Buildings**	**Transport**	**Agriculture**	**Industry**	**Energy supply**	**Waste and Others**	**Total**
GG1	-27.27	78.79	124.34	62.97	165.37	115.63	14.06	533.89
KSG objective for 2030	-25.0	65.9	83.7	57.3	119.4	108.1	5.0	414.5
Difference to Germany's 2030 objective	-2.27	12.88	40.67	5.64	45.92	7.49	9.04	119.37

Table 34. GG2's 2030 sectoral and total emissions in Mt CO_2eq and difference to Germany's sectoral climate neutrality objectives for 2030 based on a 65% emission reduction. Germany's data based on UBA, 2023a, 2023c.

Scenario	**Land-Use**	**Buildings**	**Transport**	**Agriculture**	**Industry**	**Energy supply**	**Waste and Others**	**Total**
GG2	-60.58	66.27	87.43	52.92	123.79	149.45	12.30	431.57
KSG objective for 2030	-25.0	65.9	83.7	57.3	119.4	108.1	5.0	414.5
Difference to KSG objective	-35.58	0.36	3.76	-4.41	4.34	41.30	7.28	17.05

Table 35. S1's 2030 sectoral and total emissions in Mt CO_2eq and difference to Germany's sectoral climate neutrality objectives for 2030 based on a 65% emission reduction. Germany's data based on UBA, 2023a, 2023c.

Scenario	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
S1	-44.57	68.36	33.64	47.96	110.54	145.96	10.99	372.88
KSG objective for 2030	-25.0	65.9	83.7	57.3	119.4	108.1	5.0	414.5
Difference to KSG objective	-19.57	2.45	-50.03	-9.36	-8.91	37.82	5.96	-41.64

Table 36. S2's 2030 sectoral and total emissions in Mt CO_2eq and difference to Germany's sectoral climate neutrality objectives for 2030 based on a 65% emission reduction. Germany's data based on UBA, 2023a, 2023c.

Scenario	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
S2	-55.64	90.11	68.08	47.87	105.93	93.69	10.99	361.02
KSG objective for 2030	-25.0	65.9	83.7	57.3	119.4	108.1	5.0	414.5
Difference to KSG objective	-30.64	24.20	-15.59	-9.46	-13.52	-14.45	5.96	-53.50

Table 37. S3's 2030 sectoral and total emissions in Mt CO_2eq and difference to Germany's sectoral climate neutrality objectives for 2030 based on a 65% emission reduction. Germany's data based on UBA, 2023a, 2023c.

Scenario	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
S3	-55.86	55.01	35.57	46.34	103.74	129.01	10.99	324.80
KSG objective for 2030	-25.0	65.9	83.7	57.3	119.4	108.1	5.0	414.5
Difference to KSG objective	-30.86	-10.90	-48.10	-10.98	-15.71	20.87	5.96	-89.72

Table 38. S4's 2030 sectoral and total emissions in Mt CO_2eq and difference to Germany's sectoral climate neutrality objectives for 2030 based on a 65% emission reduction. Germany's data based on UBA, 2023a, 2023c.

Scenario	Land-Use	Buildings	Transport	Agriculture	Industry	Energy supply	Waste and Others	Total
S4	-51.03	93.99	66.27	53.68	105.55	133.28	12.30	414.04
KSG objective for 2030	-25.0	65.9	83.7	57.3	119.4	108.1	5.0	414.5
Difference to KSG objective	-26.03	28.08	-17.40	-3.65	-13.90	25.14	7.28	-0.48

8.11 EnSu scenarios energy system configuration

The following Tables illustrate a selection of energy system configurations to give a more comprehensive overview on the scenarios actual expression in the modeled energy system.

Table 39. Selection of energy system configuration of scenario GG1 in the second modeling run.

	potential (ambition level)	2050	unit
RE Capacity	low (1)	169.79	GW
Hydrogen and synfuels in final energy consumption	high (4)	411.75	TWh
CCUS in 2050	high (4)	-401.65	MtCO2eq
average distance travelled per capita and year	medium-high (2)	19920.90	km/cap/year
steel production per capita and year	continuation (2)	47370.02	ktt
final energy demand per capita and year | industry		710.93	TWh
living space per capita	high (1)	56.03	m^2/cap
diet	continuation (1)		
Import/Export behaviour	Externalization		

Table 40. Selection of energy system configuration of scenario GG2 in the second modeling run.

	potential (ambition level)	2050	unit
RE Capacity	high (4)	840.50	GW
Hydrogen and synfuels in final energy consumption	medium-high	144.63	TWh
CCUS	medium	-24.75	MtCO2eq
average distance travelled per capita and year	medium (3)	18206.05	km/cap/year
steel production per capita and year	slight decrease (3)	35420.82	kt
final energy demand per capita and year | industry		633,47	TWh
living space per capita	medium (3)	43.95	m^2/cap
diet	mediterranean diet (2)		
Import/Export behaviour	less externalization		

Table 41. Selection of energy system configuration of scenario S1 in the second modeling run.

	potential (ambition level)	2050	unit
RE Capacity	medium (2-3)	661.05	GW
Hydrogen and synfuels in final energy consumption	low	68.03	TWh
CCUS	No (DAC)	-4.79	MtCO2eq
average distance travelled per capita and year	low (4)	14831.74	km/cap/year
steel production per capita and year	slight decrease (3)	35420.82	kt
final energy demand per capita and year | industry		439,25	TWh
living space per capita	medium (3)	43.95	m^2/cap
diet	planetary health diet (3)		
Import/Export behaviour	self-sufficiency		

Table 42. Selection of energy system configuration of scenario S2 in the second modeling run.

	potential (ambition level)	2050	unit
RE Capacity	high (4)	839.00	GW
Hydrogen and synfuels in final energy consumption	No	28.59	TWh
CCUS	No	-2.90	MtCO2eq

average distance travelled per capita and year	low (4)	14831.74	km/cap/year
steel production per capita and year	substantial decrease (4)	20911.09	kt
final energy demand per capita and year | industry		381,40	TWh
living space per capita	low (4)	36.22	m^2/cap
diet	planetary health diet (3)		
Import/Export behaviour	self-sufficiency		

Table 43. Selection of energy system configuration of scenario S3 in the second modeling run.

	potential (ambition level)	**2050**	**unit**
RE Capacity	medium (2-3)	613.02	GW
Hydrogen and synfuels in final energy consumption	low	77.00	TWh
CCS	No	(0)'	MtCO2eq
average distance travelled per capita and year	low (4)	14831.74	km/cap/year
steel production per capita and year	substantial decrease (4)	20911.09	kt
final energy demand per capita and year | industry		341.43	TWh
living space per capita	low (4)	36.22	m^2/cap
diet	planetary health diet (3)		
Import/Export behaviour	self-sufficiency		

Table 44. Selection of energy system configuration of scenario S4 in the second modeling run.

	potential (ambition level)	**2050**	**unit**
RE Capacity	low (1-2)	410.89	GW
Hydrogen and synfuels in final energy consumption	low	30.19	TWh
CCS	No	-2.90	MtCO2eq
average distance travelled per capita and year	low (4)	14831.74	km/cap/year
steel production per capita and year	(substantial) decrease (4)	20911.09	kt
final energy demand per capita and year | industry		361.13	TWh
living space per capita	medium (3)	43.95	m^2/cap
diet	mediterranean diet (2)		
Import/Export behaviour	self-sufficiency		

8.12 Selection of scenario specific data

8.12.1 Negative emissions in the industry sector of GG1

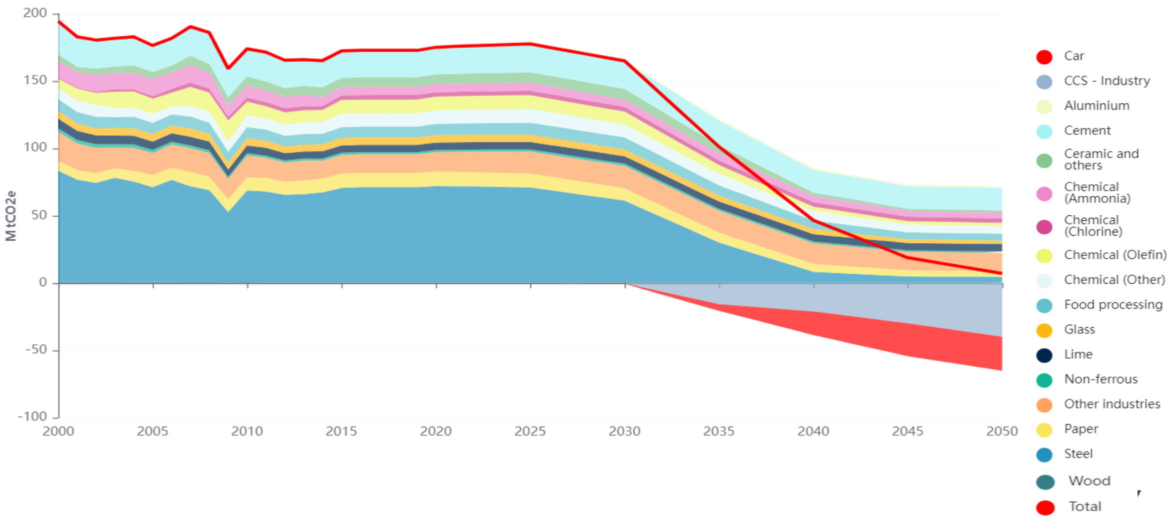

Figure 38. GHG emissions of GG1's industry sector in Mt CO_2eq between 2000 and 2050.

8.12.2 Industrial energy demand

Table 45. Industrial vectoral energy demand of all scenarios in 2050 in TWh in the second modeling run.

	GG1	GG2	S1	S2	S3	S4
Year	2050	2050	2050	2050	2050	2050
Electricity	268.55	376.22	269.17	243.21	212.27	224.80
Solid coal	10.49	3.29	2.40	17.73	11.64	17.64
Solid biofuel	26.25	7.94	6.97	8.60	7.14	8.39
Solid waste	8.56	1.81	1.41	0.99	0.93	0.96
Liquid oil	58.40	133.06	74.77	56.21	55.85	56.18
Liquid biofuel	0.18	0.03	16.68	14.22	14.21	14.28
Liquid e-fuel	24.87	19.93	0.00	0.00	0.00	0.00
Gas natural	88.88	30.96	34.13	35.79	29.91	34.54
Biomethane	0.65	0.07	5.58	6.47	5.39	6.22
Gas e-fuel	38.01	10.19	0.00	0.00	0.00	0.00
Gas hydrogen	153.71	60.34	33.66	1.99	7.95	1.99
Heat waste	39.38	5.99	4.37	4.13	3.67	3.85
Total	717.92	649.85	449.16	389.34	348.96	368.84

8.12.3 Electricity production

Table 46. Electricity production per source and net imports of all scenarios in 2050 in TWh in the second modeling.

	GG1	GG2	S1	S2	S3	S4
Year	2050	2050	2050	2050	2050	2050

Import electricity	173.96	0	0	0	0	0
RES (elec prod)	271.87	1179.56	938.39	1179.56	938.39	649.21
Nuclear	0	0	0	0	0	0
Fossil fuels (CHP)	0	0	0	0	0	0
Fossil fuels (elec-only plants)	0	0	0	0	0	0
Solid-bio-waste (CHP)	0	0	0	0	0	0
Biomass (elec-only plants)	455.64	10.80	0	0	0	89.96
Total	901.47	1190.36	938.39	1179.56	938.39	739.17

8.12.4 Vectoral final energy consumption

Table 47. Vectoral final energy consumption per energy carrier of all scenarios in 2050 in TWh in the second modeling run.

	GG1	**GG2**	**S2**	**S2**	**S3**	**S4**
Year	2050	2050	2050	2050	2050	2050
Liquid and gas eFuels	211.94	61.50	16.15	3.95	52.14	9.58
Biofuels (Solid, Liquid and gas)	119.14	117.45	73.38	124.52	59.85	113.56
Waste	8.56	1.81	1.41	0.99	0.93	0.96
Solid Coal	10.49	3.29	2.40	17.73	11.64	17.64
Liquid Oil	54.66	121.29	79.54	58.72	50.91	56.86
Kerosene	0	19.42	23.03	14.25	0	11.46
Liquid Gasoline	0.82	1.61	0.45	0.48	0	0.45
Liquid Diesel	0.39	10.98	5.30	13.40	3.54	7.81
Hydrogen	199.82	83.13	51.88	24.64	24.86	20.61
Heat	295.07	155.12	81.49	73.78	204.64	82.98
Gas natural	108.84	33.41	36.54	52.20	29.92	54.68
Electricity	899.64	926.70	753.27	694.29	574.05	688.52
Total	1909.37	1535.71	1124.85	1078.96	1012.49	1065.08

8.12.5 Sectoral electricity demand

Table 48. Sectoral electricity demand and exports of all scenarios in 2050 in TWh in the second modeling run.

	GG1	**GG2**	**S1**	**S2**	**S3**	**S4**
Year	2050	2050	2050	2050	2050	2050
Export electricity	0	193.12	74.21	439.23	226.34	0.00
Hydrogen (for sector demand)	0	48.12	77.44	37.54	35.98	30.76
Hydrogen (for efuels production)	0	16.69	29.14	7.43	88.48	17.33
Refineries (not modeled)	6.05	6.05	6.05	6.05	6.05	6.05
Transport	282.68	167.80	97.29	112.93	103.08	105.50
Network Losses	25.61	25.61	25.61	25.61	25.61	25.61
Industry	265.08	371.37	265.70	240.07	209.53	221.90
Heat	1.83	0	0	0	0	0
CHP	0	0	0	0	0	0

DAC Electricity demand	7.68	2.99	2.48	0.00	0.00	0.00
Gaseous and liquid efuels	0.00	5.73	4.32	1.08	13.54	2.56
Buildings	302.34	345.14	347.57	300.85	221.05	321.28
Agriculture	10.20	7.76	8.58	8.78	8.74	8.18
Total	901.47	1190.36	938.39	1179.56	938.39	739.17

8.12.6 Land allocation of GG2 and all sufficiency scenarios

Table 49. Land allocation of the GG2 and the sufficiency scenarios in 2050 in ha in the second modeling run.

	GG2	**S1**	**S2**	**S3**	**S4**
Year	**2050**	**2050**	**2050**	**2050**	**2050**
Frozen Agriculture	0	0	0	0	0
Non-food cropland	4000	4000	4000	4000	4000
Other	3019807.2	3019807.2	3019807.2	3019807.2	3019807.2
Cropland	9747047.58	10270827.1	10502548.6	10453800.3	10271638.8
Grassland (Permanent & temporary incl. pasture)	2757940.88	5643658.5	3388037.92	3388037.92	5118340.29
Grassland (Newly added)	0	0	0	0	0
Forest	18373690.1	14973333.5	17006373	17055121.3	15506980.4
Settlement	1855514.19	1846373.73	1837233.26	1837233.26	1837233.26
Total	35758000	35758000	35758000	35758000	35758000

8.12.7 Sectoral bioenergy demand

Table 50. Sectoral bioenergy demand of all scenarios in 2050 in TWh in the second modeling run.

	GG1	**GG2**	**S1**	**S2**	**S3**	**S4**
Year	2050	2050	2050	2050	2050	2050
Bioenergy exports	0	86.32	118.14	115.86	95.63	33.04
Buildings	8.21	0.44	0.35	2.97	0.39	3.66
Transport	82.51	107.95	41.56	89.97	28.16	78.88
Industry	27.09	8.04	29.24	29.29	26.74	28.88
Electricity production	1128.05	23.69	0	0	0	223.33
Heat production	43.53	24.16	13.09	12.09	31.87	13.33
Refineries	0	0	0	0	0	0
Agriculture	1.33	1.01	2.24	2.29	4.56	2.13
Total	1290.73	251.60	204.62	252.48	187.35	383.26

8.12.8 Hydrogen, efuels and heat demand

Table 51. Hydrogen, efuels, heat demand and exports of all scenarios in 2050 in TWh in the second modeling run.

	GG1	**GG2**	**S1**	**S2**	**S3**	**S4**
Year	2050	2050	2050	2050	2050	2050

Export Efuels	0	0	0	0	0	0
Export Heat	0	0	0	0	0	0
Export Hydrogen	0	0	0	0	0	0
Hydrogen (for sector demand)	199.82	83.13	51.88	24.64	24.86	20.61
Hydrogen (efuel production)	0	28.84	19.52	4.88	61.14	11.61
Heat (for sector demand)	295.07	155.12	81.49	73.78	204.64	82.98
Heat (Power prod)	0	0	0	0	0	0
Gaseous efuels	40.14	10.26	0	0	0	0.08
Liquid efuels	171.79	51.25	16.15	3.95	52.14	9.50
Total	706.82	328.59	169.03	107.25	342.79	124.78

8.12.9 Demand of the Transport sector

Table 52. Energy demand of the Transport sector of all scenarios in 2050 in TWh in the second modeling run.

	GG1	**GG2**	**S1**	**S2**	**S3**	**S4**
Year	2050	2050	2050	2050	2050	2050
Electricity	281.13	163.06	95.66	113.60	101.86	105.16
Liquid oil	0.07	12.85	7.68	15.94	3.88	9.29
Liquid & Gas biofuel	36.26	37.53	16.47	36.45	3.79	27.14
Liquid and Gas e-Fuel	55.15	4.65	0.89	0	2.66	1.95
Gas natural	0	0.37	0.88	0	0	0.47
Gas hydrogen	41.80	22.78	18.21	22.65	16.91	18.62
Total	414.41	241.25	139.79	188.65	129.11	162.62

9 References

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