Embedding scenarios of Austria's transition to climate-neutral economy within the context of global action to mitigate climate change.

EconTrans Working Paper #2

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1. Introduction

Anthropogenic climate change caused by currently dominant economic structures, which depend on energy from fossil fuels and exert unsustainable pressure on the environment, pose an ever-increasing threat to the future of humanity. Austria, together with virtually all other nations, is a signatory of the Paris Agreement which sets the goal of keeping the global warming well below 2 °C above the pre-industrial level and expresses the ambition to limit it to 1.5 °C. Implementation of these global goals, however, is the responsibility of national governments, that need to design adequate policies and undertake necessary actions for emission reductions. For developed countries like Austria this means rapid decarbonization of the economy while maintaining or improving well-being of the society.

Austrian policymakers (as well as their counterparts in other countries) face a double challenge of designing viable strategies of shifting the national economy towards climate neutrality and sustainability, and, at the same time, ensuring that envisaged transitions are indeed in line with the global warming targets and do not undermine efforts of other countries. This is difficult for two reasons. First, it is impossible to determine how much of a warming is caused by GHG emissions of a given country[1]. Secondly, a national economy is embedded in the global economic system, responding to, but also influencing, trends in economies of other countries and regions. Thus, it is impossible to fully disentangle contributions of individual countries to the global climate action (both positive and negative) from contributions of other regions.

A possible way of ensuring that a scenario of transformation of a specific national economy is in line with a given warming target is to embed it within a global climate change mitigation scenario, for which studies on the increase of global mean surface temperature (GMST) are available. For instance, the IPCC's "Global warming of 1.5°C" special report (Rogelj *et al.* 2018) reviews an ensemble of scenarios developed with various integrated assessment models (IAMs)[2] and feeds the resulting scenarios' GHG emission pathways into medium-complexity climate models to assess their corresponding GMST response. Yet, although feasible, embedding a national transformation scenario within a global scenario is a tedious exercise with several serious methodological drawbacks. First, adopting a global scenario to a regional context requires additional assumptions and thus multiplies uncertainties. Secondly, relying on storylines of existing scenarios limits the space for exploring new visions of radical economic transformations that developed economies need to undergo in order to reach the warming target of the Paris agreement. Indeed, it is recognized that IAMs struggle to model rapid economic and institutional changes driven by disruptive technologies (see e.g., Forster *et al.* (2018), section

[1] Indeed, climate change is a planetary-scale process driven by the total anthropogenic GHG emissions, of which emissions of a country (or region) of interest are just a fraction. As the same trajectory of national GHG emissions may contribute to different global GHG emission pathways that result in different levels of warming, it is impossible to establish a one-to-one relationship between the pathway of national GHG emissions and the future increase of global mean surface temperature (GMST).

[2] The scenario database used in the report is hosted by IIASA, https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/about)

2.SM.1.2). This is a serious limitation of such top-down modelling approaches to shed light on possible scenarios of rapid decarbonization of local economies.

The EconTrans project set out to develop an alternative, more agile bottom-up modelling framework that is better suited to model green transition of a small open developed economy like Austria's. At its core lays the concept of functionalities, which encompass both access to goods and services necessary for the well-being of the society, as well as value chains, and energy and material inputs needed to provide them. The EconTrans Working Paper #1 (Schinko et al. 2021) provides a theoretical underpinning for the concept of functionalities, discussing links between human needs satisfaction which is crucial for well-being, and energy related services that satisfy these needs. Sommer et al. 2021 analyzes the extended input-output structures needed to provide functionalities Access, Shelter, and Other Life Support in Austria, while the EconTrans Working Paper #4 (Bachner et al. 2021) discusses methodological aspects of functionality-based economic modelling and presents empirical results on feasible decarbonization pathways. The objective of this working paper is to ensure that the functionality-based modelling is well grounded within the geo-physical necessities of addressing climate change, and that the transformation scenarios developed with help of this novel framework are indeed in line with the global warming targets of the Paris agreement. To this end a robust reference allowing to scale the constraints on global GHG emissions imposed by these targets down to a national level is needed. The derivation of such robust reference builds on the study by Jonas *et al.* (2014) and its update Jonas & Żebrowski (2016).

In Section 2 we present the scientific basis for the concept of a global budget of cumulative GHG emissions which ensures that a desired level of global warming is not exceeded with a given probability. Although GHG emissions budgets corresponding to 1.5 °C and 2 °C warming targets come with considerable uncertainty, we argue that they provide a sufficiently robust basis for the derivation of reference pathways of global GHG emissions, against which progress of global mitigation efforts towards these targets can be assessed. In Section 3 we discuss how these global GHG emission budgets can be translated into globally consistent constraints on national emissions that are in line with the targets of the Paris Agreement. We use different principles of splitting these global emission budgets to assess the range of cumulative emissions available for Austria (and the whole EU region, in which Austria's economy is embedded – see Appendix). We also derive corresponding reference pathways for anthropogenic GHG emissions for Austria which are in line with the objectives of the Paris agreement.

Due to the bottom-up nature of the modelling framework explored in the EconTrans project there remain economic activities and resulting GHG emissions that are not attributed to functionalities Access, Shelter and Other Life Support. Consequently, there remains a gap between the top-down constraints on Austria's GHG emissions stipulated by the targets of the Paris agreement (discussed in Section 3) and the amount of functionality-related emissions that Austria can release and still remain on a path to meet these targets. In Sections 4 and 5 we close this gap by deriving reference emission pathways for individual functionalities similar to those for total national GHG emissions. To that end we (1) Identify (parts of) sectors in national GHG emissions inventory that are not covered by the considered functionalities; and (2) assess the future cumulative GHG emissions from these not-covered sectors. Point (1) is discussed in Section 4, where we establish a correspondence between the Austrian national GHG inventory (covering all anthropogenic emissions taking place on the territory of Austria) and GHG emissions accounted by functionalities considered in the EconTrans project. Point (2) is addressed in Section 5, where we downscale comprehensive EU-wide scenarios (EC 2018) that comply with targets of Paris agreement (cf. Appendix) to the level of Austria in order to assess cumulative GHG emissions from agriculture and waste and Land Use, Land-use Change and Forestry (LULUCF) sectors. In the same way we also assess how much of Austria's cumulative CO_2 emissions could be removed by carbon dioxide removal (CDR) technologies by 2050.

In section 6 we summarize Sections 2-5 by presenting boundary conditions for functionality-based modelling of Austria's transition to a decarbonized economy. We conclude our paper with the discussion of our results in Section 7.

2. Global GHG emission budgets

2.1 Scientific basis for deriving carbon budgets and their uncertainties.

Determining the contribution of anthropogenic GHG emissions to the increase of GMST[3] requires a detailed understanding of: (1) how anthropogenic emissions of CO_2 and other greenhouse gases interfere with cycling of these gases in the earth system, what fraction of these emissions is absorbed by the terrestrial sinks and how GHG concentrations in the atmosphere build up over time; (2) what radiative forcing is caused by the presence of GHGs in the atmosphere and what energy imbalance does it cause; and (3) how this energy flux translates into the increase of GMST. Although our understanding of these processes has improved considerably in recent years and decades, substantial uncertainties remain for each of these steps and they compound when translating anthropogenic GHG emissions to GHG concentrations to GMST increase.

Nevertheless, a robust linear relationship between the cumulative anthropogenic CO_2 emissions and the increase of GMST from the pre-industrial level (1850-1900 average) has been observed in the historical data. The best estimate of the transient climate response to cumulative emissions (TCRE) is an increase of 0.45 °C of GMST per 1000 Gt CO_2 with a 33-67% uncertainty range of [0.35 °C – 0.55 °C] - see Fig. 1 with further details in Forster *et al.* (2018, section 2.SM.1.1.2.1). Moreover, modelling experiments indicate that this relationship is to a large extent independent of the actual shape of the future CO_2 emissions pathway (as long as it doesn't exhibit radical breaks) and can be extrapolated with a manageable level of uncertainty for cumulative emissions within a range up to 6000 Gt CO_2 (Rogelj *et al.* 2018, section 2.2.2).

[3] Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperature over the ice-free regions.

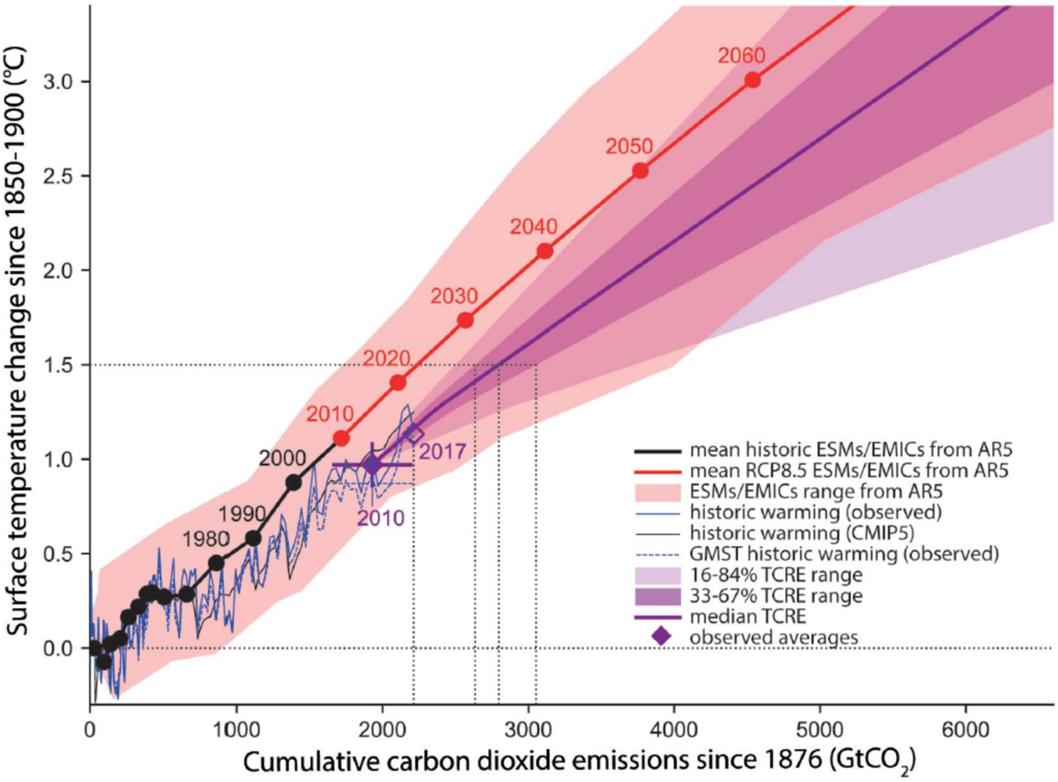

Figure 1: Temperature changes relative to 1850-1900 average versus cumulative CO_2 emissions since 1876. The near linear relationship is a basis for the TCRE calculations. (Source: Rogelj *et al.* (2018), p. 105, Figure 2.3).

The linear relationship between the cumulative CO_2 emissions and the increase of global surface temperature can be used to calculate the carbon budget that allows to keep the global warming below a specified threshold with a predefined probability. In this report we will focus on carbon budgets that will ensure meeting 1.5 °C and 2 °C with 50% probability (although, we will consider also other probability levels to explore the uncertainty of these carbon budgets).

The first step in deriving a carbon budget is to specify how much additional warming is allowed, which requires selecting a warming target, as well as choosing a reference allowing to calculate the level of warming that already took place since the pre-industrial era. The IPCC defines the current level of warming as the 2006-2015 average of GMST, which is estimated to be 0.87 °C ±0.12 °C. However, the reduced-complexity of climate models, which are used to assess the warming effect of future GHG emissions pathways, use the global mean surface air temperature[4] (GSAT) instead. The 2006-2015 GSAT average is estimated to be 0.97 °C ±0.1 °C.

[4] Global average of near-surface air temperatures over land and oceans.

Taking GSAT as a reference the allowed temperature increases for the 1.5 °C and 2 °C targets are 0.53 °C and 1.03 °C, respectively.

As a reference for the derivation of carbon budgets we choose 2010, that is the middle of the time interval 2006-2015 over which the current level of warming (GSAT average) is calculated. To derive a carbon budget $B(\Delta T)$ that gives a p% chance[5] of keeping the increase of global surface temperature below the chosen limit ΔT we use the following identity:

$$TCRE_p = \frac{\Delta T}{B(\Delta T)}$$

where $TCRE_p$ denotes the p-th percentile of TCRE estimate range based on multiple models' runs (see IPCC, 2014). To calculate carbon budgets as of 2018 we subtract from B the 2011-2017 anthropogenic CO_2 emissions, estimated to be 290 Gt CO_2 (Le Quéré *et al*. 2018). The results are gathered in Table 1.

Warming target	ΔT	Carbon budget as of 2018 [Gt CO_2]		
		67th percentile TCRE [0.55 °C per 1000 Gt CO_2]	50th percentile TCRE [0.45 °C per 1000 Gt CO_2]	33rd percentile TCRE [0.35 °C per 1000 Gt CO_2]
1.5 °C	0.53 °C	670	890	1220
2 °C	1.03 °C	1580	2000	2650

Table 1: Carbon budgets (CO_2 only) as of 2018 calculated for 1.5 °C and 2 °C warming targets

Table 1 reflects uncertainties of 1.5 °C and 2 °C carbon budgets due to uncertain estimates of TCRE. It is compounded by uncertainties in both estimates of the current level of warming and in accounting of historical CO_2 emissions (see Rogelj *et al*. (2018), section 2.2.2.2 for further details). Another serious source of uncertainty stems from the response of the Earth climate system to continued anthropogenic CO_2 emissions. No significant Earth system feedbacks were detected in historical observations and models used to assess TCRE that do not account for such feedbacks. Yet, feedbacks like CO_2 and CH_4 released by thawing permafrost or wetlands are expected in the future and are estimated to be in the order of 100 Gt CO_2 until the end of this century, with further feedbacks expected after 2100. Moreover, the linear relationship between cumulative CO_2 emissions and temperature increase critically depends on terrestrial and oceanic CO_2 sinks to continue absorbing approximately half of the anthropogenic CO_2 emissions (see Fig 2). If the strength of natural sinks falters or collapses – as may be the case with Amazon rainforests (Hubau *et al*. 2020) – the available carbon budget would be significantly smaller.

[5] This should be treated more as a qualitative statement expressing our confidence based upon multiple modelling experiments, rather than proper quantitative estimate of probability of not exceeding the warming target.

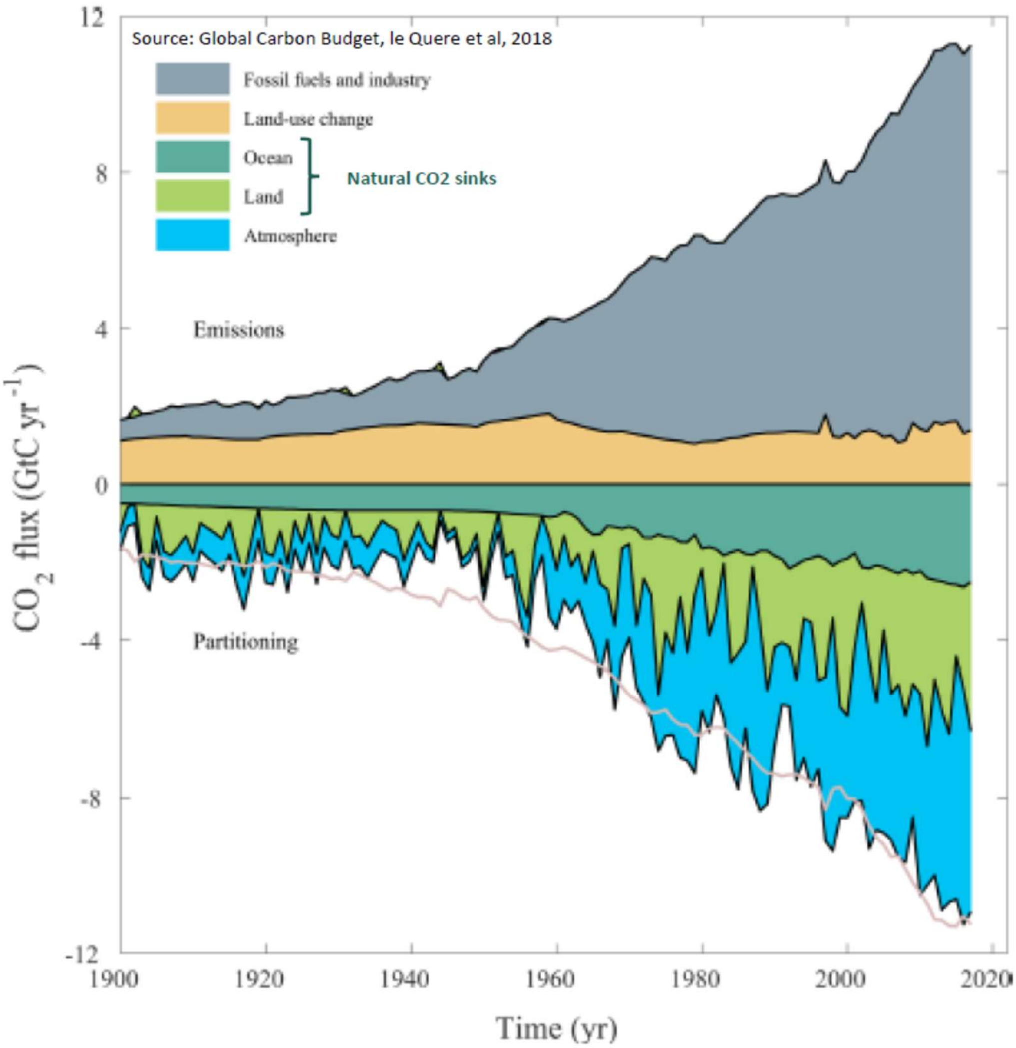

Figure 2: Combined components of the global carbon budget over time (Source: Le Quéré *et al.* (2018), Fig. 3)

2.2 Contribution of non-CO_2 gases

The TCRE-based carbon budgets presented in Table 1 refer only to cumulative anthropogenic CO_2 emissions and would ensure meeting the specified warming targets only in the absence of other climate forcing. In reality, however, anthropogenic emissions of non-CO_2 greenhouse gases contribute significantly to the global warming (approximately 20% of anthropogenic climate forcing) and thus carbon budgets need to be corrected to offset these contributions.

Non-CO_2 GHGs influence the global energy balance on various time scales. The main long-lived GHG other than CO_2 is the nitrous oxide (N_2O), which stays in the atmosphere for about 100 years. Around three quarters of N_2O emissions comes from fertiliser use in agriculture. Agriculture is also the main source of methane (CH_4) which is the most important short-lived GHG.

It lasts in the atmosphere for about a decade but has a significant global warming potential and is a precursor to ozone, which itself is a GHG. Other, less abundant short-lived GHGs are the fluorine gases, aerosols, and aerosol- and ozone-precursors.

While the increase in global mean temperature caused by the long-lived GHGs is well predicted by their cumulative emissions, the contribution of short-lived greenhouse gases to the global warming strongly depends on the shape of the actual emissions pathway. Therefore, determining the contribution of non-CO_2 GHGs to the global temperature increase needs to be based on the analysis of integrated pathways of all major greenhouse gases.

The IPCC's SR15 report (Rogelj *et al*. 2018) bases its assessment of the contribution of non-CO_2 gases to the global temperature increase on the analysis of over 200 climate change mitigation scenarios developed with various integrated assessment models. GHG emission pathways for these scenarios (consisting of yearly emissions of anthropogenic GHG broken down by type of gas) were plugged into reduced complexity climate models (FAIR and MAGICC) to assess the resulting evolution of GSAT within the time horizon of 2100. It was discovered that aggressive reductions of non-CO_2 emissions, particularly of CH_4, in the first half of the 21st century help to slow down global warming in the short term and are essential to stabilising the increase of GSAT at or below 2 °C by 2100. The peak of non-CO_2 radiative forcing is expected approximately at the same time when net zero CO_2 emissions will have to be reached. Hence it is possible to calculate by how much the CO_2-only budgets will have to be reduced to offset the non-CO_2 contribution to the increase of GSAT. First, for each scenario a peak temperature increase (caused by all anthropogenic GHGs) relative to its 2006-2015 average is calculated, together with the corresponding warming due to non-CO_2 radiative forcing at the time of zero net CO_2 emissions. Next, the reference non-CO_2 temperature contribution (RNCTC) is calculated as a median line in the quantile regression of non-CO_2 warming contribution vs. peak temperature increase – see Figure 3. The RNCTC for the 1.5 °C target (i.e. 0.53 °C of allowed temperature increase) is estimated to be 0.14 °C at the time of zero net CO_2 emissions. For a 2 °C warming target (0.93 °C of allowed temperature increase) the RNCTC is 0.23 °C. For a given target temperature increase ΔT the budget $B_{adj}(\Delta T)$ of CO_2 emissions adjusted for the contribution of non-CO_2 GHG can be calculated using the identity

$$TCRE_p = \frac{\Delta T - RNCTC_p(\Delta T)}{B_{adj}(\Delta T)}$$

where $TCRE_p$ stands for p-th percentile of TCRE and $RNCTC_p(\Delta T)$ denotes the p-th percentile of RNCTC for temperature increase ΔT. Table 2 gathers the reductions to CO_2-only TCRE-based budgets needed to offset the contribution of non-CO_2 GHGs as well as adjusted carbon budgets.

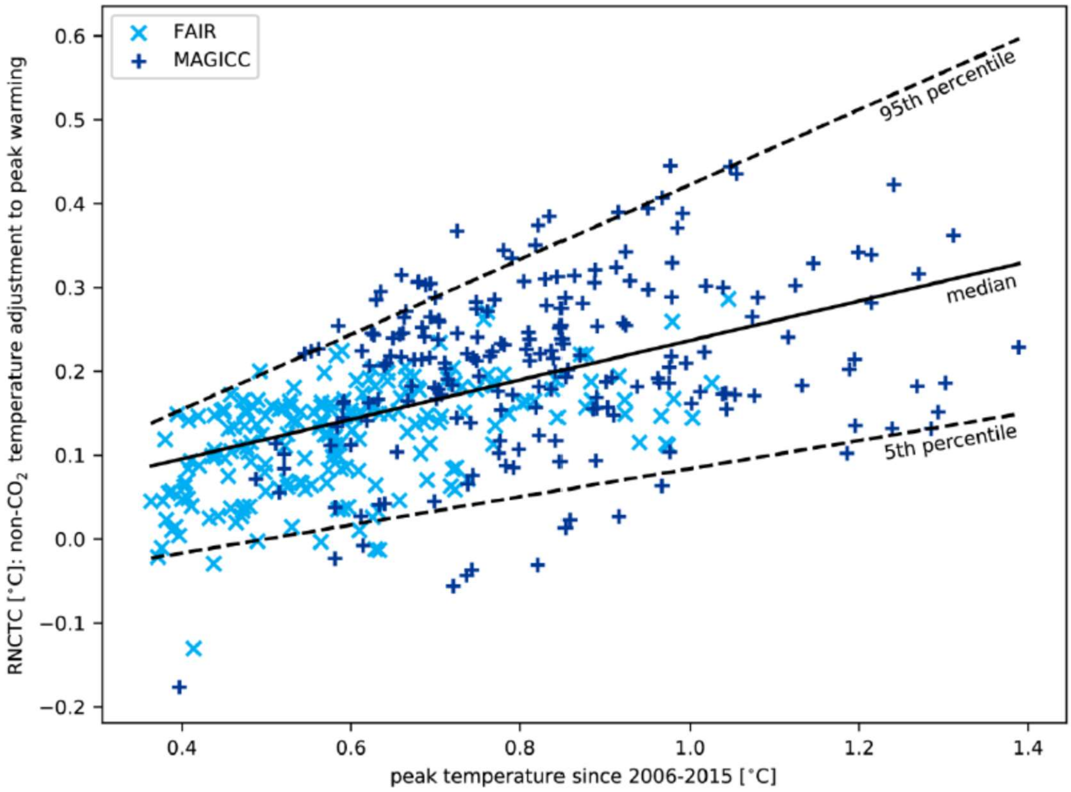

Figure 3: Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile. (Source: Forster *et al*. (2018), Fig. 2.SM.4)

Warming target	ΔT	Adjusted carbon budget as of 2018 [Gt CO_2]	Offset to balance non-CO_2 climate forcers [Gt CO_2]
1.5 °C	0.53 °C	580 [420 – 840]	310 [260 – 390]
2 °C	1.03 °C	1500 [1170 – 2030]	500 [430 – 630]

Table 2: Adjusted carbon budgets (CO_2 only) as of 2018 calculated for 1.5 °C and 2 °C warming targets. They are derived from median TCRE carbon budgets presented in Tab. 1, by subtracting the amount of cumulative CO_2 emissions required to offset the non-CO_2 climate forcing. (Source: Rogelj *et al*. (2018).

2.3 Reference global emissions pathways for 1.5 °C and 2 °C warming targets

We use the adjusted CO_2 budgets to derive reference pathways of anthropogenic CO_2 emissions for 1.5 °C and 2 °C warming targets. Since the variation in shape of CO_2 emission pathways has little effect on the resulting global temperature increase under the condition that cumulative emissions do not change, we chose a simplified shape for the reference pathway for anthropogenic CO_2 emissions. Namely, we assume constant rate (linear) reductions of net anthropogenic CO_2 emissions from 2017 onward to reach (net) zero emissions when cumulative emissions (the area under the pathway) equal the adjusted CO_2 budget, i.e.

$$\frac{1}{2}E_{net\ CO}\ (2017) \times \tau_{ZN}(\Delta T) = \ B_{adj}(\Delta T)$$

where $E_{net\ CO2}(2017)$ and $\tau_{ZN}(\Delta T)$, respectively, denote net anthropogenic CO_2 emissions in 2017 and the time of reaching zero net CO_2 emissions corresponding to the warming target ΔT. Moreover, we assume that after $\tau_{ZN}(\Delta T)$ the pathway continues the linear decrease along the same slope $a = -E_{net\ CO2}(2017)/\tau_{ZN}(\Delta T)$ until time $\tau_L(\Delta T)$ when it levels out at negative CO_2 emissions E_C, which are necessary to compensate for the climate forcing due to non-CO_2 emissions after $\tau_{ZN}(\Delta T)$. More precisely, we demand that the CO_2 removed from atmosphere must balance the cumulative non-CO_2 emissions between $\tau_{ZN}(\Delta T)$ and 2100. Thus, $\tau_L(\Delta T)$ and E_C can be computed by solving the set of equations

$$\begin{cases} \frac{1}{2}(\tau_L - \tau_{ZN})E_C + (2100 - \ \tau_L)E_C = -CE_{nonCO2} \\ E_C = (\tau_L - \ \tau_{ZN})a \end{cases}$$

where a is the slope of the pathway and CE_{nonCO2} stands for cumulative non-CO_2 emissions between τ_{ZN} and 2100.

At this point we need assumptions on the evolution of non-CO_2 GHG emissions. It is important to remember that non-CO_2 climate forcing depends on the timing of non-CO_2 emissions (particularly on that of the short-living methane). The adjusted carbon budgets were derived under specific assumptions about the shape of non-CO_2 emission pathways. Moreover, we need to know cumulative non-CO_2 emissions from the time of zero net CO_2 emissions and the end of the 21st century[6].

To be consistent with the method of calculating the adjusted carbon budget used in SR15 (and presented in section 2.2. and 2.3. of this report) we base our simplified reference non-CO_2 emission pathways for the warming targets of 1.5 °C and 2 °C on the benchmark methane and nitrous oxide emissions for the "1.5 °C low OS" and "Higher 2 °C" classes of pathways used in SR15[7]. The "1.5 °C low OS" class contains pathways which limit the warming to below 1.5 °C in 2100 with a 50-67% probability of overshooting this level of warming temporarily at some point during the 21st century; while the "Higher 2 °C" class consists of pathways limiting warming to below 2 °C during the entire 21st century (Rogelj *et al*. 2018, p. 100, Table 2.1). We choose these two categories of pathways because their definitions coincide best with the notion of 50th-percentile adjusted carbon budgets for the warming targets of 1.5 °C and 2 °C. The benchmark CH_4 and N_2O emissions are gathered in Tables 3 and 4, respectively, and our simplified

[6] Under all scenarios considered in SR15 the CH_4 emissions stabilize in the second half of the 21st century. Constant methane emissions and the fact that N_2O is a long-lived GHG imply that cumulative non-CO_2 emissions are a good predictor of the non-CO_2 climate forcing over that period.

[7] Benchmark emissions are taken to be median emissions over emissions scenarios within the class of emission pathways.

reference non-CO_2 emission pathways are based on linear interpolations between these benchmark points.

Methane emissions	2020 [Mt CH_4]	2030 [Mt CH_4]	2050 [Mt CH_4]	2100 [Mt CH_4]
1.5 °C low OS	380	240	170	170
Higher 2 °C	380	270	200	200

Table 3: Benchmark methane emissions based on median emissions for classes "1.5 °C low OS" and "Higher 2 °C" as presented on Figure 2.7. (a), SR15, Ch. 2, p. 120. We assume that emissions in 2020 are 380 Mt CH_4, which are slightly higher than 2010 emissions indicated on the aforementioned figure and is well within the range of uncertainty spanned by different estimates of current global CH_4 emissions[8]. Moreover, we assume that from 2050 on global methane emissions are constant.

Nitrous oxide emissions	2020 [Mt N_2O]	2030 [Mt N_2O]	2050 [Mt N_2O]	2100 [Mt N_2O]
1.5 °C low OS	10.5	8.5	7.5	6.5
Higher 2 °C	10.5	9.5	8	7

Table 4: Benchmark nitrous oxide emissions based on median emissions for classes "1.5 °C low OS" and "Higher 2 °C" as presented on Figure 2.6. (d), SR15, Ch. 2, p. 117.

The only non-CO_2 greenhouse gases considered here are CH_4 and N_2O, since they are responsible for approximately 98% of non-CO_2 climate forcing. Thus, the above assumptions on the evolution of methane and nitrous oxide allow us to fully specify the reference CO_2 and total GHG pathways for the global warming targets of 1.5 °C and 2 °C, displayed in Figures 4 and 5, respectively. The characteristics of these pathways are summarized in Table 5.

[8] See EPA projections: https://cfpub.epa.gov/ghgdata/nonco2/ and Global Methane Budget https://www.globalcarbonproject.org/methanebudget/

Pathway		1.5 °C			2 °C		
Percentile		67th	**50th**	33rd	67th	**50th**	33rd
CO_2	Slope a [Gt CO_2 / year]	-2.11	**-1.53**	-1.06	-0.76	**-0.59**	-0.44
	Time of zero net τ_{ZN}	2037	**2045**	2057	2073	**2088**	2113
	Time of levelling out τ_L	2040	**2049**	2063	2089	After 2100	After 2100
	CO_2 emissions E_C at the time of levelling out [Gt CO_2]	-6.65	**-6.57**	-6.81	-12.13	Levelling out after 2100	Levelling out after 2100
	Net emissions in 2050 [Gt CO_2]	-6.65	**-6.57**	7.56	17.61	**22.85**	27.77
	2018-2050 cumulative emissions [Gt CO_2]	340	**570**	820	990	**1070**	1150
Non-CO_2	Emissions in 2050 [Gt CO_2e]	**6.49**			**8.83**		
	Emissions in 2100 [Gt CO_2e]	**6.19**			**8.68**		
	Cumulative emissions from 2018 to time of zero net CO_2 [Gt CO_2e]	190	**250**	330	540	**670**	Zero net CO_2 after 2100
	Cumulative emissions from time of zero net CO_2 to 2100 [Gt CO_2e]	410	**350**	270	240	**100**	Zero net CO_2 after 2100
	Cumulative emissions 2018-2050 [Gt CO_2e]	**290**			**340**		
	Cumulative emissions 2018-2100 [Gt CO_2e]	**610**			**780**		

Table 5: Characteristics of the reference emission pathways for the global warming targets of 1.5 °C and 2 °C. Non-CO_2 emissions are expressed in [Gt CO_2e] according to 100 years global warming potentials of CH_4 and N_2O given in (IPCC 2014, p. 212).

It is important to point out that considerable discrepancies exist between our reference cumulative non-CO_2 emissions until the time of zero-net CO_2 emissions and reductions to TRCE-based carbon budgets needed to offset the non-CO_2 climate forcing. For the 1.5 °C reference pathway, the cumulative non-CO_2 emissions until $\tau_{ZN}(\Delta T)$ are 250 Gt CO_2-equivalent, while the carbon budget offset is estimated to be 310 Gt CO_2. For the 2 °C pathway this relationship is reverse, with 670 Gt CO_2-equivalent of cumulative non-CO_2 emissions vs. a 500 Gt CO_2 carbon budget offset. These discrepancies can be explained by: (1) methodological differences; (2) a short lifetime of CH_4; and (3) the different time horizons over which non-CO_2 emissions contribute to an increase in temperature. Indeed, benchmark CH_4 and N_2O emissions (cf. Tables 3 and 4) are derived as medians taken over 44 emission pathways belonging to the class "1.5 °C low OS" and 58 emission pathways constituting the class "Higher 2 °C", while offsets to carbon budgets are based on estimates of RNCTC derived by means of median regression over 205 scenarios in which net-zero CO_2 emissions are reached before 2100. Moreover, the short lifetime of methane together with the assumed benchmark methane emissions (cf. Table 3) imply that non-CO_2 radiative forcing peaks between 2030 and 2050 (see e.g., Rogelj *et al*. 2018, p. 120, Fig. 2.8.), thus requiring sharper initial reductions in CO_2 emissions to avoid or minimize the overshoot of the 1.5 °C warming target. On the other hand, in the case of the 2 °C pathway a large portion of non-CO_2 GHGs will be emitted in the second half of the 21st century. Their 100-year global warming potential will not fully play out before 2100, which is the time horizon within which the non-CO_2 contribution to a global temperature increase was analysed in SR15 to derive carbon budget offsets. This, for the 2 °C warming target, leads to the lower offset to carbon budget in relation to cumulative non-CO_2 emissions accounted in GWP-100 CO_2 equivalents.

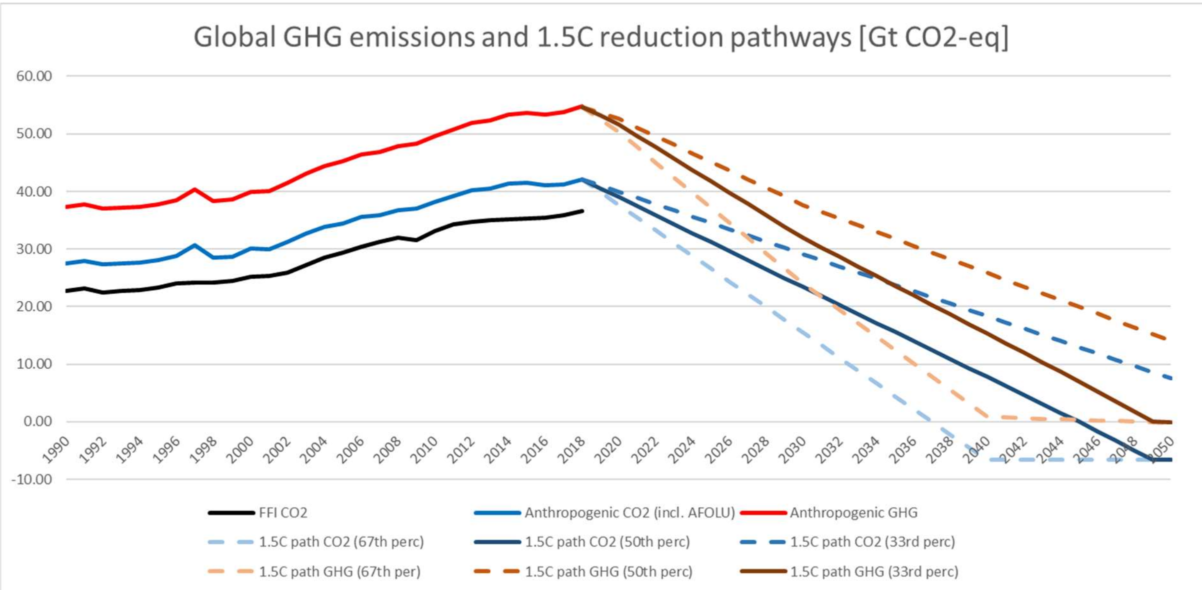

Figure 5: Historical emissions of anthropogenic GHG (CO_2 from fossil fuel burning and industry, net anthropogenic CO_2 and aggregated GHGs) and reference pathways of net CO_2 and aggregated GHG emissions for 1.5 °C target. Dashed lines indicate uncertainty ranges due to uncertainty of adjusted CO_2 budget.

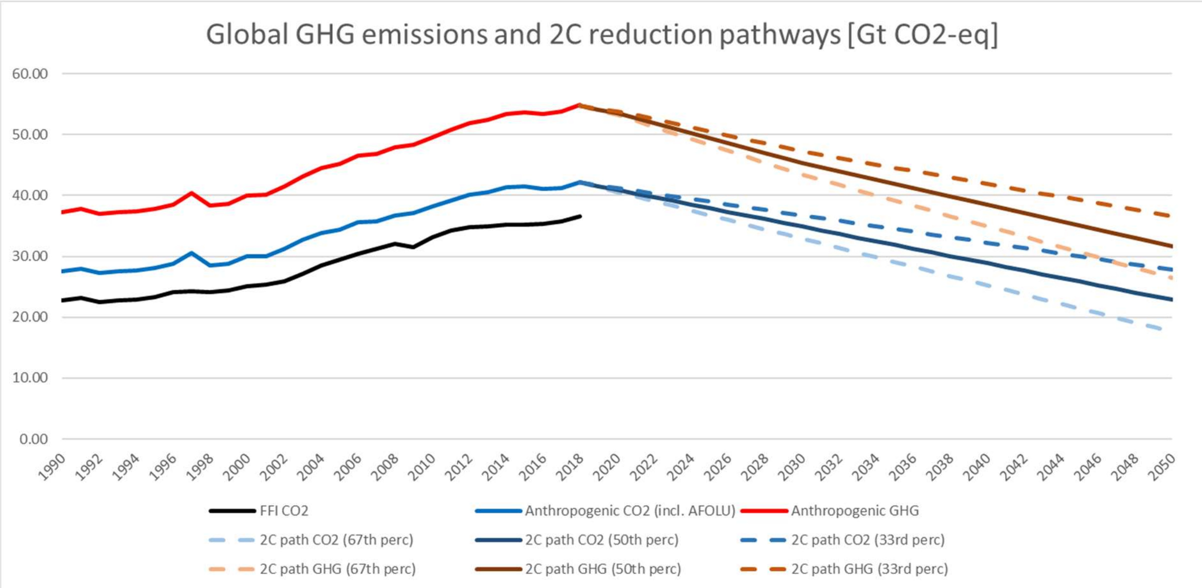

Figure 6: Historical emissions of anthropogenic GHG (CO_2 from fossil fuel burning and industry, net anthropogenic CO_2 and aggregated GHGs) and reference pathways of net CO_2 and aggregated GHG emissions for 2 °C target. Dashed lines indicate uncertainty ranges due to uncertainty of adjusted CO_2 budget.

2.4 Reference global GHG emission levels in 2050 and cumulative emissions until 2050 for 1.5 °C and 2 °C warming targets

Although anthropogenic GHG emissions already have a noticeable effect on Earth's climate, the full impact of these emissions will not be fully visible before the end of the 21st century and beyond. Yet, to avoid catastrophic levels of global warming, rapid decarbonization of the global economy within the next 2-3 decades is considered crucial, with the year 2050 believed to be the time until which the transition to a green (decarbonized) economy must be completed. The reference emission pathways discussed in the previous section are helpful to translate the long-term goals for climate stabilization to the time horizon of 2050.

Benchmark GHG emissions for 2050 are abundant in literature, but these are typically derived with the help of integrated assessment models and for specific scenarios or classes of scenarios of global climate mitigation action (see e.g., Rogelj *et al*. 2018, p. 119, Table 2.6). In contrast, we derive benchmarks for 2050 emissions directly from carbon budgets and corresponding reference emission pathways. Such benchmarks, although approximate, reflect sine-qua-non conditions, rather than the consequences of specific (often socio-economic) assumptions of particular global-scale scenarios of climate change mitigation. Thus, our benchmarks could be used as a universal reference for assessing the compatibility of any GHG emissions trajectory with a given warming target. Importantly, this applies also to emission trajectories for green transition scenarios modelled within frameworks alternative to standard mainstream IAMs.

Derivation of benchmark emissions in 2050 from our reference pathways is straightforward: these are the values the reference pathways reach in 2050. We divide them by the estimate of the size of global population[9] to obtain reference levels of per-capita emissions in 2050 that need to be reached to comply with the corresponding warming targets. Table 6 presents 2050 benchmarks for the 1.5 °C and 2 °C warming targets.

	CO_2		Aggregated GHG	
Target	Global [Mt CO_2]	Per cap [t CO_2/cap]	Global [Mt CO_2e]	Per cap [t CO_2e/cap]
1.5 °C	-6.57	-0.67	-0.08	-0.01
2 °C	22.85	2.35	31.69	3.25

Table 6: Benchmark emissions in 2050 for the 50th percentile reference emission pathways corresponding to 1.5 °C and 2 °C warming targets. Per capita emissions are calculated using medium variant projections published by the UN Population Division.

Importantly, an emission pathway that reaches the benchmark in 2050 may still not be compatible with a given warming target if its shape significantly differs from the one of the reference emission pathway[10]. For that reason, it is important to complement benchmark emissions in 2050 with reference cumulative emissions until 2050, which can be easily computed as the area under the reference pathway up to 2050. Table 5 presents the reference cumulative emissions for period 2018-2050 for the 1.5 °C and 2 °C targets.

3. Austria's reference GHG emission pathways and budgets

The reference pathways for global GHG emissions introduced above allow not only for scaling long-term mitigation goals – for 2100 and beyond – to shorter time horizons like 2050. They also offer an easy way of downscaling global efforts required to mitigate climate change to a national level. In this section we discuss how national reference emission pathways and cumulative emission budgets can be derived from the global ones using Austria as a case example.

To ensure that Austria's limits on GHG emissions are consistent with efforts of the international community to meet the targets of the Paris agreement we split global GHG emissions budgets corresponding to these targets between all countries. This way we achieve a global consistency of national GHG emission budgets with goals of the Paris agreement without a need to elaborate global socio-economic assumptions, like shared socio-economic pathways used in global-scale IAMs. This makes our national emission budgets convenient references for scenarios of green transition of local economies, e.g., ones developed with the help of local-scale modelling frameworks, for which climate change and developments of the global economy are exogenous.

[9] Here we use medium variant of estimate published by the UN Population Division (https://population.un.org/wpp/Download/Standard/Population/).

[10] For instance, an emissions trajectory which is always above the reference pathway and touches it only in 2050 (i.e. reaches the benchmark emissions in 2050) will result in higher cumulative GHG emissions and thus will lead to higher global temperature increase compared to that of the reference pathway.

3.1 Principles of allocating pools of allowed emissions to countries

To derive Austria's GHG emission budgets that are in line with the warming targets of the Paris agreement we distribute budgets of global GHG emissions (discussed in Section 2) between nations in a top-down way. There are, however, multiple ways in which this could be done and, consequently, Austria's pool of allowed emissions will vary depending on the principle guiding such distribution.

A wide range of principle-based approaches to allocate GHG emission allowances to countries is available in the literature. As our aim is to derive robust budgets of national emissions that do not rely on subjective or uncertain assumptions, we do not consider principles like historical responsibility[11] or ability to pay[12]. Instead, we focus on principles that require only easily measurable or predictable quantities such as GHG emissions and population to determine national shares in the global pool of 2018-2050 cumulative GHG emissions compatible with 1.5 °C and 2 °C warming targets. Although many such effort sharing principles are conceivable, we consider four principles, that span the range of shares in a global emissions budget that a country could claim with a certain fairness argument[13]:

1. **Proportionality to current population[14]:** the share of cumulative 2018-2050 GHG emissions is proportional to the fraction of the global population currently living in the region / country of question.
2. **Constant-rate convergence to globally equal per capita emissions in 2050[15]:** a region/country closes the gap between its per capita emissions and the global reference per capita emissions (i.e., emissions according to the reference emissions pathway divided by the projected population for each year) with a constant rate, with the gap being closed in 2050. More precisely, the pool B^i of emissions of country/region i is given by

[11] Historical responsibility takes into consideration not only current but also past GHG emissions and requires that the countries who profited from high levels of historical emissions bear higher burdens of climate change mitigation. However, the major practical drawback for this kind of principle is the need for specifying a point in time from which countries can be held responsible for their past emissions and consequent damages to climate. Such choice is a subjective decision of the modeller.

[12] According to this principle wealthier countries should reduce their emissions faster than poorer ones since implementing costly mitigation measures will cause less damage to welfare of their societies. Analysis of ability to pay is, however, based on uncertain relationships between costs of mitigation and welfare.

[13] The Paris agreement does not rely on a single comonly-agreed top-down principle of emission rights allocation. Instead its mechanism is based on nationally determined contributions declared by individual countries. Each country, however, must explain how its emission reduction goal is a fair contribution to global effors to mitigate climate change. Therefore it is important for a country to understand what pool of emisions can it fairly claim.

[14] The fairness argument backing this approach is the principle that well-being of all people is equally important and thus everyone should enjoy the same allotment of emissions to provide for his/her well-being.

[15] The fairness argument backing this approach is similar to the one for proportionality to population but recognizes that current discrepancies in per capita emissions across the world will require some time to eliminate.

$$B^i = \sum_{t=201}^{2050} P_t^i \times \left(\frac{E_t}{P_t} + \left(\frac{E_{2018}^i}{P_{2018}^i} - \frac{E_{2018}}{P_{2018}}\right) \times \left(1 - \frac{t-2018}{2050-2018}\right)\right)$$

where P_t^i and P_t denote the population of country/region i and the global population at time t, respectively, E_t stands for global emissions at time t according to a reference emissions pathway and E_{2018}^i are the emissions of country/region i in 2018.

3. **Proportionality to current territorial gross CO_2 emissions[16]:** the share of cumulative 2018-2050 GHG emissions is proportional to the ratio of gross CO_2 emissions emitted on the territory of the country/region in question to global gross CO_2 emissions in 2018.
4. **Proportionality to current territorial gross CO_2 emissions[17]:** the share of cumulative 2018-2050 GHG emissions is proportional to the ratio of gross CO_2 emissions embodied in the consumption of the country/region in question to the global gross CO_2 emissions in 2017.

3.2 Reference emission budgets and emission pathways for Austria

We apply the above principles to assess the range of cumulative GHG emissions that can be allocated to Austria. The results are gathered in Table 7.

The population of Austria constitutes only about 0.1% of the global population resulting in a small share of the 2018-2050 emissions budget. Principle of proportionality to current population means that the current excess of Austria's per capita emissions (8.2 t CO_2e/year/cap) over the global average (7.2 t CO_2e/year/cap) implies obligation to faster than average emission reductions. Such drastic emission cuts may technically and politically unrealistic and thus the share of global emissions in proportion to the current population of Austria marks the lower end of its emissions allowance for 2018-2050.

By the same token, the above-average per capita GHG emissions in Austria imply that a share of globally allowed cumulative emissions proportional to its current share in global (CO_2) emissions is the upper limit for Austria's budget of emissions until 2050. This is especially true if one uses as a reference the CO_2 emissions embodied in consumption.

Figure 7 presents reference GHG emission pathways for Austria calculated according to the constant-rate convergence to globally equal per capita emissions in 2050 (see formula above). The 2018-2050 emissions budgets corresponding to this principle (calculated as areas under these pathways) are good references which are easily scalable, allow some leeway to high-emitters and yet are acceptable on the grounds of various fairness arguments. This principle was also invoked in the ref-NEKP scenario (Kirchengast *et al*. 2019) outlining Austria's GHG

[16] High emitter countries / regions argue setting up their emission reduction targets in proportion to current emissions is their fair contribution to climate action since it is harder for high emitting economies to reduce their emissions in absolute terms.

[17] One may argue that emissions embodied in consumption are a proxy for the country's / region's welfare. Therefore, setting up emission targets in proportion to their current emissions from consumption can be considered fair since it implies proportional sacrifices in terms of welfare (regions of highest welfare will sacrifice most in absolute terms).

emission reduction targets (reaching net-GHG neutrality around 2045 with 1000 Mt CO_2e of cumulative net GHG emissions for the period 2017-2050).

The boundary conditions for functionality-based modelling of Austria's economic transition – to which we now turn – will be based on reference emission pathways and corresponding budgets derived calculated according to the principle of constant-rate convergence to globally equal per capita emissions in 2050.

Warming target	1.5 °C			2 °C		
Cumulative 2018-2050 emissions [Mt CO_2e]	CO_2	Non-CO_2	GHG	CO_2	Non-CO_2	GHG
Proportionality to current population	660	339	999	1249	402	1650
Constant-rate convergence of per-capita emissions	836	268	1104	1345	322	1667
Proportionality to territorial CO_2 emissions	1033	531	1564	1955	629	2584
Proportionality to consumption CO_2 emissions	1496	768	2264	2831	911	3741

Table 7: Austria's allowed cumulative emissions for the period 2018-2050 compatible with the 1.5 °C and 2 °C warming targets in accordance with different principles of allocating emission allowances. Emission budgets are based on 50^{th} percentile reference pathways for global emissions and the medium projection variant of population growth.

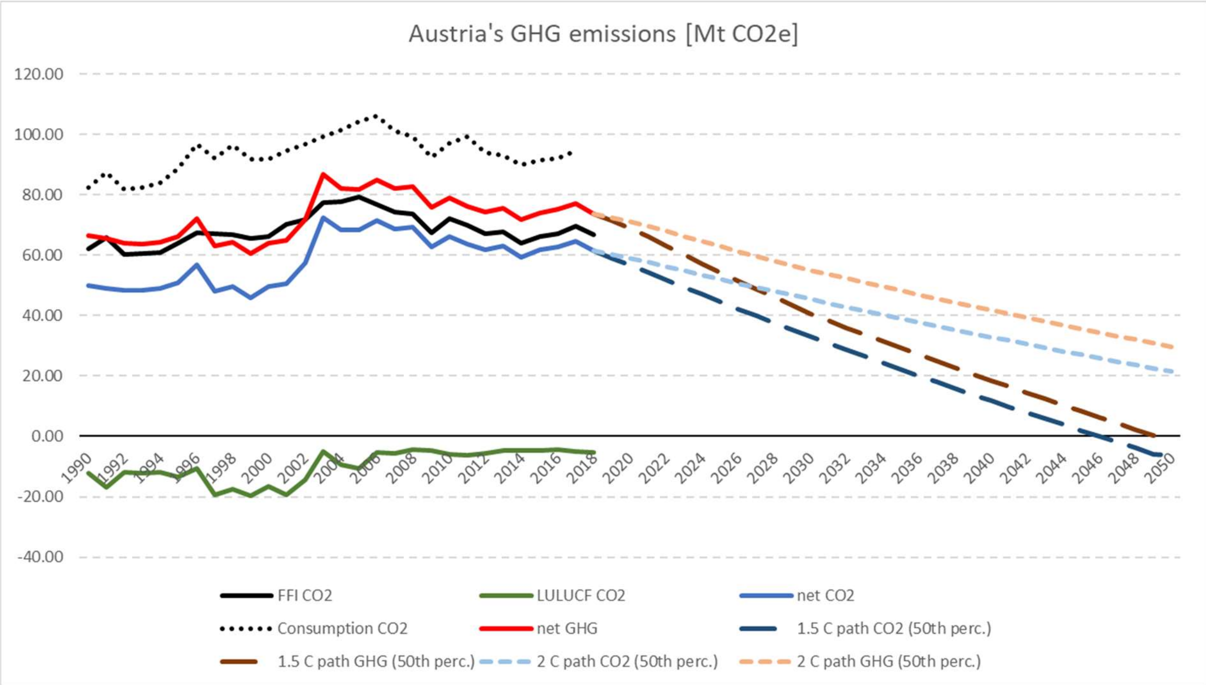

Figure 7: Austria's historical GHG emissions and reference emission pathways corresponding to 1.5 °C and 2 °C warming targets derived from 50th percentile global emission pathways using the principle of constant-rate convergence of per capita emissions in 2050.

4. Austria's GHG emissions through the lens of functionalities

Constraints imposed by warming targets of the Paris agreement on Austria's GHG emissions (outlined in the previous section) are stringent. Thus, increasingly to the fore come questions of how to use this very tight room for manoeuvre to push the economy towards climate-neutral and sustainable ways, what goods and services such a "new" economy must deliver to maintain the well-being of the society and what economic structures can provide these goods and services.

Such a shift to a demand-oriented perspective on the green transformation requires a new approach to economic modelling that focuses on the evolution of relevant value chains (cutting across multiple sectors of the economy), as well as on material and energy inputs they require, and on GHG emissions caused by them. In this vein, the EconTrans project explores the usefulness of the concept of functionalities as convenient modelling units for this alternative approach.

In this section we discuss the viability of a novel functionality-based scheme of accounting for anthropogenic GHG emissions, while in the next section we derive reference budgets for emissions related to the functionalities Access, Shelter and Other Life Support in Austria. Results presented below are based on the previous section of this report and on findings of the EconTrans

Working Paper #3 (Sommer et al., 2021), which focus on material and energy inputs as well as resulting GHG emissions needed to provide the abovementioned functionalities in Austria.

For the functionality-based approach to be fit for the task of modelling a transition to a climate-neutral economy it must allow for keeping track of all functionality-related GHG emissions, without omissions or double-counting, as well as for identifying emissions that cannot be attributed to the considered functionalities. Failing on this requirement would make it impossible to assess the compliance of scenarios of future development of functionalities with national and global warming targets. It is therefore essential to establish a mapping between emissions attributed to functionalities and national GHG emissions inventories which are currently the only comprehensive and widely accepted reference for emissions accounting.

Within the current UN FCCC arrangements countries are obliged to report their GHG emissions using the sector-based accounting scheme which reflects a traditional perspective on the economy as a collection of interacting production sectors. Mapping functionalities onto these sectors is not a trivial task, however, since different sectors are involved in providing the respective functionality. To disentangle contributions of individual sectors to the provision of the respective functionalities the EconTrans Working Paper #3 (Sommer et al., 2021) developed an extended input-output representation of the Austrian economy. This allows to attribute the required material and energy flows as well as the corresponding GHG emissions to the functionalities Access, Shelter and Other Life Support. Emissions thus ascribed to these three functionalities are presented in the first part of Table 9 (cf. Section 6) and cover:

- 99% of all GHG emissions from the Energy sector (1), excluding: non-CO_2 emissions from fuel combustion activities in the commercial/institutional and residential sectors (1A4a, 1A4b) and CO_2 emissions from non-specified mobile sources (1A5b) and fugitive emissions from fossil fuels (1B);
- 87% of all GHG emissions from Industrial Processes and Product Use (2), excluding: CO_2 emissions from non-energy products from fuels and solvent use (2D) and non-CO_2 emissions from substitutes for ozone-depleting substances (2F) and other product manufacture and use (2G)
- 100% of non-CO_2 emissions from Agriculture (3), constituting 98% of all agricultural emissions. As practically all agricultural emissions fall under the functionality Other Life Support, it is possible to disentangle them form other functionality-related emissions.

Not covered are the LULUCF (4) and Waste (5) sectors.

5. Assessing boundary conditions for the transformation of Austria's economy

Now we turn to the problem of specifying limits for Austria's cumulative GHG emissions caused by functionalities Shelter, Access and Other Life Support for the period until 2050. To ensure that these limits are in line with the warming targets of the Paris agreement (i.e., 1.5 °C and 2 °C) we need to know (1) what part of Austria's GHG emissions budgets must be reserved for the agriculture sector that satisfies nutrition needs of Austria's population; (2) how much of emissions caused by the considered functionalities (without Agriculture) and the Waste sector can be offset by natural carbon sinks; and (3) what is the potential of negative emissions technologies to provide additional leeway for staying within tight budgets of national GHG emissions.

For that we need scenarios for Austria's emissions from the Agriculture, LULUCF and Waste sectors that are in line with the targets of the Paris agreement as well as for deployment of carbon dioxide removal (CDR) technologies. The ref-NEKP scenario (Kirchengast *et al*. 2019) for Austria's reductions of GHG emissions required to meet the 1.5 °C target unfortunately does not provide a detailed insight into emissions expected form individual sectors of the Austrian economy. Therefore, to gain insights into possible future emissions from Agriculture, LULUCF and Waste sectors and the potential of CDR technologies we resort to downscaling to Austrian level comprehensive EU-wide scenarios of economic transformation from the European Commission's report "A Clean Planet for All" (EC 2018)[18]. A description of these scenarios, together with our analysis of their consistency with the targets of the Paris agreement and a summary of emissions from sectors of interest are provided in the Appendix.

5.1 Expected future GHG emissions from Austria's agriculture

Austria's agriculture production uses over 28000 km^2 roughly 1.6% of all agricultural land in the EU[19] and is responsible for approximately 7.2 Mt CO_2e of GHG emissions annually, which is approximately 1.6% of EU agricultural emissions. Therefore 1.6% is a robust scaling factor which we will use to downscale EU-wide scenarios for agriculture from (EC 2018) to the Austrian level.

GHG emissions from the agriculture sector arise in nearly equal parts from CH_4 (mainly caused by enteric fermentation and manure management) and N_2O (mainly from agricultural soils) with CO_2 emissions amounting to 2% of agricultural total. EU's agricultural emissions are declining steadily since 1990's but, due to the nature of biological processes involved in agricultural production, they will never be fully eliminated. However, EC (2018) indicates the possibility for 35% reductions of agricultural emissions (compared to current levels) by 2050 due to improvements in agricultural techniques, and up to 50% reductions if these techniques will be coupled with a change in diet of EU's population.

Mitigation of N_2O emissions has the largest potential and can be achieved through:

- optimized and reduced use of fertilizers,
- reduction of agricultural area used, especially fallowing of organic soils,
- improved manure management techniques.

[18] Here EU refers to the former EU-28 including the United Kingdom, which left the European Union in 2020, that is after the report has been published. Since this working paper is based on the data collected before 2020, the fact that UK is no longer a member state of the EU does not affect results of our analysis.

[19] As of 2015. Source: Eurostat

The latter option will also help in mitigating CH_4 emissions, which, however, are more difficult to reduce. Other possibilities for further reductions in methane emissions include:

- selective breeding improving efficiency of livestock production and thus decreasing amount of CH_4 from enteric fermentation per unit of livestock,
- use of improved feed that reduce methane from enteric fermentation,
- Reduced meat consumption, especially of beef and mutton.

Figure 8 displays the possible non-CO_2 emission pathways for Austria's agriculture based on downscaling EU-wide projections by the current fraction of Austria's emissions in the EU's agricultural sector (i.e., 1.6%). By calculating areas under emissions pathways, we conclude that cumulative 2015-2050 non-CO_2 emissions from Austria's agriculture are expected to be as high as 235 Mt CO_2e in the baseline scenario (implementing currently planned mitigation measures). They could be reduced to 210 Mt CO_2e through improved agricultural practices and further reduced to 195 by additional changes in diet (reduced meat consumption)[20].

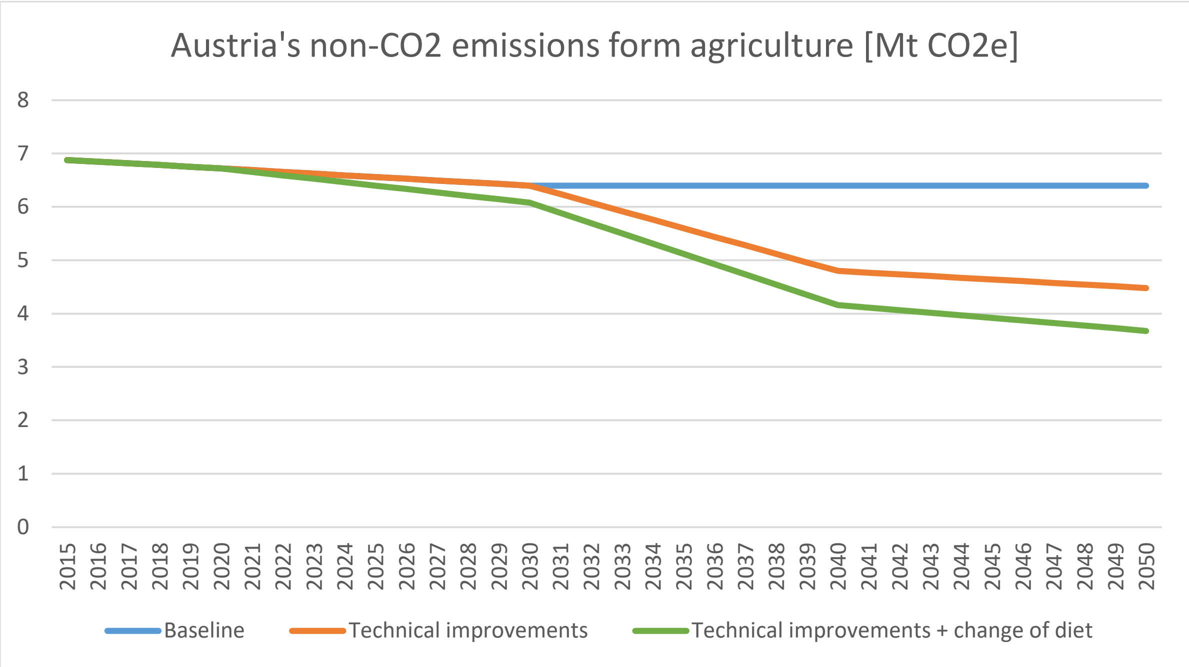

Figure 8: Possible pathways of non-CO_2 emissions from Austrian agriculture obtained by downscaling scenarios for agriculture sector of the EU to the Austrian level. (Based on EC (2018), p. 167, Figure 78.)

[20] Cumulative emissions 2018-2050 under all scenarios are 20 Mt CO_2e lower.

5.2 Expected GHG emissions from Austria's Land Use, Land-use Change and Forestry (LULUCF) sector

Forests on the territory of the EU are a strong and robust carbon sink, removing approximately 400 Mt CO_2 annually. Other types of land, however, emit greenhouse gases in the range of 100 Mt CO_2e a year, so, currently, the LULUCF sector is able of removing approximately 300 Mt CO_2e of EU's GHG emissions each year. A similar picture emerges for Austria's LULUCF sector, with a current forest sink strength of -4.3 Mt CO_2 per annum and net GHG emissions in the range of -5 Mt CO_2e (which constitutes 1.6% of EU's LULUCF emissions).

The strength of the LULUCF carbon sink may, however, diminish in the future due to e.g., aging of existing forests, deforestation, erosion of soils releasing carbon and emissions caused by the expansion of agricultural and urban areas.

The forest carbon sink strength can be preserved and enhanced by good management practices. EC (2018) indicates that methods such as:

- harvesting of wood and biomass in a way that stimulates forest growth,
- interventions improving health of forests, which in turn lead to increased uptake and storage of carbon
- introduction of new species with faster growth rates

have significant potential for maintaining the current strength of the forest carbon sink. Afforestation, reforestation and avoiding deforestation will also be of key importance.

The dominant sources of GHG emissions in the LULUCF sector are cropland and settlements. To a small extent they could be reduced by avoiding the expansion of agricultural and urban areas on the other types of land. In addition, improved agrarian practices such as reduction/elimination of tilling, leaving crop residues on the fields, use of cover crops and mixed crop-livestock and agroforestry techniques can enhance carbon sequestration in soils.

We downscale the EU-wide assessment of future LULUCF emissions to the level of Austria in the following way. We assume that the current contribution of Austria's LULUCF sector to EU's LULUCF emissions, i.e., 1.4% for net LULUCF CO_2 and 1.5% for net LULUCF GHG, will remain constant until 2050. Thus, we multiply EU-wide estimates from Table A2.4 by respective factors to derive corresponding estimates for Austria. Next, we assume that the current ratio of Austria's forest sink strength to the net LULUCF CO_2 emissions will also stay constant until 2050. The cumulative CO_2 removals by Austria's forests are calculated using linear interpolation between current emissions and expected emissions in 2050. Finally, expected changes to Austria's forested area are assumed to preserve current ratio of Austria's forest area to EU's forest area. Table 8 summarizes plausible ranges of Austria's LULUCF emissions and changes to forest area.

Emissions	In 2050 [Mt CO_2e]		2015-2050 Cumulative [Mt CO_2e]	
	Lower bound	Upper bound	Lower bound	Upper bound
Net LULUCF GHG	-6.8	-3.6	-202	-145
Net LULUCF CO_2	-6.6	-3.6	-202	-147
Forestry CO_2	-6.6	-4.3	-197	-156
Forest area	In 2050 [km²]		Change relative to 2050 [km²]	
	Upper bound	Lower bound	Upper bound	Lower bound
	38000	minimal	2200	minimal

Table 8: Plausible ranges of Austria's LULUCF emissions and changes to forest area.

5.3 Potential of negative emissions technologies in the context of Austria.

Biosphere is a potent carbon sink but even if well managed it may not be able to absorb a sufficient amount of anthropogenic GHG emissions to keep them within the limits of emission budgets. Therefore, technologies augmenting and complementing natural processes of atmospheric CO_2 removal are being actively researched. Options, like advanced weathering and biochar, aim at boosting carbon sequestration in soils but their efficacy is unproven. Currently two options for carbon dioxide removal (CDR) are considered to be the most promising: Biomass for Energy with Carbon Capture and Storage (BECCS) and Direct Air CO_2 Capture and Storage (DACCS).

The idea behind BECCS is to absorb atmospheric CO_2 in the process of biomass production, use it as a feedstock for energy generation, capture of CO_2 from resulting flue gases and then storage in geological formations. Although relatively cheap (Fussl *et al*. 2018) and having a co-benefit with energy production with existing facilities, BECCS have also significant drawbacks that may limit large scale deployment. Production of sufficient amounts of biomass feedstocks will compete for land with production of necessary food, feed and fibre, and may have negative impacts on biodiversity. Moreover, capture of CO_2 from flue gases is feasible only at large point sources, such as power plants and industrial installations. Finally, geological storage of captured CO_2 e.g., in deep saline reservoirs coal seams or oil and gas reservoirs is not proven at a large scale. Captured CO_2 may also be used for the production of synthetic materials and synthetic fuels, thus eliminating the need for fossil fuel inputs, but such technologies can be considered carbon-neutral at best.

DACCS, on the other hand, aim at removing CO_2 from ambient air. Although potentially more expensive than BECCS (Fussl *et al*. 2018), DACCS has an advantage of requiring much less area to deploy, which in addition needs not to be productive land. Thus, DACCS put much less pressure on agriculture and ecosystems. A downside of this technology, apart from reliance on unproven storage techniques, is a high energy input needed to release captured CO_2 from absorbent.

Both BECCS and DACCS are unproven technologies, currently at the stage of pilot projects. Nevertheless, they play some role in strategies of transforming the EU economy (EC 2018). They are expected to become operational only after 2035 and, in scenarios in line with the 2 °C target, deployed only to minimal extent.

According to Table A2.5. outlining the potential for carbon capture and storage technologies in the EU, their deployment can offset between 0.5 and 2 Gt CO_2 of the bloc's emissions, that is 1% to 3% of EU's GHG emission budgets (see Table A1.1). We expect that these technologies can offset similarly small percentage of Austria's allowed GHG emissions budget until 2050, that is between 10 and 30 Mt CO_2.

5.4 Boundary conditions for the transformation of the Austrian economy – a summary.

To stay on the path of the 1.5 °C warming target Austria must keep its cumulative GHG emissions for the period 2015-2050 within a tight budget of 1300 Mt CO_2e (approximately 200 Mt CO_2e of emissions in years 2015-2017 plus 1100 Mt CO_2e of 2018-2050 budget – see Table 8). By implementing far reaching reductions in GHG emissions from the agriculture sector, food production in Austria will result in emissions of 220 Mt CO_2e within this period (see section 5.1). Assuming ambitious scenario of afforestation and increased strength of the LULUCF carbon sink (-200 Mt CO_2e – see Table 12) and a high level of deployment of CDR technologies (at least -20 Mt CO_2e – see section 5.3), negative CO_2 emissions may balance agricultural GHG emissions. Moreover, based on expected trends outlined in EC (2018, sect. 4.6.3), GHG emissions from waste in 2050 may be reduced by 85% compared to current levels, which, in case of Austria, translates to reductions from 2 Mt CO_2e in 2015 to 0.3 Mt CO_2e in 2050. Thus, the waste sector will contribute another 40 Mt CO_2e in the period 2015-2050. This leaves the budget of 1260 Mt CO_2e for the remainder of technospheric emissions. These boundary conditions are depicted in Figure 9.

The warming target of 2 °C allows for a somewhat more generous emissions budget of 1870 Mt CO_2e for the period 2015-2050 (200 Mt CO_2e for 2015-2017 plus 1670 Mt CO_2e for the period 2018-2050). Assuming less ambitious reductions of agricultural emissions, 235 Mt CO_2e will have to be subtracted from this budget to cover for nutrition needs of Austria's population. Further 40 Mt CO_2e will be required by the waste sector. If the current LULUCF sink strength will be maintained, it may offset about 150 Mt CO_2 of anthropogenic emissions with approximately 10 Mt CO_2 additionally removed through limited CDR deployment. This leaves the budget of 1755 Mt CO_2e for the remainder of Austria's GHG emissions for the period 2015-2050. The boundary conditions for transformation in line with the 2 °C target are displayed on Figure 10.

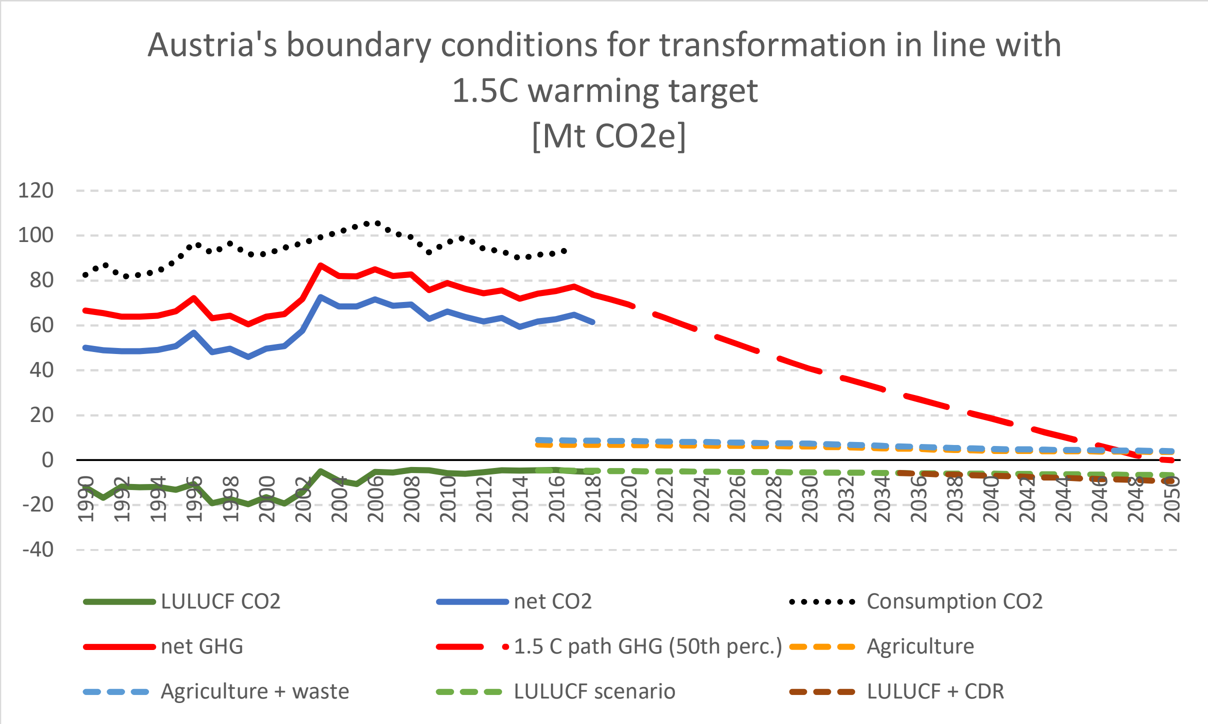

Figure 9: Boundary conditions for Austria's economic transformation in line with the 1.5 °C global warming target.

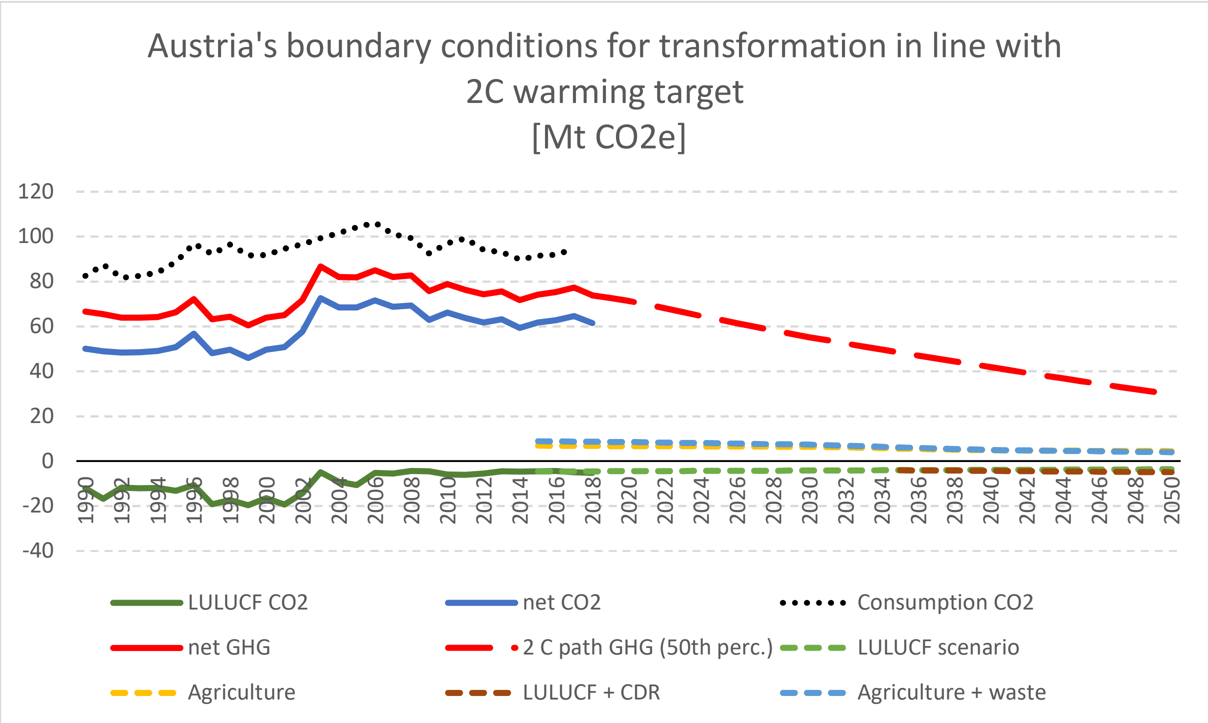

Figure 10. Boundary conditions for Austria's economic transformation in line with the 1.5 °C global warming target.

6. Reference budgets and emission pathways for the functionalities Shelter, Access and Other Life Support

As LULUCF and Waste emissions are not ascribed to neither of the functionalities Access, Shelter nor Other Life Support (cf. Section 4), future emissions from these sectors need to be taken into consideration when assessing the 2015-2050 emission budgets for functionalities considered in the EconTans project. Fortunately, the future development of functionalities can be considered to a large extent independent of the scenarios for the LULUCF and Waste sectors. It is therefore sufficient to subtract expected cumulative emissions from these sectors from the overall budget of Austria's GHG emissions. Similarly, agriculture can be disentangled form other functionality-providing activities and thus we choose to consider agriculture emissions separately. As explained in Section 5.4, subtracting cumulative emissions from these three sectors from Austria's pool of allowed GHG emissions leaves a 2015-2050 budget of 1260 Mt CO_2e for the three considered functionalities (without agriculture) in case of the 1.5 °C target and 1755 Mt CO_2e for the 2 °C target.

We split these budgets between the functionalities in proportion to their relative contributions to all functionality-related emissions in 2014. The resulting reference budgets for individual functionalities are outlined in Table 9.

Emissions [Mt CO_2e]	Target	
	1.5 °C	2 °C
2014 functionalities total	**64**	
Shelter	14	
Access	27	
Other Life Support (w/o agriculture)	23	
2050 functionalities total	**8**	**36**
Shelter	2	8
Access	3	15
Other Life Support (w/o agriculture)	3	13
2015-2050 functionalities total	**1260**	**1755**
Shelter	285	400
Access	530	735
Other Life Support (w/o agriculture)	445	620

Table 9: Austria's GHG emissions from functionalities Shelter, Access and Other Life Support in 2014, reference emission levels in 2050 and reference emission budgets for these functionalities for the period 2015-2050.

With the help of these reference budgets, we define corresponding reference emission pathways for individual functionalities as follows. We assume that emissions from functionalities decrease linearly from their 2014 levels in such a way that areas under the reference pathways equal the corresponding reference budgets. The resulting reference pathways for functionalities are presented in the context of historical emissions and expected emissions from other sectors in Figures 11 and 12, respectively for the 1.5 °C and 2 °C targets.

We emphasize that the reference emission pathways for functionalities should not be considered as projections of future emissions caused by functionalities. They are meant only as a tool for tracking the progress of emission reductions in line with a desired warming target. Should at a certain point in time actual emissions be above the reference pathway, future emissions must eventually fall below it to compensate for the previous excess. Alternatively, emissions resulting from other functionalities will have to be reduced below their corresponding reference pathways.

It is important to note that due to data limitations it was possible to establish correspondence between functionality-based emissions accounting and the UN FCCC's sectoral accounting approach only for the year 2014 which, therefore, was chosen as the starting point for the reference pathways for functionalities. Contrary to the assumptions of the reference pathways, the actual net GHG emissions between 2015 and 2017 were increasing, thus trajectories of future emissions from functionalities will have to be accordingly steeper. This is clearly seen when comparing stacked reference pathways for functionalities against the reference pathway for Austria's net GHG emissions, which was calculated starting in 2018 and thus taking into account the increase of GHG emissions in the period 2015-2017.

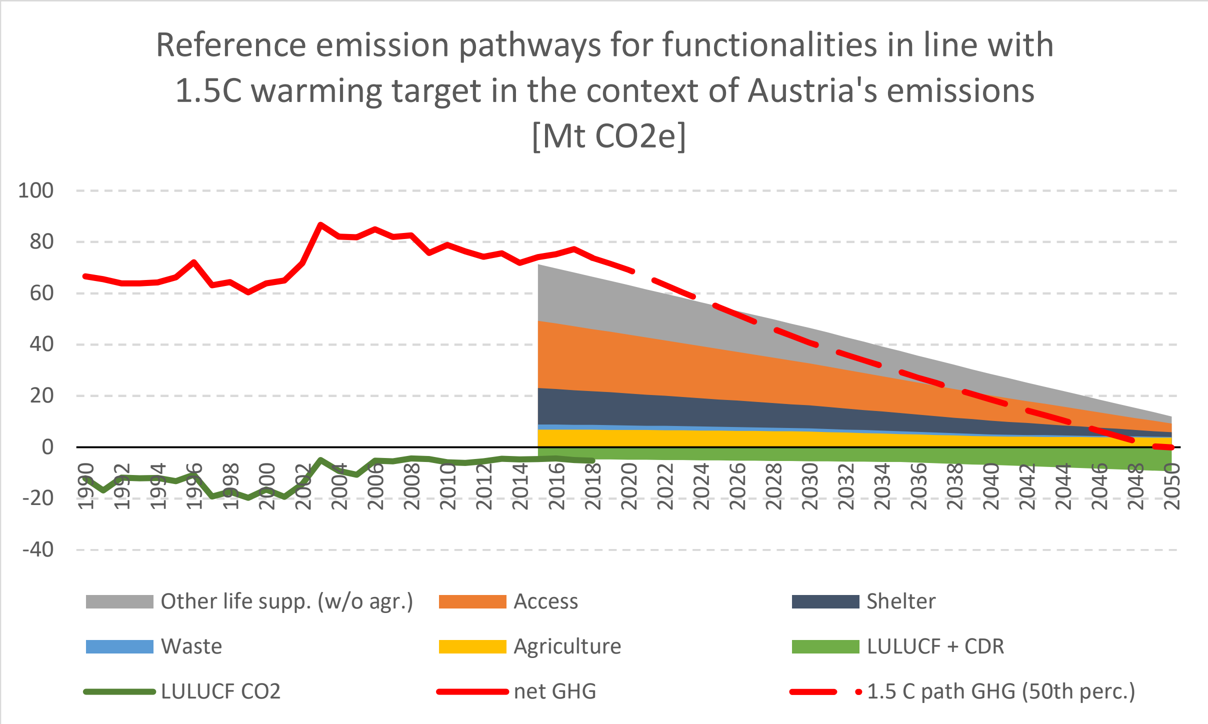

Figure 11: Reference emission pathways in line with the 1.5 °C target for functionalities Shelter, Access and Other Life Support (without agriculture) together with expected emissions from Austria's Agriculture and Waste sectors and net negative emissions for LULUCF sector aided by negative emissions technologies presented in context of Austria's historic GHG emissions and the 1.5 °C reference pathway for Austria's total net GHG emissions.

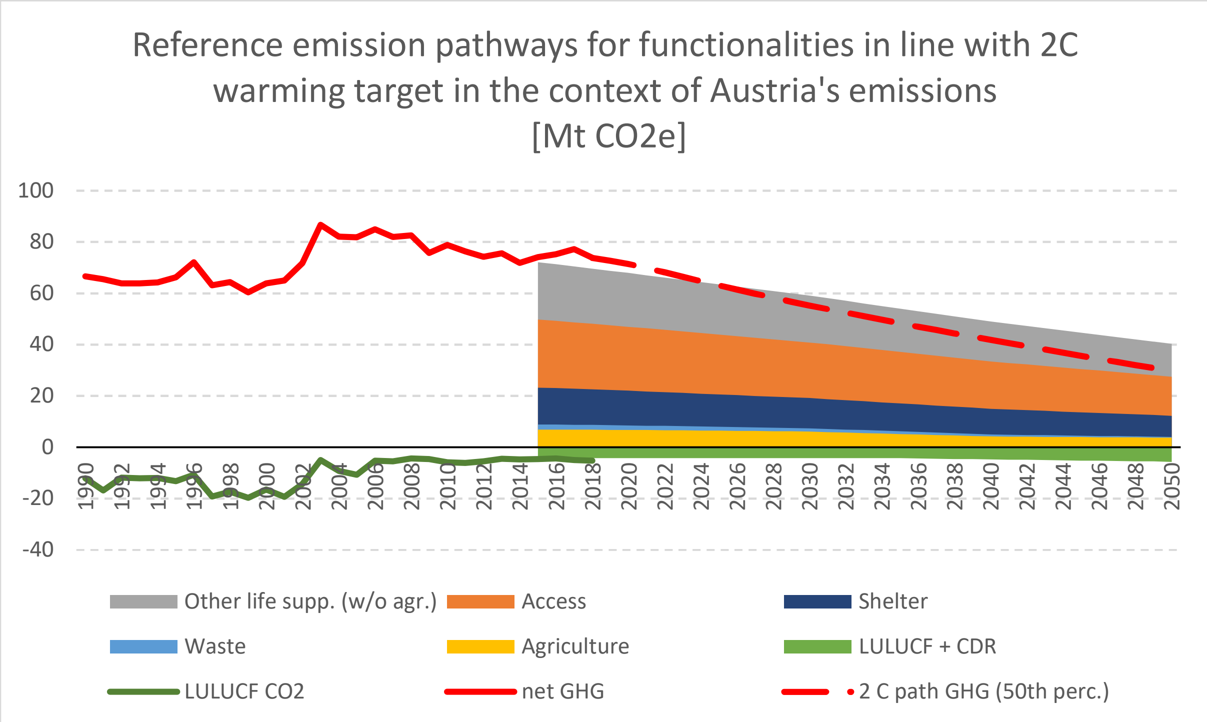

Figure 12: Reference emission pathways in line with the 2°C target for functionalities Shelter, Access and Other Life Support (without agriculture) together with expected emissions from Austria's Agriculture and Waste sectors and net negative emissions for LULUCF sector aided by negative emissions technologies presented in context of Austria's historic GHG emissions and the 2 °C reference pathway for Austria's total net GHG emissions.

7. Summary and conclusions

In this paper we present a robust and globally consistent method of translating the planetary-scale targets of limiting the increase of global mean surface temperature into national budgets of cumulative GHG emissions until 2050, which provide benchmarks allowing to appraise compliance of transformation scenarios of national economies with the global warming targets. Our approach is based on the concept of a GHG emissions budget which is considered to be a good predictor of a future level of warming. Despite some lingering uncertainties in the exact relationship between cumulative anthropogenic GHG emissions and the resulting increase of global temperature, this approach has two main advantages. First, an emissions budget is a geo-physical constraint that is compatible with any framework of integrated and/or economic modelling since it is not based on any set of particular socio-economic assumptions. Secondly, it is easily scalable, allowing to translate internationally agreed global warming targets of the Paris agreement into limits on GHG emissions for local economies, both in terms of local emission budgets and the corresponding reference emission pathways.

Such budgets of national GHG emissions can serve as a guardrail for embedding novel models of economic transformation into a broader contexts of global efforts to mitigate global warming and/or regional scenarios of economic transformations. Indeed, in this working paper we have demonstrated that a functionality-based modelling of Austria's economic transformation can be successfully related to the global warming targets of the Paris agreement. To this end we have assessed Austria's cumulative GHG emissions until 2050 not ascribed to any of the functionalities using EU-wide scenarios of economic transformation that comply with GHG emission budgets for this region (cf. Appendix), which is a difference between the Austria's budget of national GHG emissions and the pool of cumulative emissions available for providing the considered functionalities in Austria. We have further broken down this pool of emissions into reference budgets for individual functionalities for the period until 2050. These budgets can be used as benchmarks for assessing compliance of scenarios of development of individual functionalities with the warming targets of the Paris agreement. Unlike a budget of cumulative national GHG emissions, in its own a budget for an individual functionality is not a hard geo-physical constraint. Only jointly budgets for functionalities must not be violated, i.e., emissions can be swapped between functionalities, but added together, they cannot exceed the pool of emissions available for all functionalities.

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NOTE: Sections 2-4 of this working paper will also be published as a IIASA working paper.

[21] For more information on IIASA's contributions to the EconTrans project go to https://iiasa.ac.at/web/home/research/researchPrograms/RISK/180828-econtrans.html

Bibliography

Bachner, G., Mayer, J., Fischer, L., Frei, E. Steininger, K.W., Sommer, M., Köppl, A., Schleicher, S., (2021): Application of the Concept of "Functionalities" in Macroeconomic Modelling Frameworks – Insights for Austria and Methodological Lessons Learned, EconTrans working paper #4, WIFO

Sommer, M. Köppl, A., Schleicher, S.P., Bachner, G., Mayer, J., Fischer, L., Frei, E., Steininger, K.W., (2021) The concept of functionalities in a macroeconomic modelling framework for Austria. EconTrans Working Paper #3.

European Commission (2018), IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM (2018) 773 A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

(Accessed: 17.02.2021)

European Environment Agency (2020): Annual European Union greenhouse gasinventory 1990–2018and inventory report 2020.

https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2020

(Accessed: 1.03.2021)

Forster, P., D. Huppmann, E. Kriegler, L. Mundaca, C. Smith, J. Rogelj, and R. Séférian (2018): Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development Supplementary Material. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change. Available from https://www.ipcc.ch/sr15 (Accessed 17.02.2021)

Fuss et al. (2018): Negative emissions—Part 2: Costs, potentials and side effects Environ. Res. Lett. 13 063002. https://doi.org/10.1088/1748-9326/aabf9f

Hubau, W., Lewis, S.L., Phillips, O.L. *et al*. Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579, 80–87 (2020).

https://doi.org/10.1038/s41586-020-2035-0

IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jonas, M. , Marland, G., Krey, V. , Wagner, F. , & Nahorski, Z. (2014). Uncertainty in an emissions-constrained world. *Climatic Change* 124 (3), 459-476. 10.1007/s10584-014-1103-6.

Jonas, M. & Żebrowski, P. (2016). Uncertainty in an Emissions Constrained World: Method Overview and Data Revision. IIASA Working Paper. IIASA, Laxenburg, Austria: WP-16-009

Kirchengast, G., Kromp-Kolb, H., Steininger, K., Stagl, S., Kirchner, M., Ambach, Ch., Grohs, J., Gutsohn, A., Peisker, J., Strunk, B. (2019): Referenzplan als Grundlage für einen wissenschaftlich fundierten und mit den Pariser Klimazielen in Einklang stehenden Nationalen Energie- und Klimaplan für Österreich (Ref-NEKP). Publizierte Version 9.9.2019, 227 S. CCCA: Wien-Graz.
Online via: https://ccca.ac.at/wissenstransfer/uninetz-sdg-13-1

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V. Vilariño, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change. Available from https://www.ipcc.ch/sr15 (Accessed 17.02.2021)

Schinko, T., Weifner, A., Köppl, A., The interaction of energy services, breakthrough technologies and human need satisfaction EconTrans Working Paper #1, Working Paper, IIASA, Laxenburg, 2021.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P. A., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Arneth, A., Arora, V. K., Barbero, L., Bastos, A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Doney, S. C., Gkritzalis, T., Goll, D. S., Harris, I., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Johannessen, T., Jones, C. D., Kato, E., Keeling, R. F., Goldewijk, K. K., Landschützer, P., Lefèvre, N., Lienert, S., Liu, Z., Lombardozzi, D., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rocher, M., Rödenbeck, C., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., Wright, R., Zaehle, S., and Zheng, B.: Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, https://doi.org/10.5194/essd-10-2141-2018.

Appendix A1: Reference emission budgets and emission pathways for EU-28

In this appendix we focus on emission budgets and corresponding reference emission pathways for EU. Austrian economy is immersed in the economy of this bloc of countries which coordinate their policies, including environmental, climate and economic policies. Therefore, scenarios of EU-wide economic transitions can provide relevant context for modelling of Austria's transition to a decarbonized economy undertaken in the EconTrans project, provided these scenarios are in line the goals of Paris agreement. The reference emission budgets are easy to apply benchmarks allowing to assess compliance with the warming targets of Paris agreement.

Here we derive budgets and reference emission pathways for the European Union in the same way as presented in Section 3.2 for the case of Austria. Table A1.1. presents the cumulative emission budgets for EU-28[22] resulting from applying emission distribution principles discussed in Section 3.1 The reference emission pathways for the former EU-28 based on this principle are depicted on Figure A1.1.

Warming target	1.5 °C			2 °C		
Cumulative 2018-2050 emissions [Gt CO_2e]	CO_2	Non-CO_2	GHG	CO_2	Non-CO_2	GHG
Proportionality to current population	38	19	57	72	23	95
Constant-rate convergence of per capita emissions	41	17	57	69	20	88
Proportionality to territorial CO_2 emissions	53	27	80	101	32	133
Proportionality to consumption CO_2 emissions	67	34	102	127	41	168

Table A1.1: Allowed cumulative emissions for the EU-28 for the period 2018-2050 compatible with the 1.5 °C and 2 °C warming targets, calculated based on different principles of allocating emission allowances. Emission budgets are based on 50th percentile reference pathways for global emissions and medium variant projections of population growth.

[22] As of 2020 the United Kingdom has left the EU, which now consists of 27 countries. However, the EU-wide scenarios considered in this working paper are modelled for the former EU-28, UK included. For this reason we calculate emissions budgets for the former EU-28.

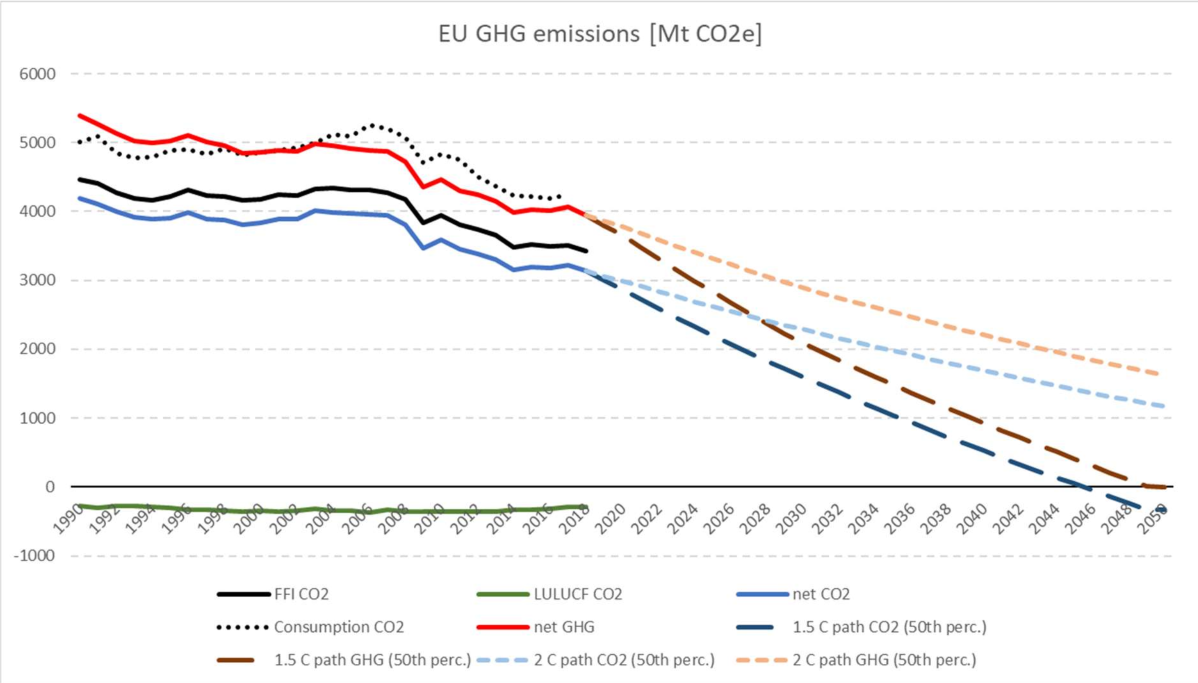

Figure A1.1: Historical GHG emissions of the EU-28 and reference emission pathways in accordance with the 1.5 °C and 2 °C warming targets, derived from the corresponding 50th percentile reference global emission pathways using the principle of constant-rate convergence of per capita emissions until 2050.

Appendix A2: EU-wide scenarios of transformation towards sustainable economy.

Scenarios of the EU-wide economic transformation presented in the European Commission's report "A Clean Planet for All" (EC 2018) are a very valuable source of information on possible trajectories of sustainable transformations. We used these scenarios in Section 5 to assess future emissions from sectors that are not covered by functionalities considered in the EconTrans project.

Basic assumptions of the 8 scenarios of transition to a low-energy and low-carbon economy within the EU presented in (EC 2018) are outlined in Table A2.1. These scenarios were modelled using an integrated assessment framework linking PRIMES, GAINS and GLOBIOM models allowing to explore potentials of different options of reducing GHG emissions and on synergies and trade-offs between these options.

Long Term Strategy Options								
	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

Table A2.1: Basic assumptions of the EU-wide scenarios of transition to low-energy and low-carbon economy. (Source: EC (2018), p. 56, Table 1.)

Appendix A2.1: Checking consistency of EU-wide scenarios of economic transformation with global warming targets of the Paris agreement

Transformation scenarios obtained with help of such detailed regional integrated assessment models are not automatically guaranteed to be consistent with the global warming targets. Indeed, (EC 2018) claims but does not justify that the six less ambitious scenarios are in line with the 2°C warming target of the Paris agreement and the two most ambitious ones are consistent with the 1.5°C goal.

The reference emission pathways for the EU presented in Appendix A.1 allow for independent verification of such consistency. Alignment of individual scenarios with the warming targets of Paris agreement can easily be checked by comparing Table A1.1 with Table A2.2 below which contains cumulative GHG emissions projected to result from the analysed scenarios.

Scenario	Cumulative 2018-2050 emissions [Gt CO_2e]			Emissions in 2050 [Mt CO_2e]		
	Net CO_2	Non-CO_2	Net GHG	Net CO_2	Non-CO_2	Net GHG
Elec	60	14	74	479	337	816
H2	60	14	74	489	337	806
P2X	61	14	75	451	337	788
EE	59	14	73	426	337	763
CIRC	58	14	72	347	337	684
COMBO	58	14	72	238	337	620
1.5TECH	49	14	63	-311	337	26
1.5LIFE	48	13	61	-261	286	25

Table A2.2: Cumulative GHG emissions projected for period 2018-2050 and emissions in 2050 under scenarios considered in the European Commission report "A Clean Planet for All" (EC 2018). Values of net cumulative CO_2 emissions are taken from EC (2018), p. 198, Table 9. Values of cumulative non-CO_2 emissions are approximations based on figures in EC (2018), section 7.7. Emissions in 2050 are taken from EC (2018), p. 198, Table 9.

For the most ambitious scenario 1.5LIFE the cumulative GHG emissions until 2050 are expected to be approximately 61 Gt CO_2e. This is 4 Gt CO_2e more than the reference budget for the EU-28 derived from the 50th percentile global reference pathway for the 1.5 °C target (assuming the medium projection variant of population growth and the constant-rate convergence to global equality of per-capita emissions in 2050). Under this scenario, cumulative non-CO_2 emissions can be as low as 13 Gt CO_2e emissions, 4 Gt CO_2e less than the reference budget. This is due to fewer options for non-CO_2 emission reductions implemented in the global scale IAMs – used in assessment of the global non-CO_2 budget, which, in turn, is the basis for our derivation of the reference budget for the former EU-28 – compared to models employed in the European Commission's report. On the other hand, the cumulative CO_2 emissions are 7 Gt CO_2 higher than the reference budget. This discrepancy is caused by the initial rates of CO_2 reductions being lower compared to the reference 1.5 °C pathway for the former EU-28. Moreover, under this scenario net GHG emissions are projected to reach near zero in 2050. Thus, we conclude that the 1.5LIFE scenario is consistent with the more ambitious goal of the Paris agreement to limit the global warming to 1.5 °C.

Similarly, we judge the 1.5TECH scenario to be in line with the 1.5 °C warming target, while the remaining six less ambitious scenarios are in line with the 2 °C warming target.

Appendix A2.2: Potential of land sink and negative emission technologies to remove CO_2 emissions of the EU-28.

Below we provide tables referred to in Sections 5.2 and 5.3 and summarizing expected evolution of EU's land carbon sink and potential of CDR technologies under scenarios from (EC 2018).

Scenario class	In line with 2 °C	In line with 1.5 °C
Forestry emissions in 2015 [Mt CO_2]	-410	
Forestry emissions in 2050 [Mt CO_2]	-300	-460
Cumulative emissions for the period 2015-2050 [Gt CO_2]	-12.7	-15.6
Increase in forest area in 2050 [km^2]	minimal	100000

Table A2.3: Potential developments of the forest carbon sink in the EU under scenarios considered in the European Commission report "A Clean Planet for All" (EC 2018). Forestry emissions in 2015 are taken from EU's NIR (EEA 2020). The expected forestry CO_2 emissions in 2050 are taken from EC (2018), p. 186, Fig 87. Cumulative emissions for the period 2015-2050 are calculated assuming linear interpolation between 2015 and 2050 emissions. Expected increase of forested area taken based on EC (2018), p. 184, Fig 85.

Scenario class	In line with 2 °C	In line with 1.5 °C
Net CO_2 LULUCF emissions in 2015 [Mt CO_2]	-320	
Net CO_2 LULUCF emissions in 2050 [Mt CO_2]	-250	-460
Cumulative emissions for the period 2015-2050 [Gt CO_2]	-10	-14
Net GHG LULUCF emissions in 2015 [Mt CO_2e]	-295	
Net GHG LULUCF emissions in 2050 [Mt CO_2e]	-240	-450
Cumulative emissions for the period 2015-2050 [Gt CO_2 e]	-9.6	-13.4

Table A2.4: Potential developments of the net LULUCF emissions in the EU under scenarios considered in the European Commission's report "A Clean Planet for All" (EC 2018). LULUCF emissions in 2015 are taken from EU's NIR (EEA 2020). The expected net LULUCF CO_2 emissions in 2050 are taken from EC (2018), p. 186, Fig 87 and the expected net LULUCF CO_2 in 2050 are taken from EC (2018), p. 196, Fig 91. Cumulative emissions for the period 2015-2050 are calculated assuming linear interpolation between 2015 and 2050 emissions.

Scenario	ELEC	H2	P2X	EE	CIRC	COMBO	1.5TECH	1.5LIFE
Carbon captured and stored in 2050 [Mt CO_2]	65	63	77	65	52	67	289	80
Cumulative CO_2 removal with CDR by 2050 [Gt CO_2]	0.49	0.47	0.58	0.49	0.39	0.5	2.17	0.6

Table A2.5: CDR potential under scenarios from the European Commission's report "A Clean Planet for All" (EC 2018). The values for carbon removed and stored underground in 2050 are taken from EC (2018), p. 193, Tab. 8. The cumulative removals of CO_2 through CDR technologies are calculated assuming linear increase in removals starting from zero in 2035.

Bibliography

European Commission (2018), IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM (2018) 773 A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

(Accessed: 17.02.2021)