Carbon dioxide emissions of transport sector transformation pathways considering CO2 emission budget allocation approaches

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***Abstract*—The IPCC's assessment report 6 shows a lack of ambition between global climate targets and what would be needed to keep global warming well below 2°C. However, while climate change is a global phenomenon, energy planning mainly occurs on national level. In order to bridge the gap between climate and energy research, we quantify cumulative emissions from 2020 up to GHG neutral provision of electricity, heat and power in Germany based on a reference and two target scenarios. Focusing on the transport sector transformation, we include end-user behavior and social and infrastructural inertia. We find cumulative emissions of between 7.2 and 12.7 Gt for the provision of German power, heat and transport energy demands. Transport sector is found to emit between 1.6 and 2.1 Gt in the analyzed scenarios, a range mainly shaped by end-user assumptions on car sales decisions. Main differences in transport sector defossilization scenarios show until 2030. Depending on value-driven allocation methods, the German share of the remaining global carbon budget is around -50 Gt (holding Germany accountable for historic emissions), 10 (if only today's population counts) or 80 Gt (if only today's emissions count). The German 1.5°C-compatible budget may be depleted very soon and neither political targets nor projections are in line with the 2°C target.**

***Index Terms*—emissions, carbon budgets, transport sector, energy transition**

I. Introduction

Eight years after the adoption of the Paris agreement of the conference of parties (COP) 21 in 2015, the gap between necessary emission limitations and transformations of heat, electricity, and transport sectors remains significant. Current pledges from national determined contributions are likely to cause global warming of 2.1-3.4°C causing hazardous changes in climate patterns across the globe. [6]

In order to keep the increase of global mean temperature below 2°C compared to pre-industrial levels with a probablity of 67%, the remaining global carbon budget (RCB) amounts to 1150 $GtCO_2$ from 2020 onwards or 500 $GtCO_2$ for a 50% probability to keep the global mean temperature increase below 1.5°C [6]. Accounting for CO_2 estimates of the years 2020-2023, around 170 $GtCO_2$ of these budgets have been depleted - by two thirds through the burning of fossil fuels.

To bridge the gap in scope between climate research and energy system analysis, it is vital to transfer global RCB to national RCBs. Different methods have been suggested for allocating the global budget varying in the role of historic emissions, economic development and population. Considering fixed global per-capita attribution, for Germany the full range of remaining national carbon budget amounts to between 4.77 - 10.98 $GtCO_2$ for the above mentioned temperature increase limitation targets (and respective probabilities). The German Advisory Council on the Environment published an update to the German RCB in March 2024 showing that Germany's budget in line with a 1.5°C compatible pathway is about to be depleted. [13]

Turning towards the originators of the bulk share of emissions, the provision of electricity, transport and heat, three complementary strategies have been assessed recently. Fuel switching describes the substitution of technologies burning fossil fuels by those using electricity to provide useful energy, e.g. internal combustion engine vehicles by battery electric vehicles or gas boilers by heat-pumps. Effectiveness of fuel switching depends on the second strategy - an expansion of renewable energy sources, in order not only to replace still significant shares of coal, lignite and gas power plants but also to compensate for the additional increase in electricity demand. The third strategy - indirect electrification - describes the substitution of fossil fuels by synthetic fuels either from green hydrogen or from biogenic feedstocks. Low efficiencies imply high electricity demands and costs for this strategy.

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Thus, minimizing the use of synthetic fuel and using them only for the hardest-to-abate sectors and applications has been suggested.

The field of energy system analysis provides methods to assess the above described strategies and calculate emissions related to transformation pathways additionally taking into account high temporal and spatial resolution to account for renewable energy power production characteristics and to assure energy supply at each moment in time. It can thus act as a bridging research field, assuring consistency with bottom-up related fields such as transport research assessing individual user behavior and global climate change related challenges.

Two trends in the last years form the basis of relating energy system analysis to climate research: Sector-coupling provides adequate sectoral coverage and transformation pathways by myopic optimization enable the understanding of inter-annual transformation dynamics. Main remaining uncertainties are the role of energy carriers imported from outside the system boundaries as well as the use of controversially discussed biofuels.

A. *Previous studies and research questions*

Van den Berg et al. have assessed the influence of seven approaches to national emission budget quantification on the remaining budgets of the six main polluting countries as well as the EU. For the EU, considering both historic responsibility and capability leads to negative remaining budgets whereas all other approaches lead to around 0-25 remaining years of CO_2 emissions. [3]

Williges et al. evaluated the carbon budget of various countries, including Germany, using different equity approaches and addressing fairness concerns raised by each allocation method. 1.5°C compatible pathways result in a German national carbon budget of -3.9 to 12.4 $GtCO_2$ between 2017 and 2050 or alternatively -4 to 14.1 $GtCO_2$ for stable 2.0°C ambitions. [15]

Habert et al. took a sector perspective and allocated carbon budgets based on different allocation methods to the building sector in selected countries. Breaking carbon budgets down to single residential buildings revealed a variation of the carbon budget of a factor 10 between different sharing principles being individually consistent from global to regional scale. The authors argue for better clarification in definition and consistency of budget allocation approaches as a key policy instrument. [9]

We assess the following research questions. How does a variety of emission reduction scenarios for the German power, heat and transport sector affect staying below a specific national budget?

II. National RCB allocations

Various approaches have been suggested to allocate the remaining global budget to national shares. This may help policy makers benchmarking both the current ambitions and the current development with what is needed to keep global warming below a specific threshold.

However, national budget allocations are subject to societal values and thus go beyond scientific reasoning. At the center of this discussion are the three values equality, responsibility and capability. Decisive differences stem from the importance of historic emissions, emission-distributions today vs. per-capita-emission rights and economic power.

We show the implications of the allocation methods grandfathering (GF), immediate per capita convergence (IEPC) and equal cumulative per capita emissios (ECPC). Others exist focussing on cost-optimal allocations or the ability-to-pay for reduction measures [3] but for showing the quality of the German budget's sensitivity to an allocation methods the three chosen methods suffice. All allocation methods rely on overarching parameters and method-specific assumptions. We carry out a sensitivity analysis based on parametric ranges given by [3] and apply them to the German case.

Uncertainty of national allocation methods are shown in Fig. 1. Compared to the politically planned and projected carbon emissions until GHG neutrality of 10-12 Gt respectively (see Fig. 7), the uncertainty range of allocation method choice ranges from around -100 to 80 Gt. With 7-8.6 Gt using IEPC (2024 updated range of 4.1-5.7 Gt), current and planned emissions are not in line with the remaining German national budget for a 67% chance to limit global climate change to 2°C. The IEPC-derived German RCB of 4-6 Gt would deplete within 6-9 years, if emissions would stay at 2023 levels.

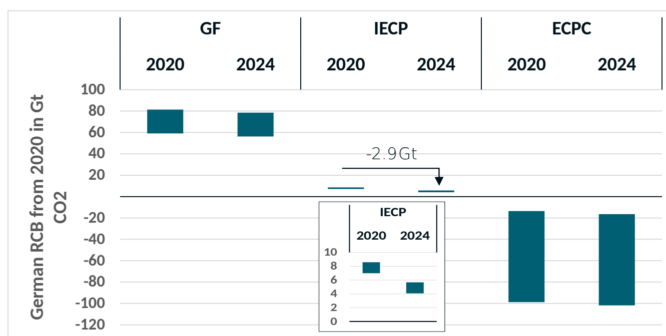

Fig. 1. Remaining carbon budget for Germany β_i^m depending on the choice of allocation methods m of the global RCB to Germany and parametric uncertainty within each method. GF: Grandfathering, IECP: Immediate equal per capita emission, ECPC: Equal cumulative per capita convergence

We show the uncertainties of sensible RCB limitations for a specific reason. It has been suggested, to top-down give a transformation budget as a constraint to energy system models for pathway optimization. However, this seems insensible in front of the large ranges shown in Figure 1. Rather, the context in front of which the German energy transition is taking place - global climate justice - can be quantified and thus provides a valuable reference for political negotiations. In the following, we will analyze the ranges of the rightmost three columns in more detail.

III. Sector coupled energy system transformation pathways

We focus on the three key novelties of our analytical approach beyond common energy system analysis research: We apply demand modeling for the development of street and aviation sector energy demands, we combine bottom-up with top-down modeling making our scenarios more relevant than expert-guesses and we evaluate the scenarios from the perspective of an indicator relevant to climate research and policy: Cumulative CO_2 emissions towards climate neutrality.

We focus specifically on the role of transport sector fuel supply by combining a cost-optimizing power system model - REMix [5] - with the fuel allocation model BENOPTex [1]. Assessing the effects of coupling transport and power sector we also shed light on the feedback effects of allowing biofuel supply on the sector-coupled energy system.

The method of coupling both models has first been demonstrated in [2], and then applied to an EU policies assessment as well as a German case study of trade-offs between imported fuels, biofuels and domestically produced synthetic fuels [1].

A. Power, heat and transport emission quantification

We suggest a life-cycle oriented approach accounting for emissions from the use phase, emissions of biofuel supply and a sensitivity considering the construction of vehicles. The functional unit for our analysis is the cumulative emissions in Germany between 2020 and its state of GHG neutrality. We consider the final energy demands and supplies of power, heat and transport related energy carriers.

The presented scenarios are relevant possibilities [4] and not forecasts. As such, they follow exogenous assumptions such as CO_2 target year emission limits, fuel and CO_2 price developments, and the development of energy demands.

The base case scenario REF is a scenario of failure and reaches 80% CO2 reduction in 2045 compared to 1990 German emissions. Two scenarios - a direct electrification (DEL) and a synthetic fuel (SYN) scenario then assess different transport sector defossilization strategies. They follow political targets in Germany and the EU as of 2022 [1]. We also assess the possibility of providing transport-sector end-use energy demand through biofuels by the scenarios DEL_bio and SYN_bio.

Due to cost-minimization under binding CO_2 emission constraints, cumulative emissions are similar across the scenarios, especially for the power sector following cost-optimality and almost reaching GHG neutrality by 2040.

To provide a broader range of relevant transformation pathways we analyze scenarios from two model suites from the AR6 scenario database - the scenarios LCEO Zero Carbon (LCEO-ZC), Open Zero Carbon (OZC) and Open Zero Carbon with High CCS (OZC-CCS) calculated from JRC-TIMES [10] as well as the three scenarios New Policies (NewPl1.5), Efficiency (Eff1.5) and Incumbents (Incumb1.5) from REMIND [11]. They are the only scenarios in the IPCC AR6 scenario database that report data at national and sector level and reach GHG neutrality in 2050. We also add the German long term scenarios in two variants: The scenarios LTS-TN (min and max) reach GHG neutrality in 2050 and were published in 2021 [7] and the scenarios LTS-T45 with the three variants DEL, H2 and PtX were published in 2022 as updates following the German Federal Constitutional Court ruling on March, 24 2021 [8].

IV. Results and discussion

Before we describe cumulative CO_2 emissions of energy system transformation scenarios, we show the ranges of budgets described in the previous section together with the full range of analyzed scenarios in Fig. 2.

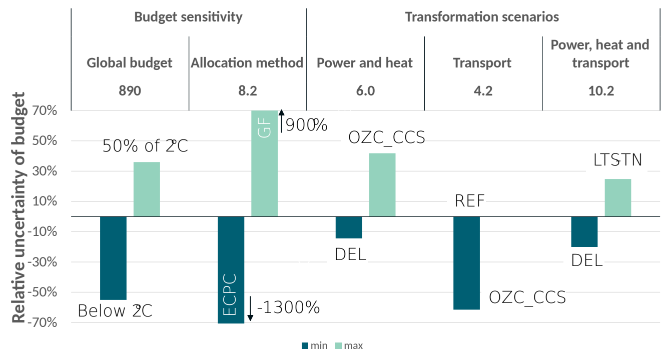

Fig. 2. Relative emission budget sensitivities towards global GHG reduction ambition (first column) and RCB allocation methods (second column). The three right columns show the sensitivity of the cumulative German emissions until GHG neutrality towards energy (third column) and transport sector (fourth column) transformation strategies as well as both combined (fifth column). The normalization reference is shown below the column label in 'Gt. Abbreviations: ECPC - Equal cumulative per capita emissions, GF - Grandfathering, OZC_CCS - OpenZeroCarbon-HighCCS, REF - reference scenarios, LTS - German long term scenarios, TN - Treibhausgasneutralität (GHG neutrality in 2050), T45-H2 - GHG neutrality in 2045 with focus on hydrogen.

The depiction contextualizes the sensitivity of the German RCB to the global GHG reduction ambitions and the allocation method. The global budget ranges from -50 to +30% of the reference as also shown in Figure 5. However, different methods of allocation are relatively more influential. This is also due to the choice of reference being a population-based metric and the small global RCB [13]. However, as this allocation method is recommended by the German Advisory Council on the Environment, it seems justified as as a reference.

The three right columns show the cumulative emissions and the range of power, heat and transport transformation scenarios. Cumulative power and heat sector emissions are among the lowest in our scenarios where direct electrification may reduce cumulative emissions by 14% against the reference. Our transport scenarios were the least ambitious compared to the scenarios from the JRC and the T45 long term scenarios. The most ambitious scenario - Open Zero Carbon with High CCS would reduce cumulative transport sector emissions by 61% from 4.2 to 1.6 Gt.

Some scenarios - such as the German long term scenarios do not publish sector emissions on the transformation trajectory, thus results can only be taken into account for cumulative emissions for power, heat and transport en bloc as shown in the rightmost column. Here, our scenarios are at the lower end of the range described by the long term scenarios TN maximum case of 12.7 Gt for GHG neutrality by 2050 as upper end [7] and our direct electrification scenario with 7.2 Gt at the lower end.

A. Cumulative emissions of energy system transformation pathways

Fig. 3 shows the cumulative power, heat and transport related CO_2 emissions between 2020 and GHG neutrality (or 2050 for REF). The total range of cumulative emissions amounts to 7-13 Gt CO_2 emissions.

The major changes in cumulative emissions within all scenarios occur in the next 10-15 years and the major differences across the scenarios can be seen from 2030 onwards. This depends not least on different approaches of modeling demand developments as described in [11] for three different models and demand scenarios.

The resulting range of annual emissions for the years 2030 and 2040 are shown in Figure 6. They amount to 300-500 Mt/a for 2030 and 100-300 Mt/a for 2040 down from 610 Mt/a in 2023.

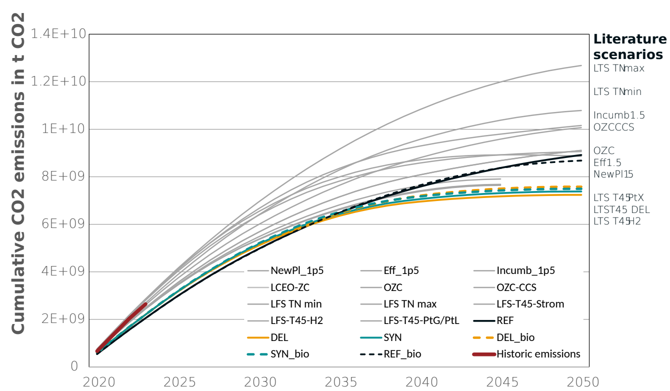

Fig. 3. Cumulative emissions of scenarios of German power, heat and transport related energy supply up to GHG neutrality. Grey lines represent scenarios from IPCC AR6 scenario database and the two sets of the German long-term scenarios TN and T45 with respective sub-variants.

With approximately 30% of cumulative energy-related emissions, a major share of cumulative emissions in most scenarios and decisions strongly being taken from heterogeneous end-user perspectives and preferences, the transport sector is specifically important when looking at reaching GHG neutrality.

However, lack of transparency of sector- let alone sub-sector-emissions reduces the number of scenarios that can be analyzed. E.g. the REMIND scenarios for Germany in the AR6 database do not indicate transport sector emissions. For the German long term scenarios, emissions are given for the years 2030 and 2045 for the T45 scenarios. We linearly interpolate for the years between. Cumulative German transport emissions of the remaining scenarios are shown in Fig. 4.

All scenarios from literature - the three JRC scenarios as well as the three T45 long term scenarios - reach down to half of the reference scenario emissions, between 1.6-2 Gt. On the contrary, our DEL and SYN scenarios arrive at around 70% of the reference, 3.1-3.3 Gt. The difference between the both is negligible with around 2 Mt.

In the scenarios REF, DEL and SYN, neither emissions from shipping leaving from German ports nor from aviation leaving from German airports are included, although electricity demand for the respective fuel provision is modeled. We will later quantify the cumulative emission by shipping and aviation on the background of cumulative German transport sector emissions.

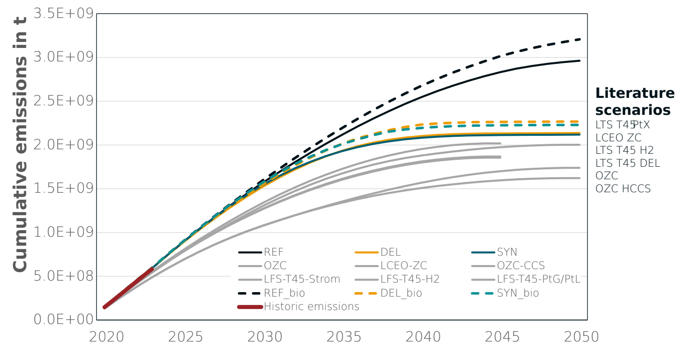

Fig. 4. German energy-related annual CO_2 emissions split in power & heat related emissions and transport sub-sector emissions. Annual emissions for vehicle manufacturing are shown for reference but not included in the cumulative emissions (right y-axis), since they occur not necessarily in Germany and are thus not counted in national emission budgets. Years between 2020, 2030, 2040 and 2050 are linearly interpolated.

The difference of almost 2 Gt between SYN and the TIMES scenario OZG-high CCS mainly results from different modeling approaches. While we assume car owners' buying behavior, both other scenario approaches do not consider the social inertia in private road transportation due to car buyers' preferences. Battery-electric vehicle fleet shares in 2030 may be overestimated which is also indicated by the development of historic emissions in Fig. 4.

This does not limit the relevance of the scenarios but has to be considered upon interpretation - the LTS assume price reductions for power, hydrogen and synthetic fuels as well as strong decreases in battery (T45-power) and fuel cell (T45-H2) prices. As a consequence, battery electric vehicles amount to 12-15 Mio. vs. 7-11 Mio. in SYN & DEL respectively.

We now analyze in-depth, what factors drive cumulative emissions of the German transport sector along different transformation pathways towards GHG neutrality.

The energy system related emissions for an exemplary transformation pathway towards carbon neutrality is shown in Fig. 8. Transport-related emissions from fuel combustion contribute around 26% of energy-related emissions in 2020, increasing to 33% in 2030, decreasing to 22% in 2040 before reaching 45% at GHG neutrality. This dynamic shows that among energy supply, transportation is harder to defossilize due to social inertia shaping the vehicle fleet through sales decisions but also to late ramp-up of synthetic fuels in aviation and shipping. The decreasing share of transport emissions between

2030 and 2040 is due to largely increasing blending quota of synthetic fuels (fuel switching) coinciding with a reduction to 54-76 Mt CO_2/a from power and heat provision (12-18% of 2020 emissions) during that decade. As a consequence, fossil gasoline and diesel are reduced from around 1000 PJ/a in 2030 to 120 PJ/a in 2040 leading to a reduction of private vehicle emissions from 72 to 9 Mt CO_2/a. In the following decade, internal combustion engine vehicles are largely replaced by battery-electric vehicles reaching a share of 87% in 2050.

The scenario shown in Fig. 8 reaches around 9 Gt of cumulative CO_2 emissions from power, heat and transport until GHG neutrality. As shown in Fig. 3 it marks a lower limit of scenarios that reach GHG neutrality in 2050 with only the eff_1p5 and the T45 long term scenarios reaching lower cumulative emissions.

We tested a range of sensitivities on the cumulative German transport sector emissions using our scenarios next to assessing model uncertainty on top of literature-based scenarios. Allowing for biofuels instead of electricity-based fuels may significantly alleviate surging electricity demands due to hydrogen demands for Fischer-Tropsch-syntheses. Since biofuel sale is very sensitive to policy framework conditions, they are expected to replace electricity based fuels rather than fossil fuels. Thus, they don't reduce cumulative transport sector emissions but rather slightly increase those due to life cycle emissions in crop plantation related emissions. This effect is shown in Fig. 4 and amounts to an increase of 2-5% of total emissions to 9.7-9.9 Gt.

Including international aviation would increase cumulative transport sector emissions by 42-43% partly due to remaining fossil kerosene emissions in the last years. Reducing policy targets from the REFuelsEU regulation (71% of clean fuels in 2050) to 100% of clean kerosene would lower this increase to 32%. Including international bunker fuels for shipping has a much lower effect of 3-11% increased cumulative CO_2 transport-related emissions. A controversially discussed topic - the life cycle emissions of vehicle construction - would have an effect in the same magnitude as including international aviation; if these emissions would be accounted for in transport sector emissions - cumulative emissions would increase by 36 and 44 % (around 800-900 Mt CO_2) in SYN and DEL, respectively.

B. *Discussion*

Since we consider only CO_2 emissions, our estimates for historic emissions underestimates climate changing emissions for the historic years 2020-2023. Non-CO_2 emissions accounted for roughly one quarter of gases causing climate change. As shown in Fig. 3, our scenarios underestimate historic emissions for the years 2020-2023. This is due to both, German reactions to limited gas supply by Russia from 2022 onwards - mainly increased coal power plant dispatch - as well as the divergence between energy planning and cost-optimality.

V. CONCLUSION

Combating climate change requires strong global ambitions of greenhouse gas (GHG) emission reductions. While the IPCC showed necessary limits to GHG emissions in its latest assessment report 6 and defined remaining carbon budgets (RCB), national determined contributions fail to hold the pledge from COP21 to keep global warming well below 2°C and target limiting temperature increases to 1.5°C.

We applied a combination of two existing methods to bridge the gap between effect-oriented climate science and cause-oriented energy system analysis, modeling the main causes of CO_2 emissions and their transformations to GHG neutrality.

We find a range of cumulative emissions of between 7.2 and 12.7 Gt for meeting German power, heat and transport energy demands. Our scenarios form the lower limit of literature studies, however with steep infrastructure transformation gradients and tapping almost the full technical potential for solar and wind power expansion in Germany by 2040. Allowing for biofuels may alleviate expansion gradients and only slightly increases cumulative emissions by 2-5%.

Transport sector is found to emit between 1.6 and 3.3 Gt in the analyzed scenarios driven by drivetrain purchase decisions. Main differences in transport sector defossilization scenarios show from 2030 to 2040. Replacing fossil fuel vehicles by electric vehicles is more impactful the earlier it occurs, despite remaining CO_2 emissions of power supply as of today. Both, emissions from international aviation from German airports and from supply chain emissions of vehicle production, each lie in the same range of around 800-900 Mt (around 40% of transport sector or around 10% of total energy cumulative emissions) for the whole period up to GHG neutrality.

This compares to a German RCB of -100 to -10 Gt when historic emissions and population shares drive the RCB and to 7-9 Gt when only current population drives RCB. Current national emission shares - an allocation basis that is controversially discussed - would yield 60-80 Gt RCB for Germany. Power and heat sectors may compensate for transport sector deficits in Germany as shown from the scenario comparison. However, Germany's budget for limiting global warming to 1.5°C may deplete this year and neither current political sector targets nor projections are in line with a German population-based share of the burden to keep global warming below 2°C with a 67% chance. Our work emphasizes both the lack of political ambition raised by the German Advisory Council on the Environment and the inconsistency of energy system modeling with population based remaining carbon budget allocations.

Policy implications of our work can be derived on two levels. First, German transport policy does not follow the transformation pathways assessed in this work. Much stronger support policies for battery electric vehicle purchases are needed to reach the 1.4-2 Mio. BEV purchases and 150,000-200,000 battery electric truck purchases per year by 2030.

However, the energy transition in Germany is not an end in itself, it draws its purpose from globally combating climate change. Lithium resources have to be made available not only to western companies. Especially on the background of economic and societal profits from German historic emissions, strong responsibility for assuring global support mechanisms arise.

VI. Acknowledgements

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Appendix

In the synthesis report of the 6th assessment report of the IPCC, probabilities and limiting temperatures are mapped to RCBs. Figure 5 is an evaluation of data given in Table 3.1 of the synthesis report for scenarios under the first four categories C1-C4 thus keeping global warming below 2°C. The three areas show the spreads in RCB for the three scenarios of reaching 1.5°C at a 50% chance, a high overshoot scenario and a 2°C scenario at a probability of 67% [6].

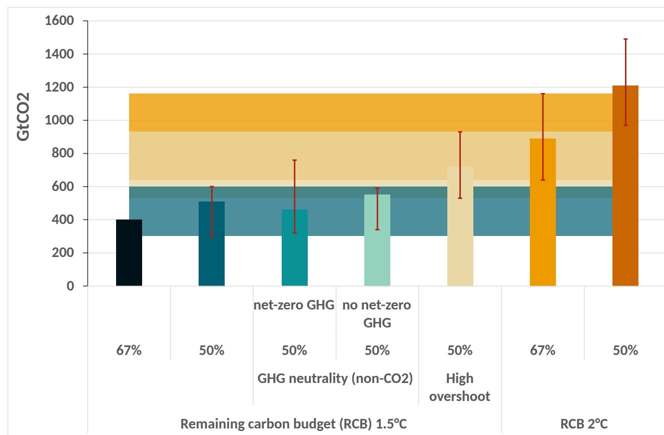

Fig. 5. Remaining carbon budgets (RCB) globally under scenarios compatible with 1.5°C and 2°C increase in mean surface temperature. For both temperature increases the probabilities 50% and 67% are given. The error bars show the 5th and 95th percentile of a broad variation of both scenario pathway characteristics and climate emulation experiments using the emulators MAGICC and FaIR. Categories 3-5 show the influence of non-CO_2 emissions and scenarios that compensate a budget overshoot by more drastically decreasing emissions in the decades up to 2050. See [6, p. 84].

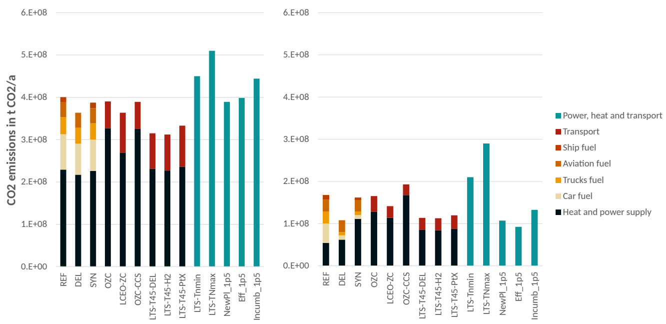

Fig. 6. Annual emissions in t CO_2/a for 2030 and 2040 across the fourteen scenarios analyzed. For the scenarios REF, DEL and SYN, emissions are specified for power and heat and transport sub-sectors. For six scenarios power and heat and transport emissions are seperated. For the REMIND and T45 scenarios, emissions are given for power, heat and transport sectors.

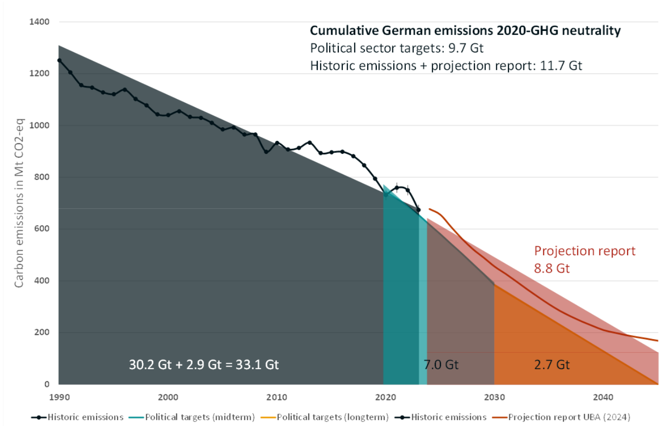

Fig. 7. Historic emissions of Germany up to end-2023, projections based on [14]. Targets interpolated based on [14].

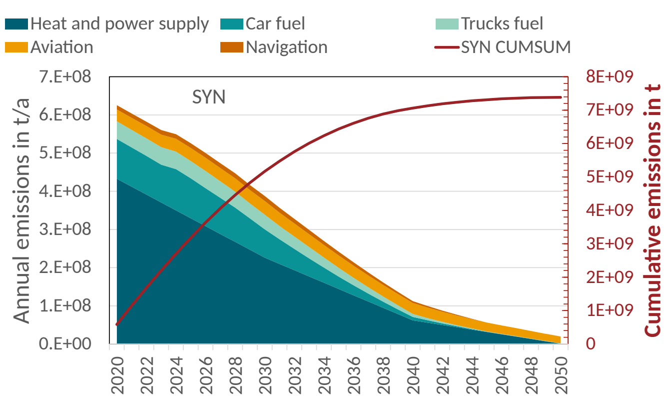

Fig. 8. German energy-related annual CO_2 emissions split in power & heat related emissions and transport sub-sector emissions. Cumulative emissions shown on the right y-axis. Annual emissions between the modeled years 2020, 2030, 2040 and 2050 are linearly interpolated. Navigation and aviation emissions are only shown for reference but not accounted for in cumulative emissions.