Technological Change: A Magic Bullet in Mitigating Climate Change? An Intersectoral Analysis for Germany

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Abbreviations

BMWK	Bundesministerium für Wirtschaft und Klimaschutz
CCS	Carbon capture and storage
CI	CO_2 intensity
CO_2	Carbon dioxide
GCEE	German Council of Economic Experts
IO	Input-Output
GDP	Gross domestic product
SRU	Sachverständigenrat für Umweltfragen
UNFCCC	United Nations Framework Convention on Climate Change

Abstract

Addressing the climate crisis requires urgent action to limit global warming and mitigate environmental degradation, with greenhouse gas (GHG) emissions being a critical factor. Despite the political focus on green growth strategies, which seek to decouple economic growth from carbon intensity through technological advancements, empirical evidence suggests that these strategies alone are insufficient.

To adress the question "Will we achieve *Net Zero* by relying solely on technological change?", I first develop a model to evaluate CO_2 emissions per sector in relation to Germany's 2045 climate target. The analysis indicates that current strategies fall short, with many sectors either missing their targets or needing additional interventions. I find that while the electricity sector and several services sectors achieve climate targets. In the motor vehicle, wholesale trade services and machinery sector additional effort is necessary to pursue a green growth strategy. As for the shipping, steel and coke sector sufficient technological change is unfeasible, a degrowth strategy is proposed in these sectors.

Secondly, a cross-sectoral approach is proposed, utilising an Input-Output table to assess how implementing a mitigation strategy in one sector affects others. This method facilitates a nuanced evaluation of climate change mitigation strategies tailored to each sector.

1 Introduction

In light of the looming climate crisis, ambitious political action is essential to curb global warming and environmental degradation. Among the various forms of environmental harm, the emission of greenhouse gases (GHG) is particularly critical because it directly contributes to global warming (Calvin et al., 2023). Although climate change policies are politically contested across countries, governments agree that joint action is necessary, leading to the ratification of several international agreements. The Paris Agreement of 2015 stands as the most ambitious international accord, requiring governments to set and monitor targets, known as "Nationally Determined Contributions" (NDCs), to keep global warming well below 2°C above pre-industrial levels, while aiming for a limit of 1.5°C (UNFCCC, 2024).

While the means to achieve this target are debated, most governments and international institutions advocate for a green growth strategy. This narrative primarily relies on technological change to reduce the emission intensity of production while maintaining economic growth, effectively aiming to decouple economic growth from GHG emissions. Empirical findings suggest however that this decoupling is not occurring fast enough, indicating that a green growth strategy reliant on technological change alone is insufficient. As Greta Thunberg famously criticised, "How dare you pretend that this can be solved with just business as usual and some technical solutions?" (NPR, 2019).
The motivation behind this thesis is the expectation that sufficient decoupling of economic growth from environmental impact is unlikely, prompting the need to identify tailored mitigation strategies per sector in Germany.

The central research question is: *Is there a magic bullet — technological change — for mitigating climate change?* Specifically, the analysis focuses on determining in which sectors of the German economy we can rely on technological change and in which sectors alternative strategies are necessary.

To address this question, I develop a model that integrates CO_2 emissions data per sector with their projected development and compare these to Germany's climate change mitigation targets of GHG neutrality (*Net*) in 2045. Additionally, I propose an approach using Input-Output tables in Environmental Economics to model the codependency of

economic sectors, allowing for an analysis of how different mitigation strategies in one sector influence other sectors.
The analysis reveals that the currently employed green growth strategy is insufficient to achieve the desired emission reductions. In the baseline scenario, targeted emissions (35.3 Mio. tons CO_2) are not reached, drastically overshooting the target with a total of 223.3 Mio. tons of CO_2 emissions. For some sectors, such as steel and shipping, the expected decoupling is insufficient, indicating the need for a degrowth strategy by reducing output. Conversely, other sectors may benefit from a green growth strategy, where technological advancements can effectively reduce emissions without compromising economic growth.

With this thesis, I contribute to the literature by providing a nuanced analysis of sector-specific mitigation strategies in the context of Germany's climate targets. While existing studies often focus on the potential of technological change to achieve decoupling, this research highlights the limitations of this approach and the necessity of considering degrowth strategies for certain sectors. By integrating Input-Output tables, I propose an approach to model sectoral codependencies to analyse the effect of implementing a mitigation strategy in one sector on other sectors.

The remainder of this thesis is structured as follows: Section 2 reviews the relevant literature on green growth, degrowth, and decoupling. Section 3 details the empirical model, methodology used in the analysis and the results. In Section 4, I propose the application of an IO approach to analyse the implication of mitigation strategies differentiated by sectors. Finally, in the conclusion, the key insights are summarised and suggestions for future research are made.

2 Theoretical Foundations of Decoupling

While decoupling CO_2 emissions from economic growth is regarded as the central objective of contemporary climate policy, the means to reduce emissions are manifold as there are several factors influencing GHG emissions. One representation of different factors is the Kaya identity where GHG emissions are the product of four different factors: population, $\frac{GDP}{Population}$, $\frac{Energy\,use}{GDP}$, $\frac{CO_2}{Energy\,use}$ (Kaya, 1990). With regard only to the economic perspective and the CO_2 emissions, the Kaya identity can be simplified by decomposing CO_2 emissions as the product of CO_2 intensity of the production and the amount of output produced (Equation 1).

$$CO_2 = \underbrace{\frac{CO_2}{output}}_{CO_2\,intensity} * output \tag{1}$$

Equation 1: Modified Kaya Equation

With the modified Kaya Equation, the CO_2 intensity and output are identified as drivers of CO_2 emissions. Reducing CO_2 emissions can therefore be achieved by either reducing the CO_2 intensity of the production or the amount of output produced.

The German government places a clear and consistent emphasis on economic growth in its political communication. Headlines like *Global economic outlook brightens* ("Weltwirtschaftliche Aussichten hellen sich auf") are followed by the description of a higher expected production (BMWK, 2024). The latest annual report by the economic expert advisory board bears the title "Overcoming sluggish growth – Investing in the future" (GCEE, 2023). The experts describe how the GDP has shrunk during the last years and deduce that investments and expansion of the total working hours are necessary to increase economic growth, without questioning the focus on growth. The growth focus is also clearly visible in the "Green New Deal" Strategy of the European Union: "The European Green Deal is a response to these [environmental] challenges. It is a new growth strategy that aims to transform the EU into a fair and prosperous society [...] where there are no net emissions of greenhouse gases in 2050 [...]" (European Commission, 2019, p. 2).

With economic growth being a cornerstone of the political agenda, the carbon intensity of production has to decrease in order to achieve climate targets. Reducing the carbon intensity is usually referred to as *decoupling*, as economic growth (e.g. output) should be decoupled from environmental degradation (e.g. CO_2 emissions). For example, in the German sustainability strategy it reads: "The use of energy and resources [...] has to be decoupled from economic growth" (Bundesregierung, 2023, p. 92). Another example is the European Green Deal which is "a new growth strategy where economic growth is decoupled from resource use" (European Commission, 2019, p. 2).

2.1 Decoupling

Decoupling or more precisely *eco-economic decoupling* is defined as a "physical theory used to describe the reduction or disappearance of the correlation between two or more physical quantities. In the analysis of the relationship between economic development and environmental quality, decoupling is defined as the break of a coupling relationship between the two variables" (Wang et al., 2019, p. 4).
The term *decoupling* is in theory neutral concerning the direction of the underlying effects. However, in the majority of papers it is used as follows: "[D]ecoupling happens when an economy is able to grow without causing more environmental pressure or damage" (Cautisanu and Hatmanu, 2023, p. 2) or "Impact decoupling refers to the reduction of environmental impacts per unit of GDP" (Wiedenhofer et al., 2020, p. 2), respectively.

2.1.1 Different Dimensions of Decoupling

Regardless of the direction of the effects, the two quantities must be defined in order to apply the concept. In the *environmental sphere*, authors usually differentiate between environmental degradation as resource use or as carbon emissions (Hickel and Kallis, 2020). Wiedenhofer et al. (2020, p. 2) denote them as two types of decoupling: "Resource decoupling refers to the relationship between GDP and biophysical resource use (materials, energy, etc), whereas impact decoupling refers to the reduction of environmental impacts per unit of GDP (e.g. emissions from energy use and landuse changes)". While the objective of resource decoupling is usually a circular economy, impact decoupling aims at GHG emission neutrality. The focus of this thesis is on impact decoupling, more specifically on CO_2 emissions as they are the most critical of the GHG emissions in terms of their contribution to global warming.

The concepts for describing the *economic development* are not restricted to GDP or GDP per capita (Sanyé-Mengual et al., 2019, p. 3). Other concepts employed are gross annual industrial output, total added value or gross added value. Several authors criticize the focus on economic indicators: Rather than regarding economic growth, well-being and social sustainability should be considered (Sanyé-Mengual et al., 2019, p. 6, Vezzoni, 2023, p. 12). Which indicator an author chooses often implies which normative target he:she pursues. With the political focus on economic growth, *decoupling* usually refers to decoupling of environmental degradation from economic growth.

2.1.2 Models for the Calculation of Decoupling

Whether decoupling takes place and to what extent it does can be calculated by different methods and models, two of the most important approaches are the Environmental-Kuznets-Curve (EKC) and variations of decoupling indices.
The EKC is a theoretical framework according to which "economic growth in the first stages of economic development is achieved on the basis of high levels of environmental degradation, but as development continues [...] the pressure on the environment decreases" (Cautisanu and Hatmanu, 2023, p. 2) thus following an inverted U-shape[1]. Usually, the EKC hypothesis is tested to data by regressing environmental impact (e.g. GHG emissions) on economic growth. A quadratic term is integrated to allow for the possibility of an inverted U-shape in the regression (Han et al., 2022, p. 4).

Another possibility to quantify decoupling is the calculation of a decoupling index. The simplest and most common approach to calculate such a decoupling index (DI) is described by Mikayilov et al. (2018, p. 618) with CO_2 denoting the CO_2 emissions emitted in a period and y the economic output.

$$DI = \frac{\delta CO_2}{CO_2} / \frac{\delta y}{y} \tag{2}$$

Under the condition of economic growth, $1 > DI \geq 0$ denotes relative decoupling and $0 > DI$ absolute decoupling. More sophisticated methods for the calculation are for example the OECD decoupling factor model, the Tapio elastic analysis (TEA) method, and the IGTX decoupling model (Wu et al., 2018) with for example the TEA method allowing for the differentiation between eight states of (de)coupling. Despite their complexity and the nuanced insights they provide, all these methods face criticism, which I will now address.

[1] Originally this framework was used to describe the hypothesis that income inequality initially increases with economic growth but at a certain point will start to decrease. In the 1990s this framework was applied to environmental questions.

2.1.3 Criticism and Problems

There are three main points of criticism towards the calculation of decoupling.
The first concern is referred to as *carbon leakage*, which occurs when lower emissions in certain industries or countries are offset by increased emissions in other industries or countries due to the relocation of polluting industries or changes in trade patterns (Antal and Van Den Bergh, 2016, p. 171). Findings of relative or even absolute decoupling should therefore be interpreted carefully.
The second criticism concerns the framing of decoupling and EKC-type developments as a process which happens without any intervention. Warlenius (2023, p. 7) points out that these developments do not originate from "spontaneous operation of the market forces, yet can be produced socially and politically, and will most likely require forceful state action [...]".
Lastly, Hickel and Kallis (2020) argue that the interpretation of studies indicating decoupling is overly optimistic about the challenge of preventing economic activities from exceeding planetary boundaries. Even if the results suggest that absolute decoupling is occurring, this does not necessarily imply that the decoupling is occurring fast enough to reduce emissions sufficiently to remain within the carbon budgets required for the 1.5°C target set by the Paris Agreement. Antal and Van Den Bergh (2016, p. 170) refer to this as the calculation of decoupling "having a flow- rather than stock-character".

Decoupling is not an end in itself but is usually embedded within an ideological framework. It is often used in the context of the *green growth narrative*, which asserts that economic growth and climate protection are not mutually exclusive. Even though "narratives, rather than information per se, play the decisive role in motivating climate action" (Hinkel et al., 2020, p. 495, it is crucial to base our strategies on the effectiveness of decoupling and align our actions accordingly.

2.2 The Dream of Green Growth

The green growth narrative is currently the most dominant narrative in studies on decoupling (Haberl et al., 2020, p. 30). Hinkel et al. (2020, p. 495) define narratives as "socially constructed stories that make sense of events and phenomena, integrating them into

worldviews". Concerning the green growth narrative this usually refers to the story that "environmentally sustainable economic growth" (Cevik, 2023, p. 3) is possible because eco-economic decoupling is feasible. For economic growth and environmental sustainability are currently linked, decoupling (them) is the central objective of this narrative's proponents.
On an international level typically four prominent proponents of green growth are identified: The Organization for Economic Co-operation and Development (OECD), the United Nations Environment Program (UNEP), the World Bank and the European Union (EU) (Jänicke, 2012) but also the German Government bases its Sustainability Strategy among others on "Durable, inclusive and sustainable economic growth" (Bundesregierung, 2023, p. 220).

2.2.1 The Green Growth Narrative

The emphasis on economic growth can be attributed to the green growth narrative's foundation in the neoclassical economic paradigm. Ecological challenges are integrated into the neoclassical paradigm by "acknowledging that nature is an important capital stock and should be accounted for" (Lorek and Spangenberg, 2014, p. 34). The mechanisms to overcome ecological challenges within the green growth narrative are thus analogous to the neoclassical mechanisms pursuing other objectives: Correcting incorrect prices that result from market failures ("internalise externalities") or promoting policies to support innovation and industrial policies (Hallegatte et al., 2012).

Another neoclassical assumption which is present in the green growth narrative is that economic growth enhances well-being (Borel-Saladin and Turok, 2013, p. 211). The idea is that wealth generated through economic growth will reach all of society as it *trickles down* (Lorek and Spangenberg, 2014, p. 34). In economic terms, the generated wealth is expected to *spill over* (Vazquez-Brust et al., 2014, p. 9).

This assumption of a positive link between economic growth and well-being allows to place emphasis on the "economic opportunities rather than challenges arising from the pursuit of environmental sustainability" (Capasso et al., 2019, p. 390). By avoiding "fearful images of loss and less" (Ossewaarde and Ossewaarde-Lowtoo, 2020, p. 11) positive images are promoted rather than costly constraints that a transformation of the economic system might evoke (Bowen and Fankhauser, 2011). In fact costs are framed as investments that allow us to change away from the current inefficient, polluting system to a sustainable system (Haberl et al., 2020, Hickel and Kallis, 2020, Borel-Saladin and Turok, 2013, p. 212).

Applying the neoclassical paradigm to ecological challenges requires the assumption that economic growth is positively linked with ecological outcomes. The mechanism most frequently mentioned to explain this link is *technological change*.

2.2.2 The Magic Bullet: Technological change

Demonstrating the beliefs behind EU politics Ossewaarde and Ossewaarde-Lowtoo (2020, p. 11) describe how the EU enforces the narrative that "green technology will solve the ecological crisis" by promoting a "technological solutionism" (Ossewaarde and Ossewaarde-Lowtoo, 2020, p. 11).
The approach to decarbonise the economy through technological change relies on the principle that resource scarcity will drive up prices, following market mechanisms. Higher prices for scarce resources incentivise economic agents to invest in technological solutions as these investments become profitable. However, in some cases, prices do not adjust due to market failures, such as unpriced negative effects of greenhouse gases (GHGs) on human health (externalities). These market failures are addressed by correcting these prices through the internalisation of these externalities. From a theoretical point of view, this approach is described by the Ecological Modernisation Theory (EMT). This school of thought claims that global capitalism has to be restructured in a way that industrial processes are transformed through technological innovation to reduce the environmental impact (Bugden, 2022, p. 228, Ferguson, 2018, p. 83).

Although technological progress is a cornerstone of the green growth narrative, it is seldom clearly defined. Popp (2012, p. 5) describes technology as an abstract concept which cannot be observed directly. Following Smulders et al. (2014, 19.f.) technical change is the "increase over time in the availability of a stock of technical knowledge that allows producing more per unit of inputs". Within the green growth framework environmental

degradation is regarded as a (natural) input, a more sustainable technology therefore allows for the production of more outputs using less resources or emitting less GHG emissions. This happens either through the usage of less resource/emission-intense inputs ("resource substitution") or by requiring less resources/emitting less GHG emissions in the production process ("factor-augmenting technological change") (Smulders et al., 2014, p. 20).
While there is extensive literature on measuring technological change (Popp, 2012), studies on decoupling often attribute ecological improvements in production, such as reduced carbon intensity, to technological change without measuring the specific inputs to that change (Capasso et al., 2019).

2.2.3 Criticism

Criticism of the green growth narrative can be divided into two strands: The first concerning the underlying assumptions and the second concerning its applicability.
The first assumption criticised is that economic growth will enhance well-being of society as the generated wealth is expected to *trickle down*, passing all income groups. D'Alessandro et al. (2020) employ a macrosimulation, suggesting that pursuing a green growth strategy increases income inequality and the unemployment rate. This even leads to a reduction of economic growth in the simulation as the green investments are offset by a loss of aggregate demand due to high unemployment rates. (D'Alessandro et al., 2020, p. 12).
The second assumption concerns the strong technology optimism: Through the correction of market prices, incentives are provided for investments in technological change which allows for a sustainable production process. This technology optimism is for example criticised by Bugden (2022): Analysing the effect of technological change (measured through patent data) on national ecological footprints yields "that while technological development can attenuate the environmental impacts of economic activity, it does so only marginally" (Bugden, 2022, p. 236). Arvesen et al. (2011, p. 14) conclude that "the conception of technology as a panacea for global environmental problems lacks solid justifications".

The other strand of critique stems from a scepticism regarding the applicability of a green growth strategy. Hickel and Kallis (2020) point out that pursuing a green growth strategy requires absolute decoupling at a magnitude necessary to achieve climate targets. For these rates are not observed, a green growth strategy cannot be applied. Taking up this critique Stoknes and Rockström (2018, p. 47) advocate for a redefinition of *green growth*. In doing so the advantages of the positive framing would be sustained while at the same time making sufficient decoupling a necessary condition to refer to *green growth*.

2.3 The Post-Growth Narrative

Instead of redefining the term *green growth* many scholars argue for the usage of another narrative and by this the implementation of another political strategy: *post-growth*. While I will use the term *post-growth* throughout this thesis, there is currently neither one single term used nor a common definition of the tradition of criticising economic growth as main objective, owing to the dynamic and the ongoingness of the process.
Parrique (2019) debates about the different terms, its various spellings and meanings. These differ between languages used and from country to country owing to different movements being present in different countries, translations of words to another language and preferences of different communities. Parrique (2019) concludes "There are not many consensuses in the degrowth scholarship but this is definitely one: degrowth defies consensual definition" (Parrique, 2019, p. 233).
The main terms used are *degrowth*, *post-growth*, and sometimes *a-growth* in various spellings, all of which can be used referring to both growth-scepticism or growth-agnosticism. For the example of *degrowth* Parrique (2019, p. 240) identifies three types of definitions. Firstly, the *degrowth-as-decline* definition, emphasising the necessity to reduce production/consumption. Secondly, the *degrowth-as-emancipation* definition is regarded: With this definition the growth ideology is criticised, emphasising that economic growth is not a value for itself. Lastly, the *degrowth-as-destination* definition is solution-oriented, envisioning a future society that embodies the principles of degrowth.

I will use the term *post-growth* throughout this thesis to describe a narrative which is emancipated from the prevailing growth focus. The term *degrowth* will be used to describe a strategy or a scenario that includes falling absolute growth (Jackson and Victor, 2011).

Concerning the justification of *post-growth* usually two seminal publications are brought forward. These are "Limits to growth" by Meadows et al. (1972) (commissioned by the

Club of Rome) and "The Entropy Law and the Economic Process" by Georgescu-Roegen (1971) (Parrique, 2019). Meadows et al. (1972) on the one hand express scepticism towards unrestrained growth and the optimism of technological solutions to it: “The basic behavior mode of the world system is exponential growth of population and capital, followed by collapse” (Meadows et al., 1972, p. 143). Georgescu-Roegen (1971) on the other hand laid the foundation for integrating natural sciences, particularly thermodynamics, into economics.

In the resulting paradigm, *Ecological Economics*, the justification to follow a post-growth narrative stems from the emphasis to stay within planetary boundaries. The central tenet is thus not efficiency but sufficiency (Parrique et al., 2019, p. 6). Regarding climate change mitigation, the assumption is that mere decoupling (if present) is not necessarily sufficient to mitigate climate change. To achieve sufficient reduction of resource use or GHG emissions, either a change in behaviour (D’Alessandro et al., 2020, p. 6) is necessary or adequate policies.

While, like the green growth narrative, in the post-growth narrative positive social effects are emphasised, the underlying mechanisms are fundamentally different. Unlike the neoclassical view that wealth "trickles down" and that continued consumption benefits society, ecological economists argue that pursuing social objectives, such as equality, may lead to a reduction in economic growth. According to Ferguson (2018, p. 59), the post-growth narrative contends that "in the presence of mounting costs and impending limits to growth, the preference for growth should be considered illegitimate." Within the post-growth narrative economic growth is not considered to have an intrinsic value, economic activities are rather justified by their use for the (just) society (Sandberg et al., 2019, p. 136).

Following this approach, I consider decoupling as an analytical tool from which political strategies can be derived. If decoupling proves to be effective, a green growth strategy can be pursued; if it does not, a post-growth strategy should be considered. The critical question is: Will we achieve *Net Zero*, and if not, which strategies will be most effective in doing so? Before analysing the German economy, the empirical literature on decoupling will be reviewed.

2.4 Empirical Evidence of Decoupling

The literature on decoupling is extensive and has been synthesised multiple times. Therefore, it will not be discussed in detail in this thesis, as doing so would exceed its scope.

Parrique et al. (2019) synthesise insights from decoupling literature for both resource and impact decoupling. For GHG emissions, they take into consideration thirty studies finding that relative decoupling is frequently found. Even though some studies find evidence for absolute decoupling, Parrique et al. (2019) note that this holds mostly during short time periods and only in specific locations. Other studies suggesting that absolute decoupling is possible, use production-based indicators and are not robust to switching to consumption-based indicators. It is therefore concluded that no global pattern of absolute decoupling is found (Parrique et al., 2019).
In another meta study, detected decoupling rates are compared to decoupling rates necessary to reach climate targets (Hickel and Kallis, 2020). This analysis is performed for both resource decoupling and impact decoupling. Concerning GHG emissions, they find that "while absolute decoupling of GDP from emissions is possible[...], it is unlikely to happen fast enough to respect the carbon budgets for 1.5°C and 2°C against a background of continued economic growth" (Hickel and Kallis, 2020, p. 480).
In a recent study, Vogel and Hickel (2023) analyse the decoupling rates of high-income countries with regard to the nation-specific requirements resulting from the Paris Agreement (limiting global warming to 1.5°C with a chance of 50 %). From the 36 countries analysed, 11 countries (among them Germany) achieved absolute decoupling of consumption-based CO_2 emissions between 2013 and 2019. Combining this with climate targets yields however that none of these countries is expected to stay below the 1.5°C target.

Most studies are focused on the calculation of decoupling on a global level or country-level. Implementing targeted climate change measures requires a disaggregation of the economy by providing a clear picture of the performance of each economic sector. Frequently, the five sectors as used in the IPCC report (Calvin et al., 2023) are taken into account: energy, industry, AFOLU (Agriculture, Forestry and Other Land Uses), transport and buildings. Lamb et al. (2021) analysed these five sectors including 21 subsectors, focusing on the drivers of GHG emissions trends, finding that "sectoral trends reveal limited progress towards decarbonisation" (Lamb et al., 2021, p. 26). An exception from this is the energy sector "in Europe, where a combination of stable demand, energy efficiency improvements, fuel switching and a scale up of renewables has led to an absolute decline in emissions" (Lamb et al., 2021, p. 25).

Calculating decoupling indices for eighteen EU countries and six different pollutants for two periods (1995-2001 and 2001-2008) Naqvi and Zwickl (2017) find that the economy exhibits relative or even strong decoupling of economic growth from CO_2 emissions in many sectors. Specifically, the agricultural, manufacturing, and services sectors show strong decoupling in both periods, while the transport and electricity sectors exhibit relative decoupling. Solely the sector "Other", including mining and quarrying, construction, and wholesale and trade, is categorised as negative coupling (increasing emissions while the output decreases).

The empirical evidence has to be contextualised by taking into account the role of *decoupling* in the green growth and the post-growth narrative. While many authors find that (absolute) decoupling and therefore green growth is possible, it is important to note that these findings do not necessarily signify that the achieved decoupling is sufficient to reach climate targets.

3 Reaching *Net Zero*

The objective of this analysis is to assess whether the German economic sectors are on track to meet climate targets. This would mean they reduce CO_2 emissions sufficiently to achieve GHG emissions neutrality (*Net Zero*) by 2045. The analysis is performed in three steps: Firstly, the future CO_2 emissions are calculated by extrapolating and multiplying economic output and CO_2 intensity ($\frac{CO_2}{output}$). Secondly, the projected CO_2 emissions are compared with the target from the German climate change mitigation law. Lastly, political strategies for different sectors are deduced to reach climate targets concerning the adjustment of the carbon intensity trend and the output trend.

3.1 Data

Both the economic output data and CO_2 emissions data for each sector were drawn from the Genesis database, which is part of the German Federal Statistical Office. Using this data allows for analysing many sectors, while at the same time the common source facilitates merging the economic and the ecological data. Input-Output tables containing gross output are available between 2008 and 2020 (destatis, 2024b)[2] This time span allows for the analysis of recent trends in technological developments, while including the relevant economic crises of the last decades. Input-Output tables are used because in the second part of this paper the sectoral interdependencies are analysed.

The data on carbon emissions is drawn from the statistical report *Umweltökonomische Gesamtrechnungen (UGR)* (destatis, 2023). While in this analysis the focus is on CO_2 emissions, the dataset also contains measurements on other greenhouse gases and thereby allows for a simple extension of the analysis performed in this thesis.

Both reports employ the *WZ 2008* classification of economic sectors by the Federal Statistical Office (destatis, 2008). This classification allows for five different levels of detailing. For this thesis, the second level is used, containing 88 divisions (*"Abteilungen"*). Since not all sectors are available on the division-level in both datasets, the two datasets were merged together. To perform a merger the division's rows and columns were added together, aggregating output, respectively the CO_2 emissions to align with a higher ranking division. The Input-Output tables originally contained 72 divisions and the CO_2 data 53 divisions. One merger was performed in the CO_2 data, all others in the Input-Output tables, resulting in 52 sectors in the final dataset. The merging reduces the level of detail, especially in the services sectors, due to the limited availability of the CO_2 data (Figure 12 (Appendix) for further details).

Taking a look at the current state of CO_2 emissions per sector (Figure 1) yields that the largest share of CO_2 emissions originates from the electricity sector with about 38 % of total CO_2 emissions in 2020, followed by the iron sector and the ceramics sector. As current CO_2 emissions per sector are only one factor in predicting future CO_2 emissions, this information is combined with the expected future development and the current state

[2] The data for the years before contains only twenty sectors.

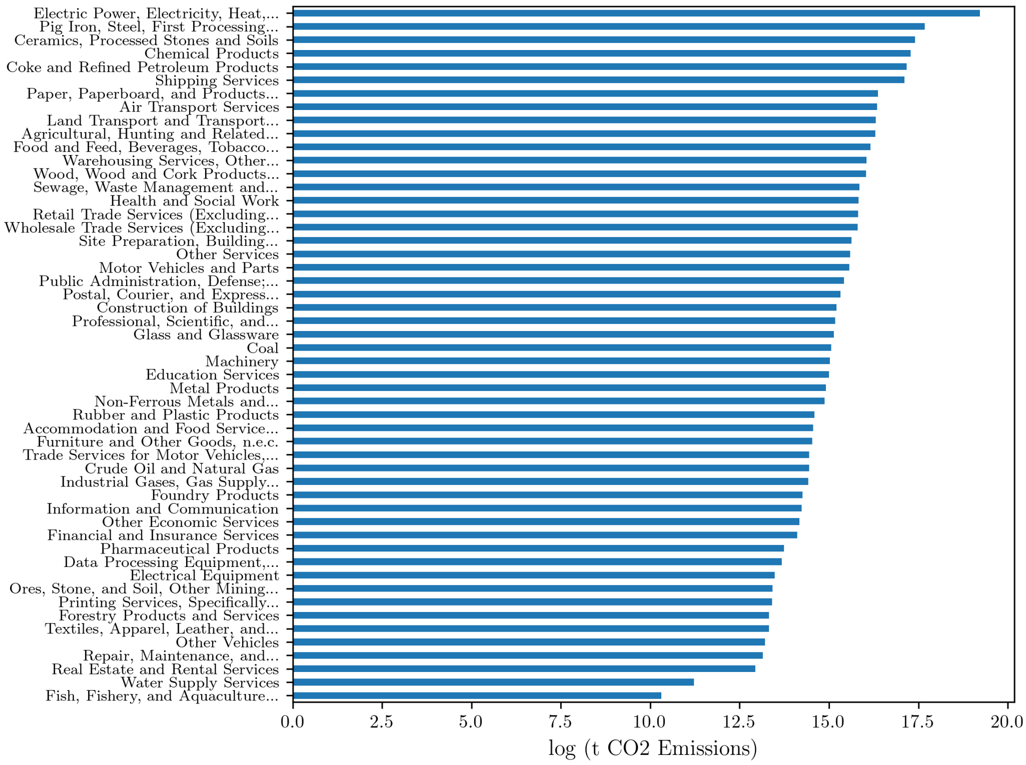

Figure 1: Logarithmised CO_2 emissions in 2020 per sector: The Electricity sector makes up by far the largest share of CO_2 emissions (38 % of total emissions), suggesting that decarbonising this sector will pose a significant challenge.

of the gross output and CO_2 intensity of production per sector. As high values in any of these metrics suggest possible difficulties in reaching climate targets, these five key metrics are represented in Figure 2, where the sector with the highest value for each metric is represented. The number of depicted sectors reduces from five to four because the crude oil sector has the highest value in two metrics: The current CO_2 intensity of production and the projected CO_2 intensity of production in 2045.

We see that the electricity sector has on the one hand by far the highest CO_2 emissions and ranks among the sectors with the highest CO_2 intensity of the production. On the other hand it also has a strong negative development of the CO_2 intensity. This is explained by the former reliance on fossil energy sources, having changed in the last years to the usage of renewable energy sources like wind and solar energy.
The real estate sector has the highest monetary output but a very low CO_2 intensity, because it comprises only selling and renting real estate but not its construction. While the crude oil sector has the highest metric in both the current CO_2 intensity of the production and the development of the CO_2 intensity its output is quickly shrinking due

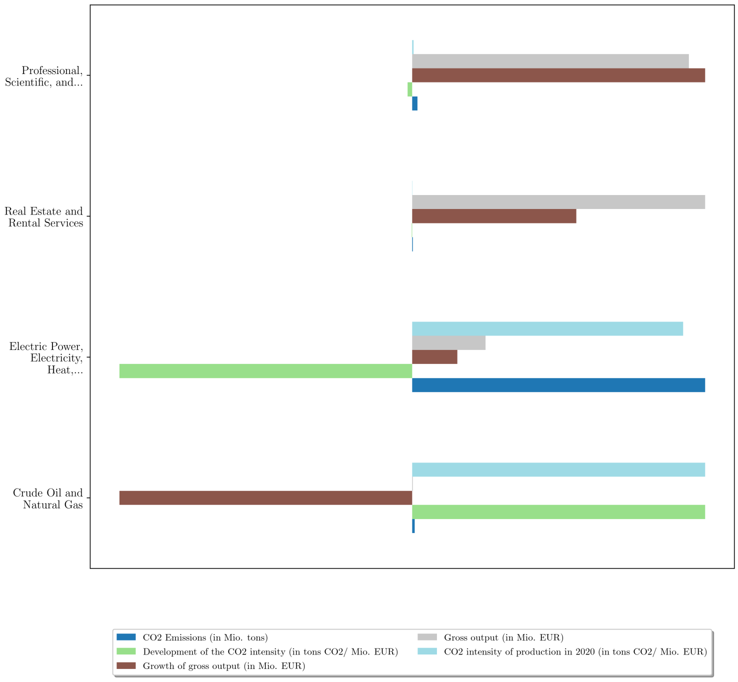

Figure 2: The five key metrics to examine the progress towards climate targets: While each sector exhibits very high values in at least one of these metrics, indicating potential challenges in meeting climate targets, all of them manage to achieve the targets by 2045. This suggests that while these metrics are important for assessing progress toward climate goals, none of them alone provides a complete picture. The interplay between metrics means that a comprehensive model is essential to integrate and balance them effectively.

to a lower reliance on crude oil. Lastly, the sector for professional, scientific, and technical services has, similar to the real estate sector, high gross output while at the same time very low CO_2 emissions.

Calculating the future CO_2 emissions of these sectors reveals that all of these sectors will meet climate targets in 2045 since high values in one metric can be offset by low values in another metric. Consequently, a single metric is not sufficient for determining whether a sector is on track to meet climate targets.

In a next step, all this information is combined and compared to the German climate target. By this, the progress towards reducing emissions sufficiently to achieve *Net Zero* by 2045 is determined.

3.2 Model

Extending Equation 1 future CO_2 emissions are calculated as the product of expected future output and the expected future CO_2 intensity, while assuming for both a linear trajectory:

$$
\begin{aligned}
CO2_i = & \underbrace{\frac{CO2_i}{output_i}}_{CO2\,intensity\,(CI_i)} * output_i \\
& = \underbrace{[\hat{CI}_{2021} + (i-2021) * \Delta CI]}_{CI_i} * \underbrace{[\hat{output}_{2021} + (i-2021) * \Delta output]}_{output_i} \\
& \text{for } i \in \{2022, 2023, \ldots, 2045\}
\end{aligned} \tag{3}
$$

with $\hat{x_{2020}}$ depicting the fitted value for the year 2020 from fitting a trend line to the values by means of OLS.

The values for future output and future CO_2 intensity are thus projected to the future (1) to subsequently calculate the future CO_2 emissions ($CO2_i$) (2) which are ultimately compared to the German climate target (3).
(1) The future values for economic output and CO_2 intensity are calculated by means of an OLS regression to avoid an overweighting of shocks, since the trend line is considered relevant.

The assumption of extrapolating economic growth linearly is based on the fact, that we saw linear economic growth over the last years in Germany (destatis, 2024a). With the prevailing growth focus in the political communication of the German government, economic growth rates are expected to continue on this trajectory. Using an OLS regression to project future values corrects for outliers due to shocks like the beginning of the COVID-19 pandemic in 2020 its economic impacts (Figure 3).

Figure 3 displays the extrapolated gross output for each sector, showing a linear output growth. The highest relative growth rates can be observed in the services sectors, while several fossil sectors as well as the shipping and the air transport sector observe negative growth rates (Figure 13 (Appendix)). Following the trend since 2008, three sectors reach a null output before 2045, this holds for the crude oil, the coal, and the gas sector (their development is depicted in Figure 14 in the Appendix).

Similar to the projection of economic growth, the CO_2 intensity is linearly projected to the future (Figure 4). CO_2 intensity is expected to remain on its trajectory from the last years due to the prevailing green growth narrative and therefore the heavy reliance on

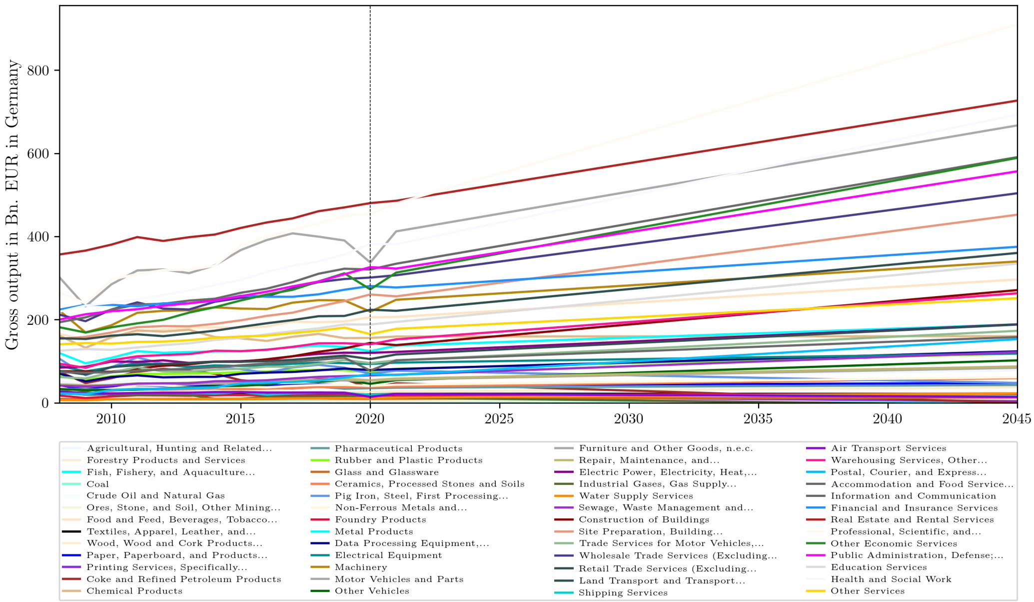

Figure 3: Gross output is linearly extrapolated to the future. The highest growth is expected in the services sectors, while in several fossil sectors negative growth output is observed.

technological progress in mitigation climate change. As such, CO_2 intensity serves as a key indicator of technological change. It is evident, that for some sectors carbon intensity is strongly increasing. Notably, the shipping, air transport and coke sectors experience high growth rates in carbon intensity.

(2) Given the projected values for economic output and CO_2 intensity, future CO_2 emissions are calculated as a product of the two (Equation 4).
With this approach, CO_2 emissions do not necessarily follow a linear trajectory. As overall economic output increases and total emissions decrease, the product of carbon intensity (CI) and output results in a concave function. This reflects a gradual adjustment process in the economy, where the rate of CO_2 emissions reduction accelerates over time.
The German Expert Council for Environmental Issues (SRU, 2024) point to the necessity to stipulate climate targets as emission budgets instead of target values, since the assumption of point targets that emissions decrease linearly does not hold. The SRU further elaborates that a fair calculation of this budget across all countries should be based on a country's population, instead of the share of current emission. Based on these considerations, they calculate that the German carbon budget to keep within the 1.5°C target is already exhausted (SRU, 2024).
Despite these concerns, I will base my calculation on the German climate change miti-

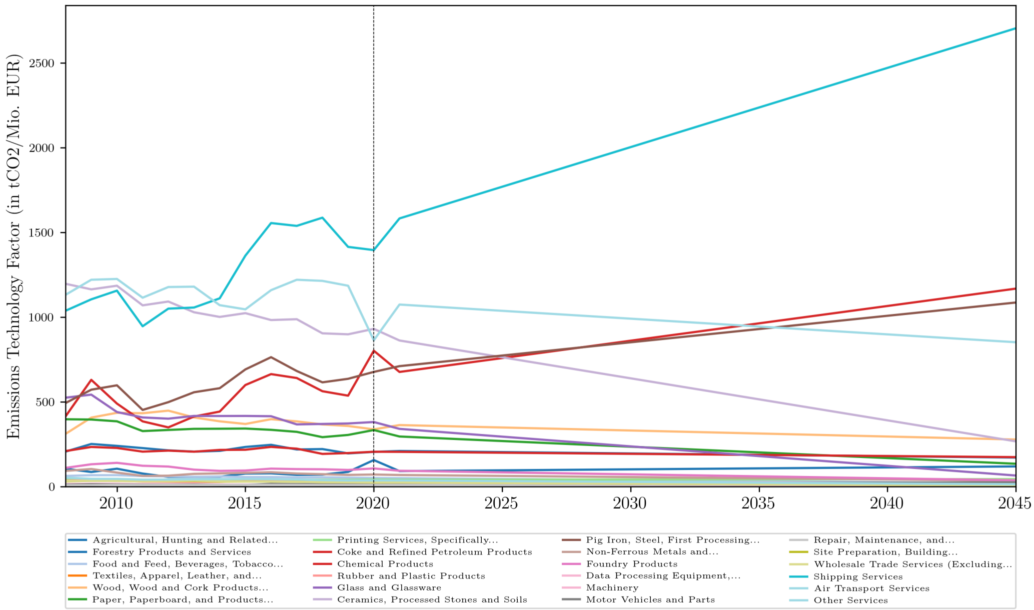

Figure 4: The CO_2 intensity is linearly extrapolated to the future, suggesting that while in most sectors the trend points towards a decrease of the CI, in some sectors it is increasing, notably in the shipping, air transport and coke sectors.

gation law, as this is the legal framework in which the German government can operate. In the German climate change mitigation law, GHG emissions are to be reduced by 65% in 2030 and by 88% in 2040 compared to 1990. In 2045 net GHG emissions neutrality should be achieved. Due to the aforementioned limitations, this approach is likely to underestimate the effort required for effective climate change mitigation.

(3) For the analysis in this thesis, the German climate target for 2045 is taken into account and compared to the projected CO_2 emissions in 2045. In the German climate change mitigation law the target is formulated as *GHG emission neutrality* or *Net Zero* in 2045, which is defined as "The balance between anthropogenic emissions of greenhouse gases from sources and the removal of such gases by sinks" (Bundes-Klimaschutzgesetz (KSG) § 3), as sinks absorb GHG emissions from the atmosphere. The value for these natural sinks is given in the law as target for the sector "Land use, land use change and forestry": -40 Mio. tons CO_2 equivalents (GHG emissions) in 2045. Since CO_2 emissions accounted for a share of 88.2% of all GHG emissions (in CO_2 equivalents) in 2020, the target for CO_2 emissions in this thesis is set to 35.3 Mio. tons of CO_2 emissions in 2045.

While this target only considers natural carbon sinks, negative emissions can theoretically also be achieved through technological carbon sinks. The inclusion of technological

carbon sinks in climate change scenarios has been controversial, with significant debate surrounding the concept of carbon capture and storage (CCS).
Many calculations and scenario projections, including the IPCC report, rely on the development of technologies to capture and store carbon dioxide. However, calculating the potential yields widely varying results. Concerning natural carbon sinks, calculations vary, too, but the differences in the calculations are not as pronounced as for technological sinks.
The Federal Environmental Agency calculates natural carbon sinks of 17 to 22 Mio. tons CO_2 equivalents in 2045, depending on the measures (Harthan and Förster, 2023, p. 23). In a recent study Agora Verkehrswende (2021, p. 19) calculates 11 Mio. tons of natural carbon sinks in 2045. However, adding together natural and technological carbon sinks result in 65 Mio. tons CO_2 equivalents.
The feasibility of CCS will not be discussed in detail here, but it has to be noted that sincere doubts about it have been expressed: Hickel and Kallis (2020, p. 477) describe how CCS was proposed as a fallback option if other measures failed. However, the authors originally proposing it around the turn of the century have criticised that their idea had been misused as it was taken up and been included into the IPCC report as a standard assumption (Hickel and Kallis, 2020).

Given the limited empirical evidence on the feasibility of CCS, relying on CCS is considered an optimistic assumption regarding technological advancements. Another reason to stick to the target for natural carbon sinks from the German climate change mitigation law is that already this target is considered optimistic: While the target value for GHG emissions is at 40 Mio. tons (in CO_2 equivalents) in 2045, in 2020 only 3.5 Mio. tons of CO_2 equivalents have been absorbed by natural sinks (destatis, 2023).

3.3 Results

While the target value is at 35.3 Mio. tons CO_2 emissions in 2045, the calculation performed in this thesis yields a total of 223.3 Mio. tons of CO_2 emissions in the baseline scenario. To address this discrepancy, a net zero scenario is developed by modifying the trajectory of CO_2 intensity.

3.3.1 Baseline Scenario

Under the baseline scenario, twenty-eight sectors achieve to reach *Net Zero* in 2045 (Figure 5). Among these twenty-eight sectors are most services sectors but also some fossil sectors and most notably the electricity sector.

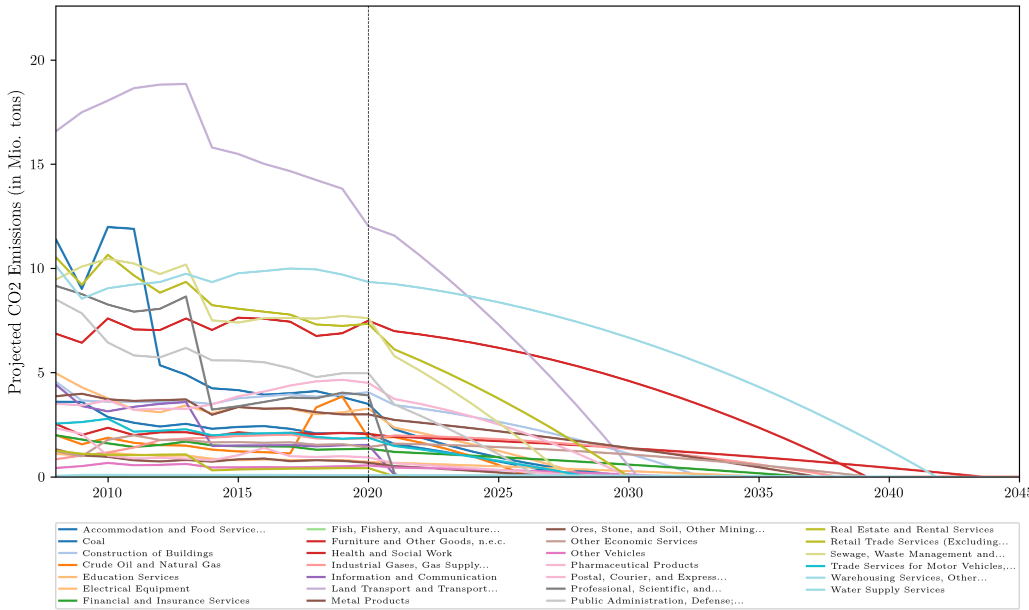

Figure 5: Twenty-eight sectors meet climate targets in the baseline scenario, indicating that with the current pace of technological change (carbon intensity) and output growth, they are on track. This includes most service sectors and some fossil fuel sectors, such as coal and crude oil. The electricity sector was excluded from this graph due to its disproportionately high emissions, totalling 350 million tons of CO_2 in 2008.

For the baseline scenario, CO_2 intensity and gross output were linearly extrapolated, calculating the future CO_2 emissions as a product of the two. The projected sector specific CO_2 emissions in the baseline scenario are illustrated in Figure 6. The top 10 emitting sectors in either 2020 or 2045 were marked in distinct colours, all others were merged in *Others*. One can see that the top 10 emitting sectors from the two years mainly overlap. However, for example the electricity sector, by far the highest emitting sector in 2020, reduces its emissions drastically and is no longer relevant in 2045. Conversely, for example the iron, shipping, and motor vehicles sectors increased their emissions.

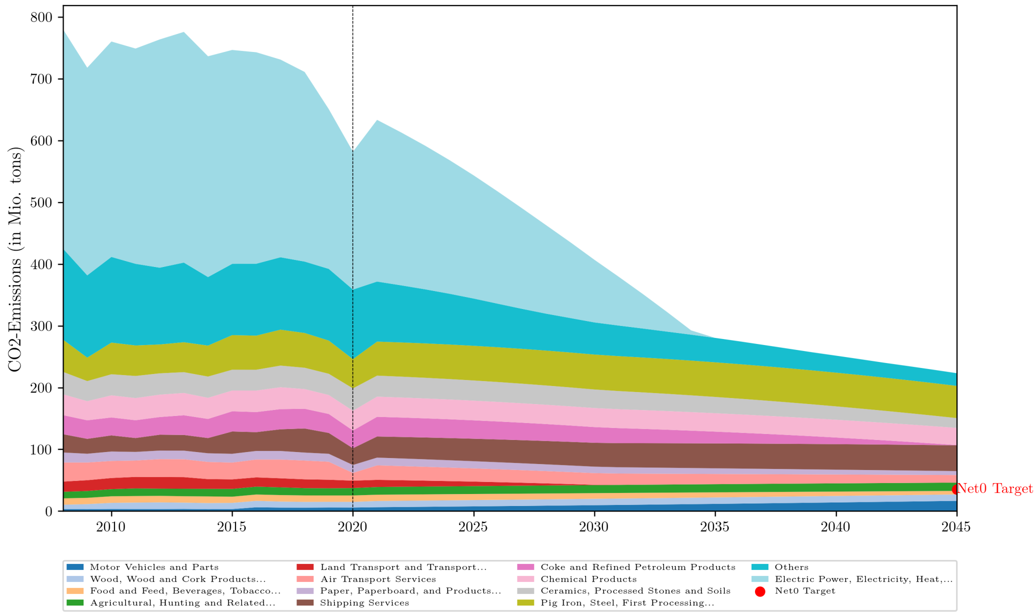

Figure 6: Calculating the expected CO_2 emissions in the baseline Scenario yields a total of 223.3 Mio. tons of CO_2 emissions in 2045, compared to the target value of 35.3 Mio. tons of CO_2.

3.3.2 *Net Zero* Scenario

To reach climate change mitigation targets (*Net Zero*), in the following section the net zero scenario is calculated in which the target of 35.3 Mio. tons of CO_2 emissions in 2045 is met. Reaching *Net Zero* in 2045 is modelled by distributing the targeted 35.3 Mio. tons of CO_2 emissions proportionally among sectors based on their emissions in the baseline scenario 2045. The projected development of the CO_2 emissions is illustrated in Figure 7.

For this analysis, out of the initial fifty-two sectors, only those which do not meet climate targets are taken into account. Twenty-eight sectors, which achieve zero emissions in the baseline scenario, are excluded from the analysis (Figure 5). While most of the excluded sectors' CI is reducing sufficiently fast, in three sectors (crude petroleum, coal, and the gas sector) the output falls to zero before 2045 (Figure 14 in the Appendix).

In the remaining twenty-four sectors, *Net Zero* can be achieved by either adjusting the development of the CO_2 intensity or the output. In a first step, CO_2 intensity is adjusted since the feasibility of technical solutions should be tested and thereby the green growth narrative. For comparison, in a next step the development of economic output is adjusted.

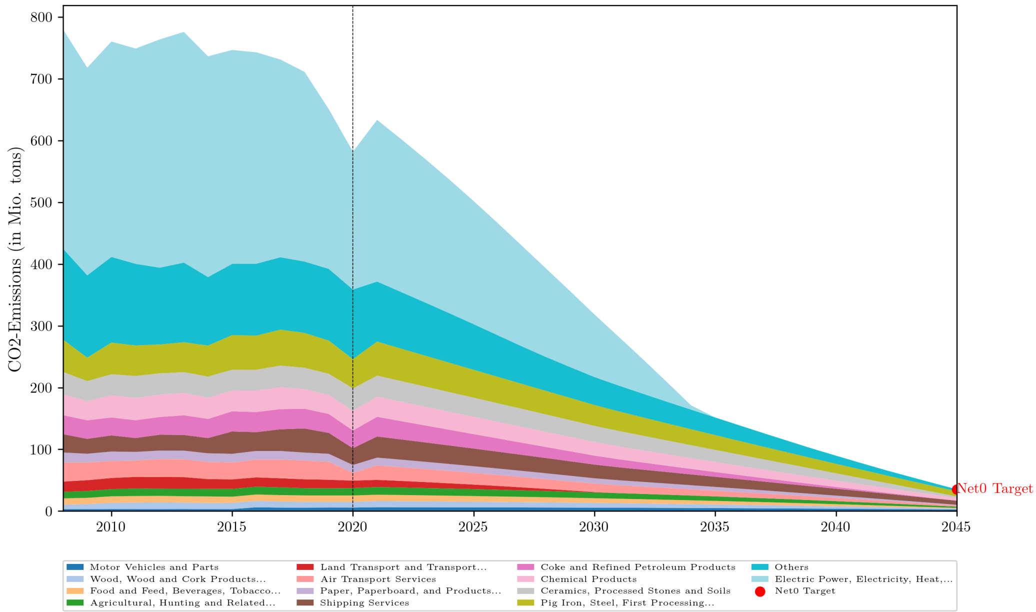

Figure 7: Calculating the expected CO_2 emissions in the net zero scenario which means that the CO_2 target in 2045 is reached by adjusting the CI in the sectors that do not reach the target in the baseline scenario.

The new development of CO_2 intensity for these twenty-four sectors was calculated by first calculating the CO_2 intensity (CI) for 2045 which is required to reach *Net Zero* and then linearly linking the CI in 2021 to the CI in 2045. The value for CI in 2021 is derived from the fitted values of the linear regression extrapolation. The values for 2021, therefore, align with those from the baseline scenario. This approach assumes that no further measures were taken in 2020 to reduce either output or CO_2 intensity. Starting from 2021, measures to reduce carbon intensity can be implemented.

Future values for carbon intensity are calculated using the following equation:

$$CI_i^{net0} = CI_{2021}^{base} + (i - 2021) * \frac{CI_{2045}^{net0} - CI_{2021}^{base}}{2045 - 2021} \quad \text{for } i \in \{2022, 2023, \ldots, 2045\} \tag{4}$$

where the carbon intensity value for 2045 is calculated as:

$$CI_{2045}^{net0} = \frac{CO2_{2045}^{net0}}{output_{2045}}.$$

The projected trajectories of the CI (CI_i^{net0}) for each sector resulting from this calculation (dotted line) are depicted in Figure 8 alongside the with the development of the CI in the baseline scenario (solid line).

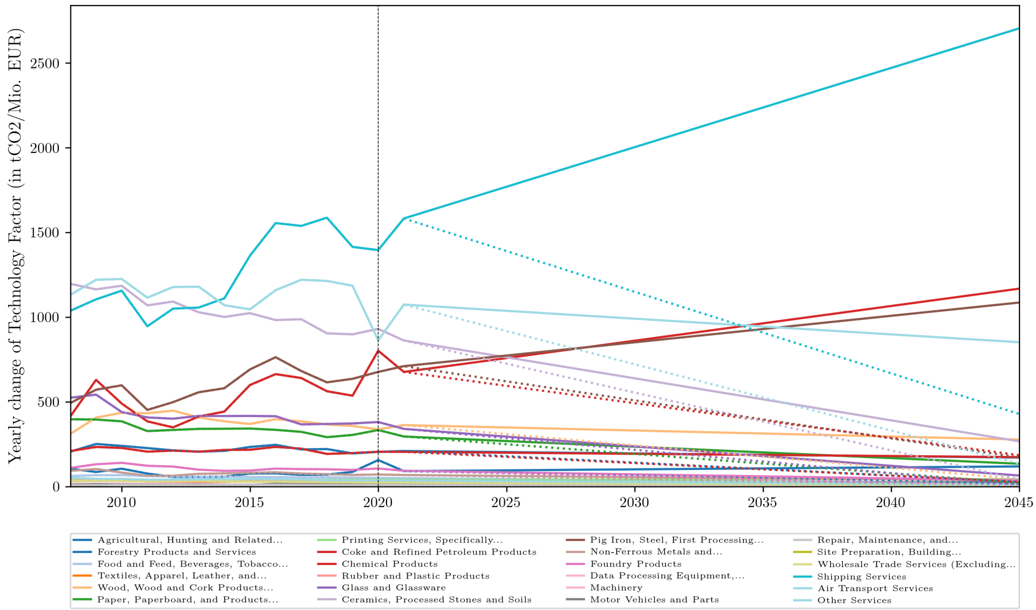

Figure 8: While in most sectors CI is reducing, albeit insufficiently, in some sectors CI is even increasing whereas drastic reduction is necessary, this concerns the shipping, coke and iron sectors. The solid line represents the development in the baseline scenario, while the dotted line is the required CI in the net zero scenario.

While in most sectors the CI is reducing, albeit insufficiently, in some sectors the CI is even increasing whereas drastic reduction is necessary. This concerns the shipping, the coke and the iron sector.
This discrepancy is further analysed and depicted in Figure 9. In this figure the absolute change in carbon intensity per year between 2020 and 2045 is highlighted for both the baseline and the net zero scenario. It is evident that decarbonisation through technological change of sectors like shipping, coke and iron is especially challenging. It is unlikely for these sectors to achieve sufficient reduction in CI and would require substantial efforts, therefore a degrowth strategy is proposed in these sectors.

While reliance on technological change is a feasible strategy in twenty-eight sectors, in the others different strategies are necessary to meet climate targets. For sectors where technological advancement is unfeasible, reducing output growth or substituting more carbon-intensive activities with less intensive ones could be viable options.
Modelling a substitution effect would require modifications to the production function, necessitating changes to the Input-Output table. This would require additional data and assumptions about future production functions, presenting a significant challenge that falls outside the scope of this thesis. Another option to meet climate targets is to model

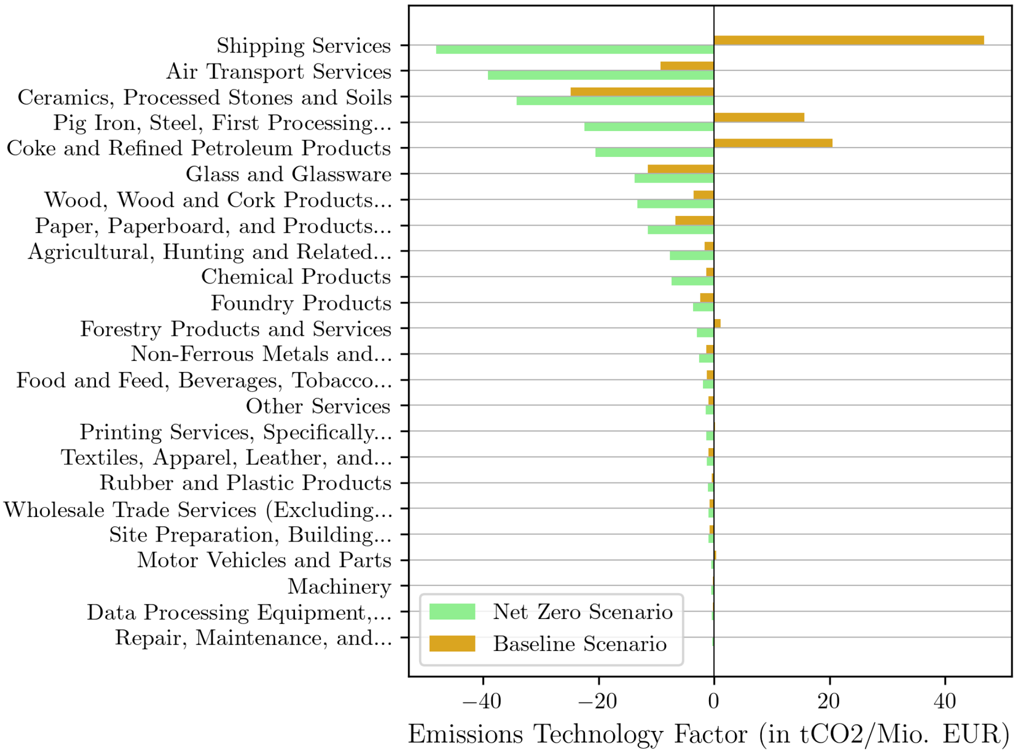

Figure 9: In this figure the absolute change in CO_2 intensity per year between 2021 and 2045 is depicted, suggesting that especially the shipping, iron and coke sector will face challenges by relying on technological change as a decarbonisation strategy. In these sectors a degrowth strategy is proposed instead. In other sectors the required CI and the CI in the baseline scenario are similar, in those sectors a green growth strategy (technological change) is a feasible option, as only minimal effort is necessary to achieve climate targets.

a reduction in output. For this approach, instead of adjusting the CI trajectories, the output growth rates are altered (Figure 10).

Regarding the shipping, iron and coke sector, where reliance on technological change to curb CO_2 emissions is unfeasible (Figure 9), shows that altering the output growth instead appears to be a feasible option. Especially in the coke sector, the yearly change in output is almost at the level necessary to meet climate targets. And in the shipping sector where yearly change in CI would have to be reduced by more than 200 %, the yearly change in output is very small. Either a substitution with other sectors or a degrowth strategy are plausible options in this sector, especially since the overall output is not strongly affected. Taking into account the strong preference for economic growth it is obvious that for example the motor vehicle, wholesale trade services and machinery sectors would have to drastically decrease output while only relatively low adaptions of the CO_2 intensity are necessary to reach climate targets. This suggests that a reduction of CI intensity

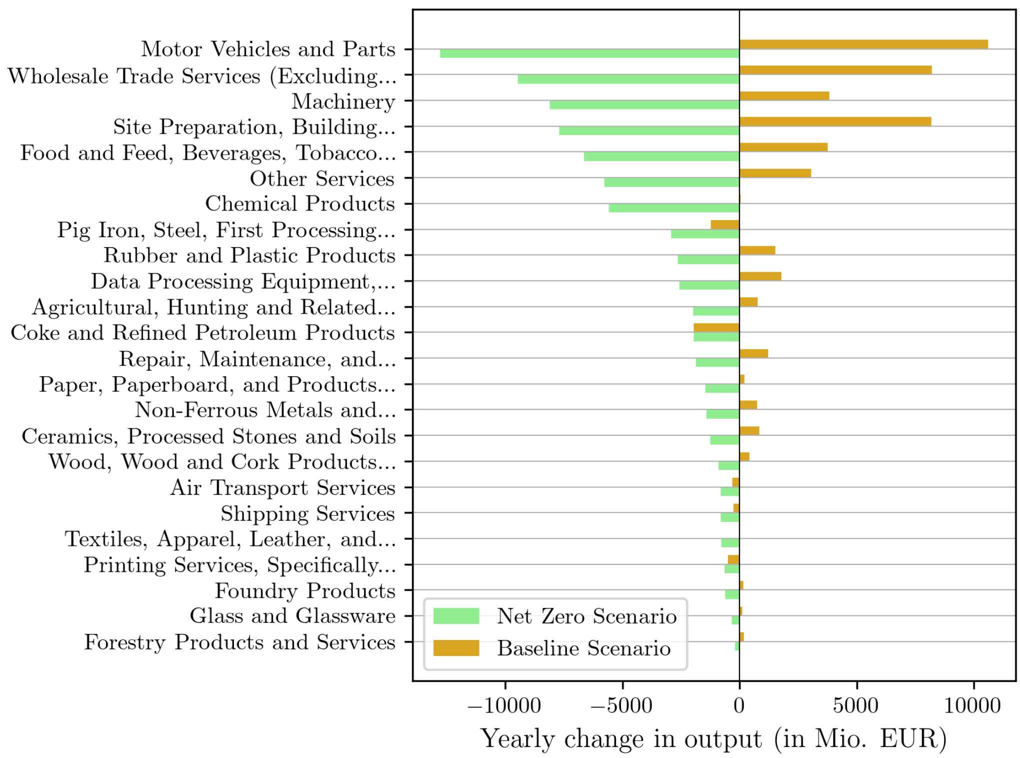

Figure 10: Examining the differences between the required output growth (net zero scenario) and the expected output growth (baseline scenario) suggests that in sectors with a low difference between both scenarios a degrowth strategy should be pursued, this concerns for example the coke sector or the shipping sector. Conversely, in the motor vehicle and the wholesale sector, adopting a degrowth strategy would result in a significant loss of output growth.

(technological change) is a feasible option in these sectors and thereby promoting green growth by enhancing investments in technological solutions in these sectors.

These findings suggest that it is essential to apply differentiated strategies to different sectors, following a *post-growth Narrative*. To maintain high growth rates while minimising investment in technological change, tailored approaches for each sector are necessary. For instance, the shipping, coke and iron sectors requires significant investment to decarbonise but have relatively low growth rates. Reducing their growth rates would have little impact on the overall economy while saving on investment costs. Conversely, the motor vehicle, wholesale trade services and machinery sectors, which require only small investments to reduce carbon intensity, would need to significantly lower its output growth rates to meet targets.

The findings are in line with empirical studies concluding that decoupling is observed but not at a sufficient rate. While for certain sectors green growth strategies with a reliance on technological change can be pursued, in other sectors a degrowth strategy should be followed. In these sectors, technological change is found to develop too slow, or as Arvesen et al. (2011, p. 14) conclude: "the conception of technology as a panacea for global environmental problems lacks solid justifications". By placing the target to stay within planetary boundaries as the main objective, even while taking into account a preference for economic growth, I pledge for the application of a post-growth narrative. The differentiation by economic sectors allows for the application of tailored strategies to each sector.

4 Missing *Net Zero* - An Intersectoral Perspective

While these decarbonisation strategies can be applied to individual economic sectors or companies, influencing one sector will also have consequences for other sectors, as they are codependent of each other. I will take into consideration this intricate web of sectoral relations by employing an Input-Output-Analysis (IO-Analysis).
The notion for this approach is that those sectors which do not meet climate targets in the baseline scenario will face costs either for investments in decarbonisation technologies or for the acquisition of CO_2 certificates. They are expected to at least partially hand through these costs to other industries and final consumers buying their products. While investing in decarbonisation technologies would correspond to a green growth strategy, using an IO approach also allows for examining a degrowth approach and its impacts within the economy.

4.1 Ecological Input-Output-Analysis

Input-Output-Analysis was developed in the 1930s by Wassily Leontief (Leontief, 1936). This type of analysis is an analytical framework used to examine how changes in production or prices in one sector will affect upstream and downstream sectors, providing crucial insights into the interdependencies within an economy.

Employing an IO-Analysis requires the IO matrix ($\mathbf{Z}$), a final use vector ($\mathbf{f}$) and a total output vector ($\mathbf{x}$). Following the notation of Miller and Blair (2009), this can be expressed in vector notation as

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \quad \mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix}.$$

The IO matrix contains the interindustry flows, with z_{ij} representing a flow from sector i to sector j. The economy can be represented as followed:

		Buying				
		Sector 1	$\cdots$	Sector n	Final use	Total use
Selling	Sector 1	z_{11}	$\cdots$	z_{1n}	f_1	x_1
	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$
	Sector n	z_{n1}	$\cdots$	z_{nn}	f_n	x_n
	Value added	l_1	$\cdots$	l_n	l_f	L
	Imports	m_1	$\cdots$	m_n	m_f	M
	Total prod value	x_1	$\cdots$	x_n	F	X

Table 1: This simplified IO table represents the flows within an economy.

A key application of this analysis is to investigate how changes in final demand (denoted as $\mathbf{f}$) influence overall production output (denoted as $\mathbf{x}$). With $a_{ij} = \frac{z_{ij}}{x_j}$ it holds that $\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f}$.

$$\begin{aligned} \mathbf{x} &= \mathbf{A}\mathbf{x} + \mathbf{f} \\ \Leftrightarrow (\mathbf{I} - \mathbf{A})\mathbf{x} &= \mathbf{f} \\ \Leftrightarrow \mathbf{x} &= (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \\ \Leftrightarrow \mathbf{x} &= \underbrace{\mathbf{L}}_{Leontief-Inverse} \mathbf{f} \end{aligned}$$

While the original IO framework was used to describe solely economic phenomena, it was extended by "satellite accounts" to include social and ecological accounts (destatis, 2011). Environmentally-Extended-Input-Output-Analysis (EEIO) allows for the calculation of consumption- instead of production-based emissions. While in a production-based approach the emissions are attributed to the producer of a good, emitting CO_2 in the production process, with the consumption-based approach the amount of CO_2 comprised in a final product is calculated.

Analytically, the consumption-based approach is implemented through the introduction of a pollution matrix $\mathbf{D}$, which can comprise several pollution vectors, for example for different greenhouse gases. For the pollution matrix $\mathbf{D}$ it holds that the pollution vector $\mathbf{x}^p = \mathbf{D}\mathbf{x}$. With

$$\mathbf{x}^p = [\mathbf{D}\mathbf{L}]\mathbf{f}$$

the "pollution impact generated per dollar's worth of final demand presented to the economy" (Miller and Blair, 2009, p. 447) is calculated as $[\mathbf{D}\mathbf{L}]$.

Empirical applications of EEIO are frequently used to come from a production-based perspective of emissions to a consumption-based perspective. destatis (2011, p. 20) calculate the consumption-based GHG emissions for Germany, finding that they are slightly lower than in the production-based calculation.

Another application of the IO framework is a multiregional IO-Analysis (MRIO). By this, carbon leakage is counteracted as the resources/emissions are assigned to the country or region where they are consumed instead of produced. An application for this is performed by Wieland and Giljum (2016) finding for example that GHG "emitted in China appear to play an increasingly important role" (Wieland and Giljum, 2016, p. 16) in the carbon footprint of Europe. While IO tables are useful for distributing emissions to different industries or countries/regions, the IO framework can also be used to analyse the effect of climate change mitigation strategies. An application by this is the analysis of the effects of a carbon tax (Perese, 2010). The findings suggest that a large part of the tax burden falls on private household expenditure.

Adding to these applications of Input-Output tables in Environmental Economics, I propose an approach in which the interindustry relations depending on carbon intensity of the inputs can be analysed. With this approach, the codependency of the economic sectors is modelled. This approach allows for an analysis of how different mitigation strategies (green growth or degrowth) influence other sectors since for example costs as investments in decarbonisation technologies affect downstream sectors.

4.2 Sectoral Emissions

For the IO analysis, CO_2 emissions per sector are distributed according to the inputs from other sectors. This is to say: If sector k with a total output of x_k and emissions e_k sells 5 % of its total output to sector l, also 5 % of k's emissions are attributed to the *sectoral emissions* of sector l. With the calculation of the *sectoral emissions* I illustrate how carbon intense a sector's inputs are, which the sector purchases from other sectors.
For this analysis, the projected CO_2 emission data in 2045 (*baseline scenario*) is used to show in which sectors it is necessary to take further measures to decarbonise the production. The IO table at the basis for this analysis is taken from 2020, thereby assuming the production function from 2020. For production functions adjust slowly, this is a good proxy for the following years. To perform this analysis for future years, further assumptions have to be made concerning the adaption of the production function and thereby an alteration of the IO matrix. This would mean to change the inputs each sector uses.

I introduce an emissions vector $\mathbf{e}$, which can be viewed as one vector in the pollution matrix $\mathbf{D}$. The emissions vector $\mathbf{e}$ represents the CO_2 emissions for each sector. For assigning each vector the emissions from the input it uses as well as the emissions comprised in the final product, the *sectoral emissions* are calculated.
First, the emissions a sector is assigned due to the inputs it buys are calculated, the *Production Input Emissions (PIE)*. By $\mathbf{A}^T\mathbf{e}$ each sector is assigned not the emissions it produced in the production, but the emissions from the inputs it used (also from itself).
Second, with the element-wise multiplication $\mathbf{f} \odot \mathbf{e}$ the emissions assigned to the monetary flows in the final product are calculated, the *Final Expenditure Emissions (FEE)*.

$$sectoral\,emissions = \underbrace{\mathbf{A}^T\mathbf{e}}_{PIE} + \underbrace{\mathbf{f} \odot \mathbf{e}}_{FEE}. \tag{5}$$

Adding the two together yields the *sectoral emissions* of a sector. The sectoral emissions are calculated for the projected CO_2 emissions in 2045 and the Input-Output-table of 2020 the results of which are depicted in Figure 11.

The CO_2 emissions emitted in each sector in 2045 as projected in the baseline scenario are represented as red bars. The *sectoral emissions* are divided in the *production input emis-*

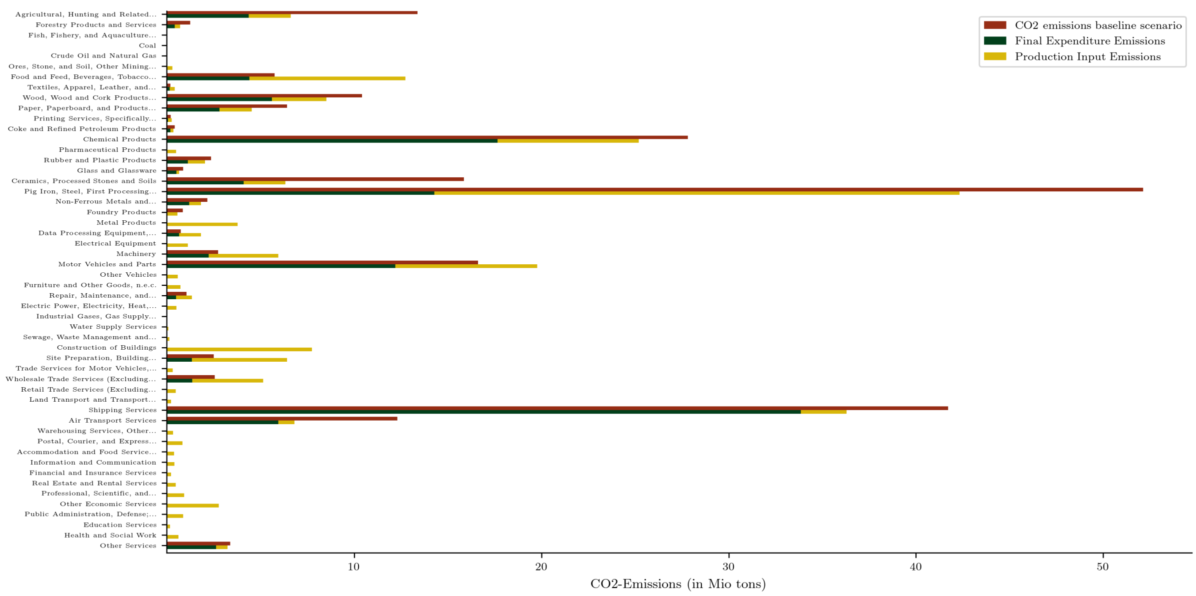

Figure 11: The calculated Sectoral emissions with the IO table of 2020 and the CO_2 emissions of 2045 of the baseline scenario. Red represents the CO_2 emissions of this sector in the baseline scenario. The green bars represent the emissions sold to final consumers, and the yellow bars the emissions bought from other sectors as inputs.

sions (yellow), calculated as $\mathbf{A}^T\mathbf{e}$ and the *final expenditure emissions* (green) calculated as $\mathbf{f} \odot \mathbf{e}$. Differentiating between PIE and FEE enables a more precise understanding of which sectors are indirectly affected by costly investments or degrowth measures. Investment costs can be borne by the sector making the investment, by downstream sectors, or by final consumers of either the investing or downstream sectors if the costs are passed down.

The steel sector is an example of a sector with a large discrepancy between the baseline emissions and the sectoral emissions. This means that many sectors buy CO_2 intense inputs from the steel sector, suggesting that high decarbonisation costs in the steel sector will also affect other sectors (yellow) and the final consumers (green). Since a degrowth strategy is proposed for the steel sector, downstream sectors should consider whether a substitution of these inputs is possible. Otherwise, they are expected to face high costs of investments in decarbonisation technologies in the steel sector.

Conversely, several sectors with higher *sectoral emissions* than *baseline emissions* are identified, industries in these sectors are expected to face costs of decarbonisation. This concerns for example the services sectors: While very few CO_2 emissions are emitted by these economic activities, the services sectors are still affected by other sectors' emissions (or emission reduction costs) for the services sectors use inputs from other carbon intense industries. The same holds for the food sector and the construction sector, whose *sectoral emissions* are very large compared to their *baseline emissions*. Companies which operate in these industries have to carefully choose their inputs and should consider choosing less carbon intense inputs.

With this analysis awareness should be created among companies to carefully choose their inputs, as due to the codependency between the economic sectors high decarbonisation costs in one sector will also affect downstream sectors. Input-output analysis provides a robust framework for understanding the interdependencies within an economy. This initial proposal outlines the potential applications of the IO framework for future research. In extending this framework, the impact of following either degrowth or green growth strategies in different sectors can be represented. By this, either the transmission of costs of investments in decarbonisation (green growth) is illustrated or the reduction of production in a sector (degrowth) and thereby either the reduction of production in other sectors or the substitution of inputs. Another possible extension of this framework concerns the assumption of homogeneous costs of decarbonisation in different industries for so far high CO_2 emissions and therefore decarbonisation costs were compared to other sectors' CO_2 emissions. A future challenge with regard to the IO matrix concerns the adaption of this matrix to expected change in production functions. If, for example, the steel sector electrifies its production route by using electric arc furnaces instead of burning coal, the inputs in its production function change.

5 Conclusion

In this thesis, I develop a model to integrate CO_2 emissions data by sector with Germany's climate change mitigation targets. By focusing on the concept of decoupling, I examine which policy strategy should be pursued based on the effectiveness of decoupling within different sectors. The current dominant strategy in the political discourse involves reducing CO_2 intensity, relying heavily on technological advancements. The central research question addressed is whether Germany will achieve its 2045 target of *Net Zero* emissions.

The analysis indicates that the current political strategy of green growth will not achieve the desired emission reductions. In the baseline scenario, the targeted 35.3 Mio. tons

CO_2 emissions are not reached, resulting in 223.3 Mio. tons of CO_2 emissions instead. This suggests that technological change is in fact not a magic bullet and green growth is not feasible, which is why for some sectors a degrowth strategy is proposed.

Based on these findings, I propose dividing strategies according to the expected decoupling potential in each sector. In twenty-eight sectors emission targets are met in the baseline scenario, notably the electricity sector and several services sectors. But also the coal, crude oil and industrial gases sectors achieve climate targets in the baseline scenario as their economic output falls to zero before 2045.
For the remaining twenty-four sectors which do not meet climate targets in the baseline scenario, diverging strategies are proposed according to the development of the CO_2 intensity and the gross output in these sectors. For the sectors with a great difference in the expected and the necessary reduction of CO_2 intensity, a degrowth strategy is proposed, notably the shipping, steel and coke sector.
For the sectors in which an adjustment of the CO_2 intensity is feasible while at the same time the discrepancy between the expected and necessary change in output is large, a green growth strategy is proposed. This means that additional investments in technological change is necessary in these sectors. This concerns for example the motor vehicle, wholesale trade services and machinery sector.

The interconnected nature of these sectors implies that both green growth and degrowth strategies will have cross-sectoral impacts. Consequently, an approach that considers cross-sectoral interdependencies is essential for effective climate change mitigation, where strategies in one sector consider and complement the strategies in others. For this, an Input-Output approach is proposed, in which CO_2 emissions of each sector are distributed according to the sector's inputs and outputs.

While the green growth narrative remains dominant in the political communication, its assumptions about technological change and economic growth will not suffice to meet climate targets. A reconsideration of degrowth strategies, particularly in certain high-emission sectors, is necessary to achieve sustainable and effective climate change mitigation. Future research should continue to explore the interplay between different sectors and the potential for integrating degrowth to develop a more effective approach to climate policy.

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Appendix

Figure 12: Merging together the IO tables and the CO_2 data per sector required merging together some sectors. Since especially in the services sectors the CO_2 data was not as detailed as the IO data, several mergers were necessary here.

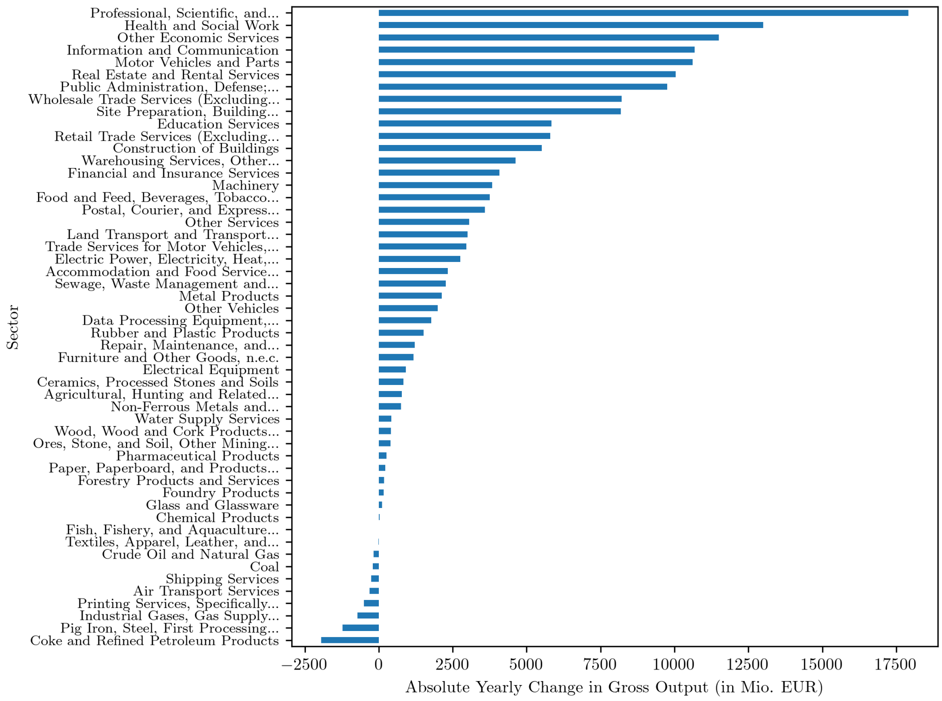

Figure 13: The Absolute Yearly Change in Gross Output is depicted, revealing that the highest growth rates are observed in the services sectors, while some of the fossil sectors are among the sectors with the lowest growth.

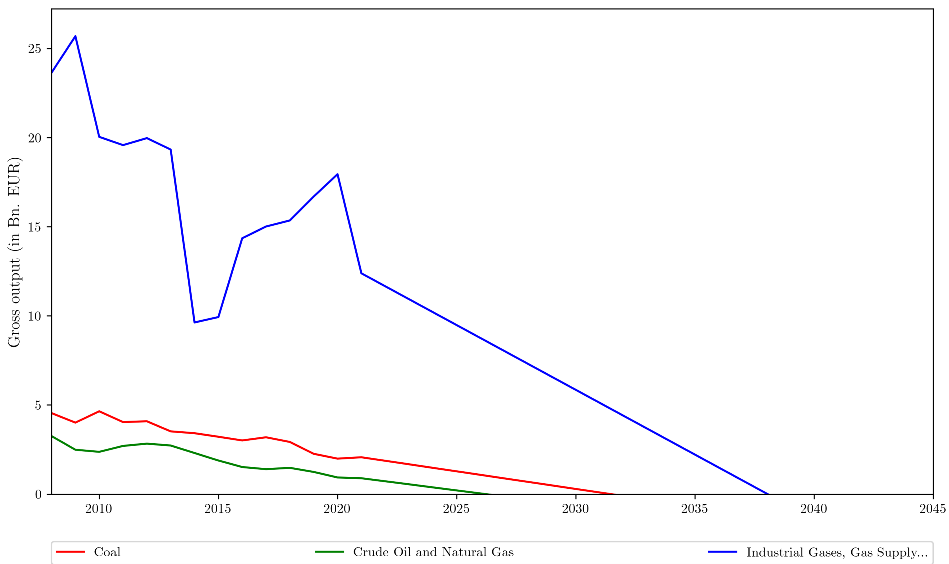

Figure 14: These three sectors (coal, crude oil and industrial gases) reduce their output in the baseline scenario to zero before 2045. Their emissions are therefore considered zero after their output ceases.