Publizierbarer Endbericht

Gilt für Studien aus der Programmlinie Forschung

A) Projektdaten

Allgemeines zum Projekt	
Kurztitel:	**CE DC**
Langtitel:	**Circular Economy and Decarbonisation: Synergies and trade-offs**
Zitiervorschlag:	Haas, W., Meyer, I., Virág, D., Kalt, G., Baumgart, A., Eisenmenger, N., Sommer, M., Kratena, K. (2024). Circular Economy and Decarbonisation: Synergies and trade-offs. Endbericht ACRP Forschungsprojekt KR19AC0K17512
Programm inkl. Jahr:	12th Call ACRP, 2019
Dauer:	01.09.2020 bis 31.08.2023
KoordinatorIn/ ProjekteinreicherIn:	Universität für Bodenkultur (BOKU), Wien Department für Wirtschafts- und Sozialwissenschaften – Institut für Soziale Ökologie
Kontaktperson Name:	Willi Haas
Kontaktperson Adresse:	Schottenfeldgasse 29 1070 Wien
Kontaktperson Telefon:	+43 1 47654-73720
Kontaktperson E-Mail:	willi.haas@boku.ac.at
Projekt- und KooperationspartnerIn (inkl. Bundesland):	Österreichisches Institut für Wirtschaftsforschung (WIFO), Wien
Schlagwörter:	Circular economy, decarbonisation, social metabolism, sustainability transformation
Projektgesamtkosten:	294.520 €
Fördersumme:	294.520 €
Klimafonds-Nr:	KR19AC0K17512
Erstellt am:	30.11.2023

B) Projektübersicht

1 Kurzfassung

Ausgangssituation, Projektmotivation und Forschungsziele

Im Koalitionsvertrag der österreichischen Regierung (2020) wurde das Ziel festgelegt, bis 2040 Klimaneutralität zu erreichen. Das Projekts sollte untersuchte, welche Auswirkungen eine solche Dekarbonisierung (DE) auf den Materialbedarf haben und welchen Beitrag eine Kreislaufwirtschaft (CE) zur Erreichung der Klimaneutralität leisten kann, indem verschiedene Szenarien in einem kombinierten physischen und ökonomischen Modellansatz analysiert werden. Die Kreislaufwirtschaft wird hier als ein Konzept verstanden, das erstens auf eine Verringerung, zweitens eine Verlangsamung und drittens auf eine Schließung von Kreisläufen von Ressourcenströmen abzielt. Um eine qualitativ hochwertige stoffstrombezogene Szenarioanalyse zu erreichen, musste der Umfang der Analyse auf ausgewählte Sektoren beschränkt werden. Aufgrund ihrer Material- und Kohlenstoffintensität und ihrer Verflechtung wurden die Sektoren Gebäude, Verkehr (Personen- und Güterverkehr) sowie Elektrizität ausgewählt. Während der Projektlaufzeit einigte sich die österreichische Regierung auf eine CE-Strategie, die darauf abzielt, den inländischen Materialverbrauch (DMC) bis 2030 auf 14 t/Kopf und bis 2050 auf 7 t Materialfußabdruck/Kopf zu reduzieren. Als Reaktion auf diese neue CE-Strategie der Regierung wurde untersucht, inwieweit verschiedene Szenarien die Klimaneutralität, aber auch die CE-Ziele bis 2040 erreichen können. Da ein Rückgang der Materialflüsse auch Ausgaben einspart, können diese die Nachfrage nach anderen Produkten und Dienstleistungen steigern. Unsere Motivation war daher, die wirtschaftlichen Auswirkungen im Sinne von makroökonomischen Rebound-Effekten zu untersuchen. Zuletzt analysieren wir unserer Szenarien hinsichtlich Synergien und Trade-Offs mit den Nachhaltigkeitsziele.

Projektstruktur und Methodik

Zwei verschiedene wirtschaftliche Projektionen (dargestellt durch 1 oder 2 im Szenario-Akronym) wurden formuliert. Zu diesen wurden vier Szenarien entwickelt. Die Szenarien umfassen ein Referenzszenario (R1, R2), ein Dekarbonisierungsszenario (A1, A2), eine Dekarbonisierung plus schwache CE-Strategien (B1, B2) und eine Dekarbonisierung plus starke CE-Strategien (C1, C2). Wir entwickelten biophysische Sektormodule für Verkehr, Gebäude und Elektrizität. Zudem wurde das makroökonomische WIFO.DYNK-Modell der österreichischen Wirtschaft mit dem biophysischen CeAT-Modell verknüpft, um die Bestands- und Nachfrageanpassungen des biophysischen Modells auch im makroökonomischen Modell abzubilden und die Auswirkungen auf Beschäftigung, Wertschöpfung und verfügbares Einkommen zu analysieren.

Ergebnisse

Die folgenden Szenarioergebnisse basieren auf der wirtschaftlichen Projektion (1), d. h. einem moderaten durchschnittlichen BIP-Wachstum von 1,3 % nach einer zügigen Erholung von der COVID-19-Pandemie. Das Referenzszenario (R1), eine Fortsetzung der Entwicklung vor der Pandemie mit den bereits umgesetzten einschlägigen Maßnahmen, zeigt einen Anstieg der Processed Materials (PM) um 16 % auf 102 Mio. Tonnen für die drei Sektoren (Verkehr, Gebäude, Strom) bis 2040. Das Dekarbonisierungsszenario (A1) zeigt eine leichte Verringerung des Materialeinsatzes im Vergleich zum Referenzszenario (R1), da der schrittweise Ausstieg aus fossilen Brennstoffen Materialeinsätze einspart und

teilweise durch den Materialbedarf für die Sanierung von Gebäuden, die Umstellung von Heizungssystemen, die Elektrifizierung des Verkehrs und eine Verlagerung des Modal Split sowie die Umstellung auf Ökostrom kompensiert wird. Ein Szenario, das zusätzlich zu den Dekarbonisierungsmaßnahmen einen schwachen CE-Ansatz verfolgt (B1), zeigt für die drei Sektoren einen Rückgang des PM um 15 % im Vergleich zu R1. Im Szenario mit starkem CE-Ansatz (C1) wird der Materialverbrauch Österreichs im Vergleich zum Referenzszenario (R1) um 75% reduziert. Nur in diesem Szenario werden sowohl die Klimaneutralität als auch die Ziele der österreichischen CE-Strategie erreicht. Die Maßnahme mit der stärksten Auswirkung auf den Materialverbrauch ist der Ausstieg aus dem Neubau von Gebäuden und Straßen auf unbebautem Land bis 2030. Um den Wachstumseffekt des BIP zu diskutieren, haben wir zusätzlich zu R1 eine Nullwachstumsprojektion als alternatives Referenzszenario (R2) verwendet, wodurch sich die Ergebnisse des biophysikalischen Szenarios um etwa ein Viertel weiter verringern. Die Verknüpfung der Ergebnisse des physikalischen Szenarios mit dem WIFO.DYNK und den korrelierten Wirtschaftssimulationen hat gezeigt, dass die angegebenen sektoralen Veränderungen bei Konsum und Produktion, einschließlich der Investitionen, zu einer starken Verringerung der inländischen Ausgaben und folglich ceteris paribus zu einem Anstieg der Sparquote und zu einer Schrumpfung der Wirtschaft führen, es sei denn, die Sparquote wird auf den gleichen Satz wie im Referenzszenario (R1) festgelegt. In letzterem Fall können die gesamtwirtschaftlichen Auswirkungen, einschließlich des Rebound-Effekts, positiv oder negativ sein, je nachdem, wofür die freiwerdenden Geldmittel ausgegeben werden. Werden sie in erster Linie für Rohstoffe ausgegeben, können die Auswirkungen auf das BIP-Wachstum aufgrund des damit verbundenen hohen Importanteils negativ sein. Werden sie vor allem für inländische Dienstleistungen ausgegeben, ist der wirtschaftliche Effekt in allen simulierten Fällen positiv. Das verfügbare Nettoeinkommen der Haushalte wird (im Vergleich zum BIP) durch die geringeren Ausgaben für die Abschreibung ihres dann geringeren Kapitalstocks, d. h. Gebäude, Fuhrpark usw., stärker positiv beeinflusst. Die Beschäftigung wird in allen Szenarien positiv beeinflusst, jedoch hauptsächlich in den Niedriglohnsektoren.

Schlussfolgerungen

Das Schließen von Kreisläufen, d.h. Recycling, ist wichtig, aber bei weitem nicht ausreichend, um Klimaneutralität und die Ziele der österreichischen CE-Strategie zu erreichen. Daher müssen die CE-Strategien zur Verringerung und Verlangsamung von Materialflüssen weitaus mehr Aufmerksamkeit erhalten als die Verbesserung der Recyclingaktivitäten. Die starken CE-Szenarien (C1, C2) spiegeln diese Prioritäten wider und sind die einzigen, die beide Ziele erreichen. Während das Referenzszenario (R1) das zurechenbare Kohlenstoffbudget der drei Sektoren um 60% überschreitet, bleibt A1 innerhalb des Kohlenstoffbudgets und C1 verbraucht nur drei Viertel des Kohlenstoffbudgets während der Transformation bis 2040. Mit einer kumulativen Reduktion des Materialverbrauchs um zwei Drittel im Vergleich zu R1 ist das C1-Szenario das einzige Szenario, das sich auf einem Pfad in Richtung der CE-Ziele befindet. Der Rebound-Effekt kann nur durch eine strukturelle Verschiebung des Konsums und der Produktion, einschließlich der Investitionen, hin zu einer dienstleistungsorientierten Wirtschaft vermieden werden. Zusammenfassend lässt sich sagen, dass die Erreichung der österreichischen Klima- und CE-Ziele eine Reihe von politischen Maßnahmen erfordert, die im Wesentlichen einen Ausstieg aus dem Neubau auf unbebautem Land (Gebäude und Straßen) fördern und Anreize für den Konsum und die Produktion von Dienstleistungen zu Lasten von materialintensiven Gütern und Dienstleistungen schaffen.

2 Executive Summary

Initial situation, project motivation and objectives

The Austrian government coalition agreement (2020) set the goal to achieve carbon neutrality by 2040. The project set out to better understand what implications such a decarbonization (DE) may have for material requirements and what a circular economy (CE) can contribute to achieve carbon neutrality by analyzing different scenarios in a combined physical and economic model approach. The CE here is understood as a concept that opts firstly for narrowing, secondly for slowing, and thirdly for closing loops of resource flows. To achieve a high-quality stock-flow-related scenario analysis, we had to restrict the scope of our analysis to specific sectors. Because of their material and carbon intensity and their interconnectedness we selected the building, transport (passenger and freight), and electricity sectors. During the project duration, the Austrian government agreed on a CE strategy which aims to reduce the domestic material consumption (DMC) from 18 t/cap to 14 t/capita by 2030 and to 7 t material footprint/cap by 2050. In reaction to this new governmental CE strategy, we have analyzed the extent to which different scenarios can achieve carbon neutrality, but also the CE targets by 2040. As the reduction in demand in the three sectors cause a reduction in production activities, the relevant saved expenditures can be redirected and shifted to other products and services. Our motivation was hence to investigate the economic impacts in terms of macroeconomic rebound effects. Lastly, the effects of our scenarios are explored for potential synergies and trade-offs with regard to the sustainable development goals (SDGs).

Project structure and methodology

Two different economic projections (represented by 1 or 2 in the scenario acronym) were formulated, for which four scenarios were developed. The scenarios are a reference scenario (R1, R2), a full decarbonisation scenario (A1, A2), a decarbonisation plus weak CE strategies (B1, B2) and a decarbonisation plus strong CE strategies (C1, C2). We developed biophysical sector modules for transport, building, and electricity. The macroeconomic WIFO.DYNK model of the Austrian economy was linked with the biophysical CeAT model in order to reproduce the stock and demand adjustments in the biophysical model in the macroeconomic model and to analyze the effects on employment, value-added and disposable income. Further, trade-offs and synergies with SDGs have been screened.

Results

The following scenario results are based on the economic projection (1), i.e., a moderate average GDP growth of 1.3% after a smooth recovery from the COVID-19 pandemic. The reference scenario (R1), a continuation of the pre-pandemic development with the relevant measures already implemented, shows an increase of processed materials (PM) of 16% up to 102 Mt for the three sectors (transport, buildings, electricity) until 2040. The decarbonisation scenario (A1) shows a slight reduction of material use compared to the reference scenario (R1) as the phasing out of fossil fuels saves material inputs and is partly compensated by the material demands for refurbishing buildings, changing heating systems, electrification of transport, and a modal split shift as well as the transformation to green electricity. A scenario following a weak CE approach in addition to the decarbonization measures (B1) shows a decrease of 15% of PM compared to R1 for the three sectors. In the strong CE scenario (C1), the material consumption of Austria is reduced by 75% compared to the reference scenario (R1). Only this scenario achieves both carbon neutrality and the targets of the Austrian CE strategy. The measure with the strongest effect on material use is the phasing out of new construction for buildings and roads on unbuilt land until 2030. To discuss the growth effect of GDP we used a zero growth projection as an alternative reference scenario (R2) in addition to R1 which further decreases the biophysical scenario results by roughly a quarter. The interlinking of the physical scenario outputs with the WIFO.DYNK model and the correlated economic simulations showed that the stated sectoral changes in consumption and production, including investments, lead to a strong reduction of domestic expenditures, and, consequently, to a ceteris paribus increase in saving rates, and to a shrinking of the economy, unless the savings rate is set at the same rate as in the reference scenario (R1). In the latter case, the overall economic impact, including the rebound effect, may be positive or negative, depending on how the freed-up monetary resources are spent. If they are primarily spent on commodities, then the impact on GDP growth can be negative due to the high related import share. If they are spent primarily on domestic services, the economic effect is positive in all the simulated cases. Households' net disposable income – the gross income less depreciation – is more positively affected than GDP results due to the lower depreciation expenditure on their then lower capital stock, i.e. buildings, cars, etc. Employment is affected positively in all scenarios, but mainly in low-wage sectors.

Conclusions

Closing loops, i.e. recycling, is important but by far not sufficient to achieve carbon neutrality and the Austrian CE strategy's goals. Therefore, the CE strategies narrowing and slowing resource flows need far higher attention than improving recycling activities. The strong CE scenarios (C1, C2) reflect these priorities and are the only ones to achieve both goals. While the reference scenario (R1) overshoots the attributable carbon budget of the three sectors by 60%, A1 stays within the carbon budget and C1 uses only three quarters of the carbon budget during the transformation till 2040. With a cumulative material consumption reduction of two thirds compared to R1, the C1 scenario is the only scenario on a trajectory towards the CE goals. The rebound effect can only be kept at bay with a structural shift in consumption and production, including investments, towards a service-oriented economy. In sum, achieving Austrian climate and CE goals require a range of policy measures to foster essentially a phasing out of new construction on unbuilt land (buildings and roads) and to incentivise the consumption and production of services at the expense of material-intensive goods and services.

3 Background and objectives

Initial situation and motivation for the project

The Austrian government coalition agreement from 2020 set the goal to achieve carbon neutrality by 2040. In addition, the concept of the Circular Economy (CE) concept has grown in popularity in recent years, with its proclaimed selling point of combining an economic narrative with benefits for employment, local economies, the environment and particularly the climate. The project set out to better understand both the implications of a decarbonization until 2040 on material requirements and the potential contribution of CE measures to achieve carbon neutrality. CE here is understood as a concept that firstly focuses on narrowing resource inputs, secondly on slowing resource throughput and thirdly on closing loops via resource recycling and recovering (Potting et al., 2017; Morseletto, 2020). To achieve a high-quality stock-flow-related analysis we had to limit the scope to three sectors; we selected the transport (of persons and freight), building and electricity sectors due to their high material and carbon intensities and their mutual interconnectedness. During the first project phase, the Austrian government agreed in December 2022 on a CE strategy, which aims to reduce the domestic material consumption (DMC) to 14 t/capita by 2030 and to 7 t/capita from a material footprint perspective by 2050. In order to address this highly relevant development, we slightly readjusted the project focus and explored the option space to achieve both carbon neutrality and, at the same time, the targets of the Austrian CE strategy, while sticking to the time frame up to 2040. To this end we further developed a biophysical and mass-balanced model (CeAT). Since reductions in production and consumption could easily be canceled out or even overcompensated by consumption shifts, our motivation was to investigate economic feedbacks, i.e., rebound effects by using a macroeconomic model (WIFO.DYNK) of the Austrian economy. Lastly, the effects of measures are explored by assessing implications for potential synergies and trade-offs with regard to the sustainable development goals (SDGs).

Project objectives

1. To what extent can CE measures contribute to reaching the goal of carbon neutrality of the Austrian economy by 2040/2050 without exceeding the national carbon budget of 1,000 Mt CO2-eq?
    a) What are the consequences of key sectors' transformation (energy and transport system, buildings) in terms of demolition waste and material requirements as well as in additional energy demand and GHG emissions over the period up to 2040/2050?
    b) To what extent can CE measures alleviate material requirements and reduce depletion of natural resources?
    c) What are the potentials of CE strategies to mitigate GHG emissions associated with transformations in the specific sectors?
    d) What can far-reaching CE measures contribute to carbon neutrality by 2040/2050 as a whole and differentiated by measures?
2. What are implications of measures beyond their contribution to carbon neutrality?
    a) What are implications for resource use, waste and other emissions beyond GHG-emissions?
    b) What are the impacts on employment?
    c) What are the economic implications?
    d) Are there synergies and trade-offs with regard to Sustainable Development Goals (SDGs)?
3. In sum: What are the most promising measures when considering all aspects in an integrated way? GHG- emissions, resource use, waste & emissions, employment, value-added and SDGs?

4 Project contents and results

4.1 Results and project milestones

4.1.1 Biophysical results of CeAT

Austria's resource use in 2040: Comparing scenarios

Collectively, the three sectors (buildings, transport, and electricity) account for 49% of Austrian DMC (see Figure 8), or 74 Mt, in 2018 (Figure 1a). While the reference scenario DMC slightly increases to 101 Mt in 2040, a decarbonisation (A1) and a decarbonisation with weak CE measures (B1) reduces 2040 DMC to 79 and 72 Mt, respectively. In contrast, decarbonisation with strong measures (C1) decreases DMC to 15 Mt, 20% of its baseline value in 2018. Cumulative DMC from 2018 to 2040 (Figure 4c) would likewise be highest for the reference scenario with ca. 2,140 Mt, followed by A1 (1,780 Mt) and B1 (1,650 Mt). Scenario C1 cumulative DMC would be significantly lower at ca. 760 Mt.

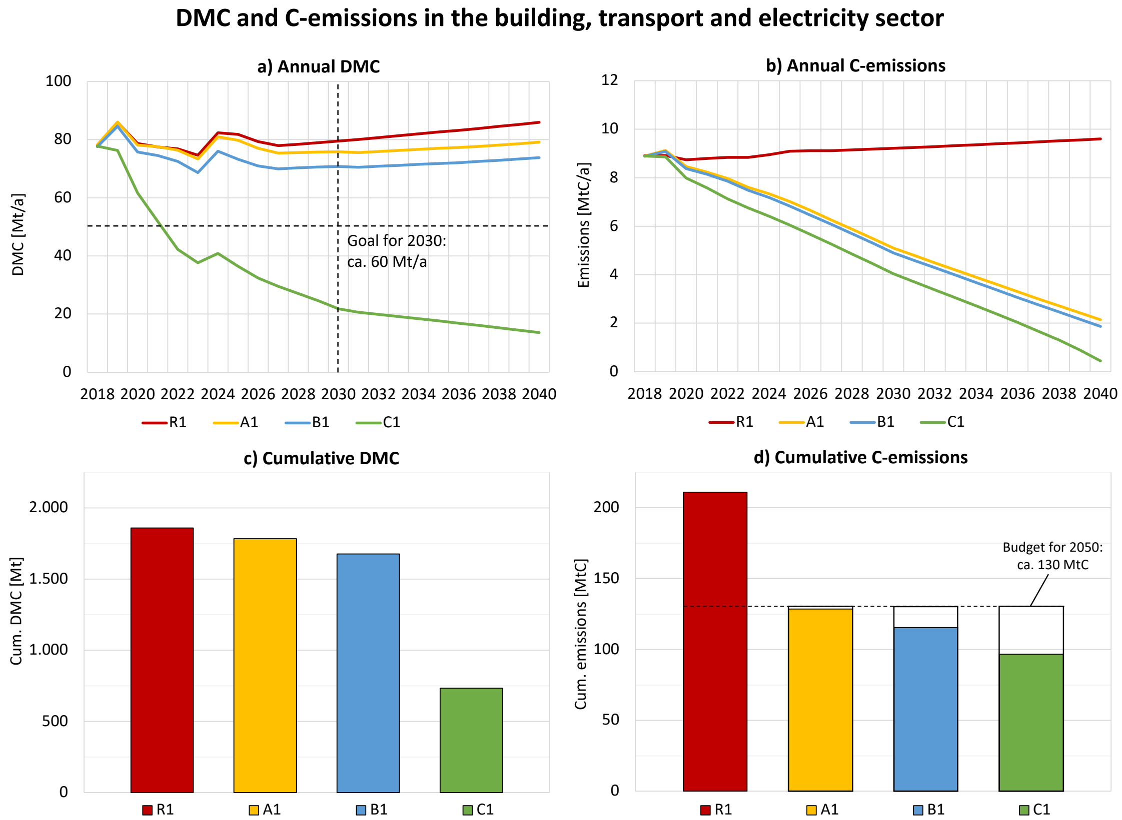


Figure 1: Annual domestic material consumption (DMC) (a) and carbon emissions (b) in Mt for the buildings, transport, and electricity sector for the four scenarios R1 reference, A1 decarbonisation, B1 decarbonisation and weak CE, and C1 decarbonisation and strong CE. Below bar charts (c) and (d) display the cumulative DMC and carbon emissions for the period 2018 to 2040. The cumulative carbon emissions in (d) are shown together with the sectoral carbon budget for the buildings, transport and electricity sector which is estimated to be roughly 130 MtC. Both the 2030 DMC goal of 14 t/capita of the Austrian Circularity Strategy correspond to 60 Mt in absolute terms (BMK, 2022) shown in (a) as well as the 2050 carbon budget shown in (d) were proportionally attributed to the sectors buildings, transport, and electricity based on their 2018 share in overall DMC and emissions (see Kirchengast et al., 2019). Note that in Figure 4b the remaining carbon emissions in 2040 can be attributed to domestic up-stream activities outside of the sectors (e.g., manufacturing of building materials

In 2018, the three sectors accounted for carbon emissions worth 8.9 MtC (considering only carbon emissions covered in the national GHG inventory). With continuing trends (R1), emissions would climb to 9.6 MtC, or cumulative 211 MtC (Figure 1b and 1d), thereby overshooting the 2050 carbon budget for the three sectors of ca. 130 MtC (target for all sectors: 1,000 MtCO2-eq until 2050: see Kirchengast et al., 2019) by more than 60%. In all other scenarios, this budget is abided by, especially in the C1 scenario where, with a cumulative 97 MtC, only 74% of the budget is used.

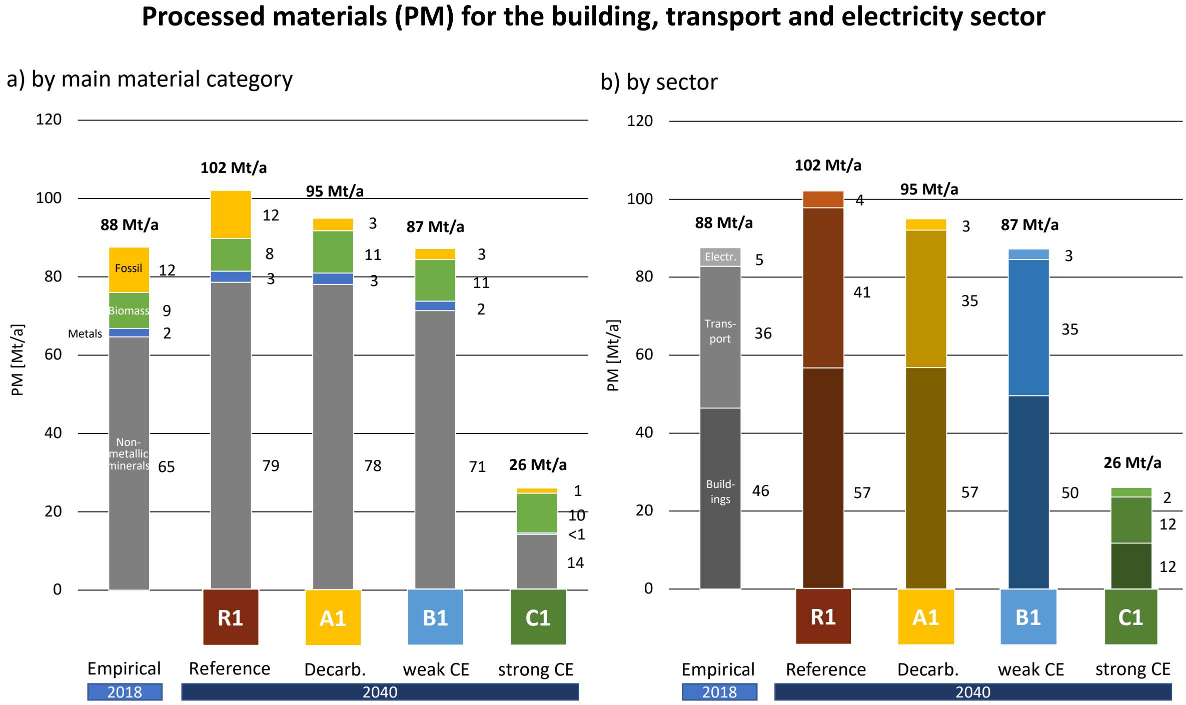


Figure 2: PM, which is DMC + recycling and backfilling, for 2018 and scenario results for the economic projection 'smooth economic recovery' for 2040; the reference scenario (R1), a decarbonization scenario with no CE strategies (A1), a weak CE (B1), and a strong CE scenario (C1). While a) shows the breakdown into the four material categories for all three sectors, b) displays the sector split for buildings, transport, and electricity.

For Austria of the year 2040, our CeAT model calculated the amount of 102 Mt of processed materials (PM) for the three sectors buildings, transport, and electricity for the economic reference projection 'smooth economic recovery' (R1) (see Figure 2a). In contrast to DMC, PM also includes secondary materials from recycling and backfilling. 102 Mt is an increase of 17% compared to 2018 and still demands 12% fossil fuels in PM. The reference scenario is the result of the GDP projection taking into account improvements in material intensity in line with past trends. When we introduce a strict decarbonization for the three sectors (A1), PM is reduced by 7% compared to R1, which is the net-reduction of phasing out fossil fuels on the one hand and the additional material demand for the sectors' reconstructions on the other hand. The remaining fossil fuel carriers are to a lower degree the use of plastics and mainly the fossil fuel requirements in other sectors that are not decarbonized in our CeAT model, for supplying concrete, bricks, heat pumps, and the like. The increase in biomass use is mainly due to the use of wood for improved thermal insulation of windows and roofs and a small share of the increase is for wood fuels. If we then introduce a weak set of CE strategies, as described in Figure 2 (B1), it results in a decreased PM by 15% compared to R1. Next to phasing out fossil fuels and the material demand for reconstruction this is mainly a result of reduced construction activities, as the modal shift of persons and cargo traffic away from roads demands fewer new roads, and the limitation of per capita floor space requires fewer new buildings. Finally, when we implement a strong set of CE strategies (C1), R1 can be decreased by 75%. This is a result as no material is demanded for expansion and lesser material for replacement and maintenance as the stock is stabilized over the period. In the strong CE scenario, half of the replacement buildings are made of wood. However, biomass use in this scenario is about the same as 2018, slightly less than in A1, the decarbonization scenario, and the same as in the weak circularity scenario B1. The increased wood use for wooden buildings in the C1 scenario compared to A1 is thus compensated for, as the lower number of new buildings entails less wood use in conventional buildings and a lower heating demand including biomass (which contributes 1% in GW for producing electricity). However, the lion share of the PM reduction is the reduced use of non-metallic minerals due to the reduced construction activities (Figure 2).

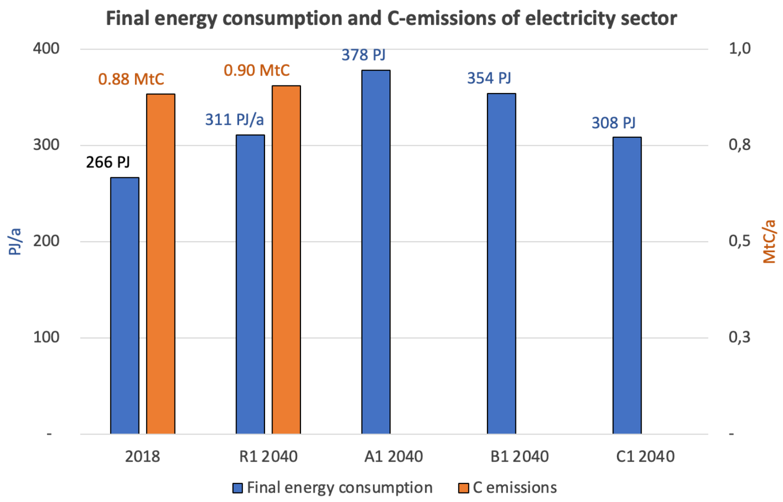


Figure 3: Final energy consumption (electricity) and carbon emissions for 2018 and for 2040 for the four scenarios for the three sectors

Amongst the sectors, the electricity sector has the lowest demand for PM in all scenarios. The decarbonization of the electricity sector phases out the use of fossil fuels and thus the tons required for fueling power plants, but material demand per MWh for building power plants based on renewables is higher than for conventional plants. One reason is that the installed capacities per produced energy unit need to be higher due to volatility in production to buffer a 'dunkelflaute', windless days with low sunshine intensity. Another reason is that the material intensities of the installed capacity (t/MW) are different. Gas and oil power plants need about 100 t material per MW, wind turbines 650 t/MW, ground-mounted PVs 500 t/MW. Only roof-top PVs need the low amount of 60 t/MW (Kalt et al., 2021). In sum, there is only a slight reduction in processed materials for the electricity sector between the reference scenario R1 (conventional plants) and the A1 (decarbonization) and B1 scenario (weak CE). Scenario C1 (strong CE) shows reduced material requirements, this is because the transport and building sector demand less final energy in this scenario (Figure 3), resulting in a lower installed capacity.

The electricity demand increases quite essentially in the smooth recovery projection from 2018 to the 2040 reference scenario (R1), which is due to the assumed economic growth. The carbon emissions grow slower, since the planned closing down of coal power plants and the already planned new wind power installations show an effect. For the decarbonisation scenario (A1), the electrification of road transport and heating (increased use of heat pumps) further boosts the final energy consumption but eliminates carbon emissions in the three sectors. In the decarbonization scenario (A1), the final energy consumption is, with 378 PJ, about 40% higher than in 2018. The weak CE scenario (B1) moderates this growth in energy consumption, again, due to modal shift and limited per capita living space in new buildings. In the strong CE scenario (C1), electricity demand is strongly reduced compared to the other scenarios, albeit 16% above 2018 levels. Less road transport of persons and cargo as well as no new buildings except for replacements stabilizes overall heated floor space and results in comparably less electricity demand than in all other scenarios.

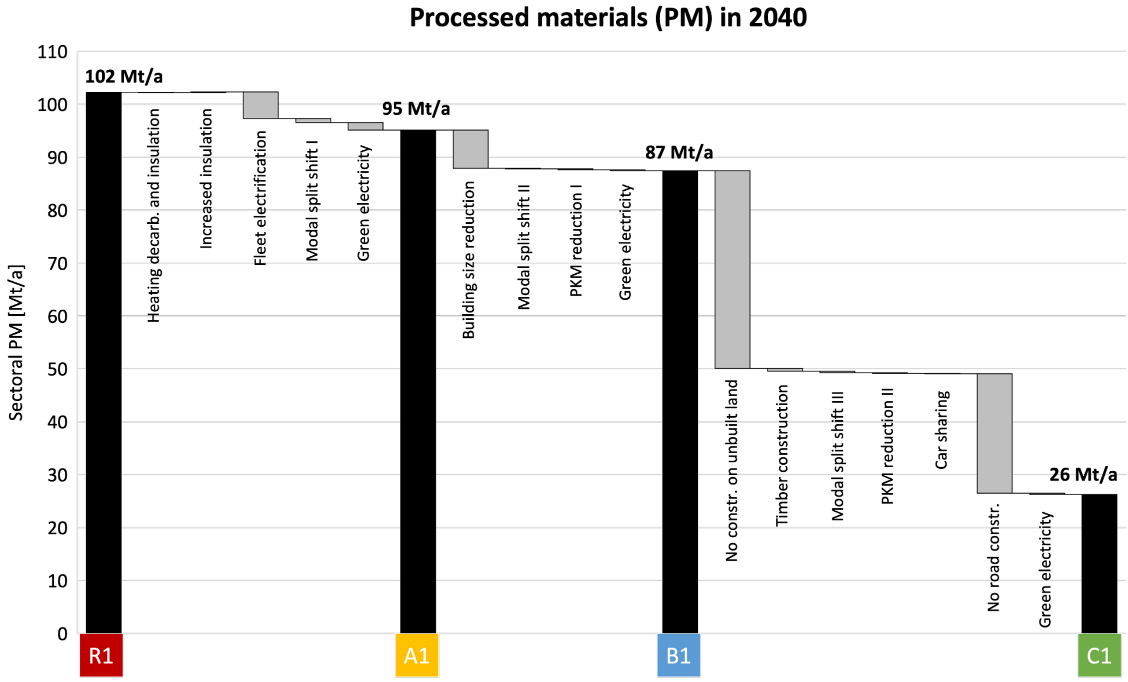


Figure 4: Material implications of decarbonisation (from R1>A1), weak (A1>B1) and strong CE strategies (B1>C1) for processed material for the economic projection 'smooth recovery' and the year 2040.

When we decompose the reductions by measures (Figure 4), we can gain further insights for each scenario on which measure reduces which material category by what amount. We found that for the year 2040, a mere decarbonization (A1) can only achieve slight reductions in processed materials (7 Mt) with fleet electrification being the most effective measure in this scenario with a reduction of 5 Mt. While fleet electrification increased demand for metals, these expansions are quantitatively overcompensated by fossil fuel reductions. Similarly, a replacement of heating systems to reduce carbon emissions from fossil fuel use requires additional materials, but quantitative savings in fossil energy carriers more or less balance this out. Additional weak CE measures (B1), especially a reduction in the per-capita living space of newly constructed buildings by 25% by 2025, have the potential to reduce processed materials by 9 Mt. A substantial reduction can be reached with strong CE measures (C1), where most material use savings can be made through stopping construction on unbuilt land (-36 Mt) and road construction in general (-23 Mt).

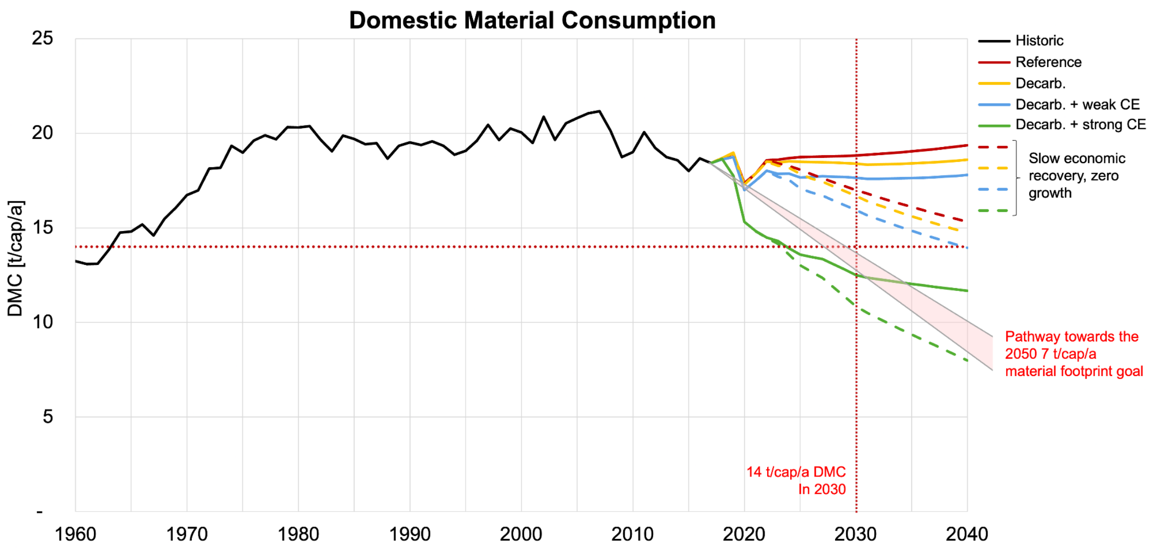


Figure 5: Domestic material consumption (DMC) per scenario and economic projection in relation to the 7 t/capita/a material footprint goal as formulated in the Austrian Circularity Strategy (BMK, 2022).

Reductions of material footprints in the observation period until 2040 are insignificant in all scenarios except C1 (deep decarbonization). We found that economic growth has a substantial impact, as material use reductions in all scenarios based on the second reference scenario (no growth) are substantially larger. Even in the most ambitious scenarios, reductions in the three sectors seem insufficient to get on track to reaching the target of 7 t material footprint/capita in 2050 (Figure 5), as formulated in the Austrian Circularity Strategy (BMK, 2022). However, it has to be taken into account that our results are based on changes in three modules (transport, buildings, energy provision) only, while all other economic sectors are assumed to remain unchanged.

Bulk and scarce material demand

The impact of sustainable transition measures on material demand varies for bulk and scarce materials. While bulk material demand gradually decreases with each scenario (Figure 1a), scarce material demand is significantly increased due to decarbonisation (Figure 6). A back-of-the-envelope quantification of material demand of technology-critical elements (TCE), or rare earth elements (REE), including Neodymium (Nd), Praseodymium (Pr), Dysprosium (Dy), Lanthanum (La), Cerium (Ce), Germanium (Ge), Gallium (Ga), and Tellurium (Te) in vehicles and electricity production (e.g., thin-film photovoltaic, wind power turbines) showed that the decarbonisation scenario TCE demand increase by a factor of 6 is primarily due to their widespread use in electric vehicles. Even though TCEs are used in the manufacturing of conventional internal-combustion engine vehicles, their application in electric vehicles is significantly higher with an average electric vehicle containing up to 1.3 kg of TCEs in permanent magnets alone (Habib et al., 2020).

In a decarbonisation scenario (A1), TCE use would increase from 84 t in 2018 to 772 t in 2040. Because of the predominance of this TCE application, reducing dependence on vehicles or cutting personal vehicle ownership, either through modal shift splits, car sharing, or pkm reductions, have great potential in decreasing overall TCE demand. While weak CE strategies (B1) would reduce TCE consumption by a quarter, with strong CE strategies (C1), TCE consumption would decrease to near reference scenario levels with 181 tons in 2040.

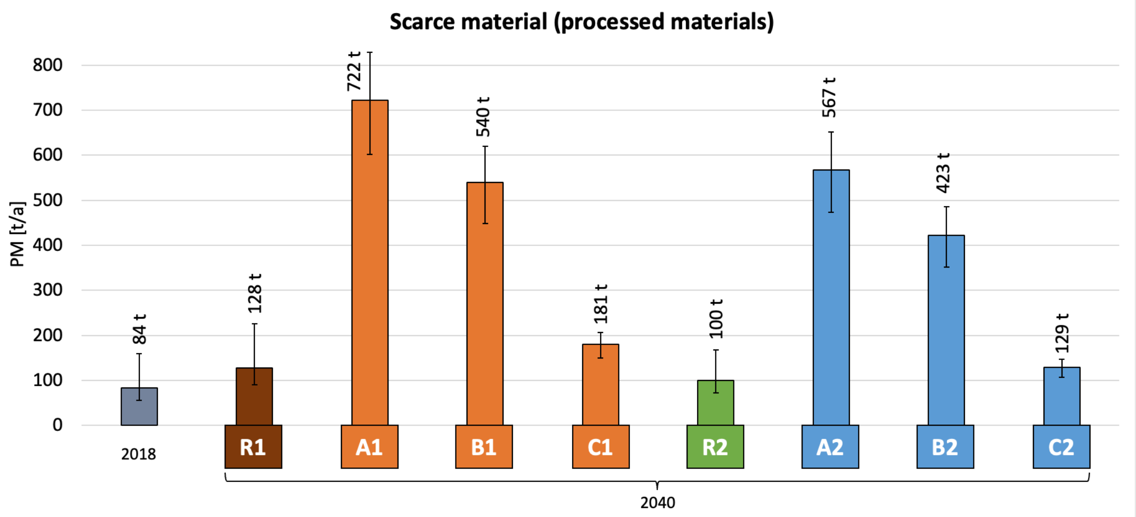


Figure 6: Total scarce material consumption per scenario in vehicles, PV, and wind turbines

4.1.2 Economic impact assessment by WIFO.DYNK model (WP4)

Economic results

The scenarios A, B, and C in the CeAT model represent a strong reduction of investments and consumption to different extents. In any economic model a reduction of expenditures leads to an increase in savings rates and to a decrease in domestic production and value-added. However, in this project it is assumed, in each scenario, that the savings rate of private households in each year is equal to the one in the reference scenario. This means, the previous expenditures for dwelling debt payments or car repair are spent otherwise. We defined two possible variants of this re-spending (rebound effect). On the one hand, re-spending of the freed-up monetary means is dedicated to material intense commodities only[1]. This is equal to the 'M' scenarios. On the other hand, in the 'S' scenarios the re-spending is simulated for service demand only[2]. The former is rather material and import intense whilst the latter demand is rather employment intense and has lower upstream imports. The two re-spending variants in combination with the three main scenarios A, B, C result in six scenario results shown in Figure 7. In this figure, the average growth rates between 2018 and 2040 regarding employment, GDP and disposable income are displayed. The Reference scenario here is the moderate growth projection (R1).

The same scenarios have been implemented with a lower reference GDP growth projection (R2). The results show qualitatively the same results. Therefore, here we focus on the moderate reference growth scenario R1 only.

Figure 7a shows that GDP grows by slightly over 1.35% per year in the moderate growth projection (R1). Depending on the altered investments and expenditures in A, B, and C according to the biophysical scenarios, and the re-spending on commodities (M) or services (S), deviations from the reference growth are computed. In the A scenarios full decarbonization takes place. Fossil based heating, electricity and mobility is replaced by alternative, renewable energy technologies. The isolated reduction in demand for fuels leads to a slight decrease in GDP growth by 0.01%-points. The decrease is very moderate

[1] Categories CPA01 to CPA33, except cars (CPA29), energy commodities (CPA 05,06,19,35) because they are determined by the scenario inputs from CeAT

[2] Categories CPA41-99, except construction services (CPA 41-43) and rents (CPA 68), because they are determined by the scenario inputs from CeAT

because in scenario A, imported fossil fuels are replaced with more domestically provided sources (as ambient heat). Overall operation costs are lower and the saved means can be re-spent until the savings rate is equal to the one in the reference scenario. We find a positive impact on GDP growth in both cases under re-spending on commodities (A1.M) and services (A1.S). The latter has a more positive impact because services have a relative low import intensity and a high wage intensity inland. Thereby a higher share of the re-spending generates domestic value-added.

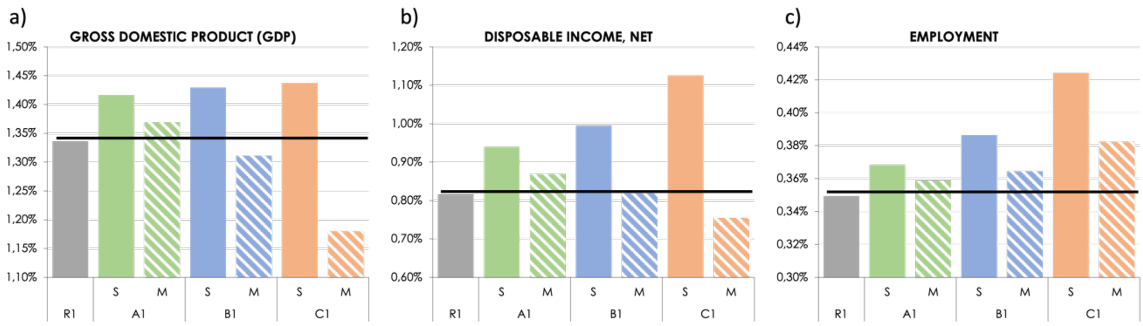


Figure 7: Average annual growth rates (2018- 2040) of GDP (a), disposable income (b), and employment (c) with respect to the reference scenario R1 in A, B, and C scenarios. Solid colors stand for the service-oriented (S) and hatched colors for the commodity-oriented (M) re-spending (rebound-effects). WIFO simulations.

In the B1 scenario the expenditures and investments in dwellings and private mobility decrease more strongly. Without re-spending, the GDP growth would decrease by 0.14%-points to 1.20% per annum. However, the positive impact of re-spending is only slightly higher. The reason for that is, that in the A scenario mainly the demand for imported fossil fuels is replaced by expenditures on commodities or services which has a positive impact on GDP[3]. The B scenario extends the decline in fossil fuel demand by a reduction in investments in capital stocks, i.e. construction and private car ownership maintenance services. These reductions have a much larger domestic component. Car repair services and dwelling maintenance are domestically provided services. By reducing the demand for these items, the primary negative impact on value-added is higher than in the A scenario. Therefore, the re-spending in domestic services B1.S is only slightly higher than in the A1.S scenario. Re-spending on material-intense commodities even reduces GDP growth by 0.03%-points because – on average – the commodity mix has a higher import share than domestic construction and car repair services replaced. In the C scenario the changes of the B scenario are amplified but lead structurally to the same results. The isolated demand reduction in C would reduce the GDP growth to below 1% p.a. The re-spending improves the growth again to 1.44% (C1.S) and 1.18% (C1.M).

The disposable income of households (Figure 7b) is an important indicator on how households are affected by the A, B and C scenarios. One important driver of gross disposable income[4] is the development of salaries and wages which is a part of GDP. In this project we have a close look on the net disposable income. The net disposable income is equal to the gross disposable income subtracted by the depreciation of the private capital stock of dwellings. In other words: the difference between the two is the share of the

[3] A reduction in Imports has a direct positive impact on GDP, since GDP = Consumption + Investment + Exports - Imports

[4] See components of disposable income at non-financial sectoral accounts: https://ec.europa.eu/eurostat/databrowser/view/nasa_10_nf_tr

income that is necessary to maintain the stock of dwellings. Hence, when the stock – that needs to be maintained – decreases, a larger share of the income is available for other consumption purposes. And this share is the net disposable income which is a more accurate indicator for the well-being of private households than gross income. Next to the GDP impacts described above, the net disposable income is positively affected by a decrease in the dwelling stock. Consequently, the changes in growth rates in Figure 7b) structurally follow the GDP variants but show an additional positive impact, namely the lower necessary expenditures for maintaining dwellings which can be spent otherwise. In all cases except C1.M the net disposable income is affected positively.

The impact on employment is positive in all scenarios (Figure 7c). Disclosed on a sectoral level, three areas seem to be particularly positively affected by the re-spending on commodities (scenarios ‘M’), thereby increasing the labor demand to the displayed values. The first area is the production and processing of food. The second is trade services (retail and wholesale) and the third is transport services. The reason for that lies in the structure[5] of the re-spending. In the base years, households’ commodity consumption shows large shares of agricultural and food products. Both are labor-intense. Furthermore, the consumption of these commodities is interlinked with transport and trade. All three areas profit from the re-spending primarily on commodities and are (low-wage) labor-intense. In summary, in the B1.M and C1.M scenarios the spendings on construction and vehicles are replaced by expenditures on commodities. These commodities have a higher import share along their value chain and thereby reduce the GDP growth (Figure 7a). But the labor intensity in the value chain of commodities is higher than in construction and vehicles. Hence the employment effect of the re-spending is overall positive. Even though the wage rates in the sectors agriculture, food processing, trade and transport services are rather low. Therefore, in C1.M, the disposable income is lower than in R1 while employment is higher.

In our economic impact analysis of the defined scenarios, we do not account for different energy and CO2 price trajectories for R and A, B, C scenarios respectively because different price assumptions and market reactions are implicit in the biophysical results. The introduction of energy and CO_2 prices in the macroeconomic model would have affected household energy demand and the energy mix thereof, which is, however, already covered in the biophysical model and transferred in the macroeconomic model as exogenous variables. Of course, one can still argue that increasing prices of energy and CO_2 certificates would increase the nominal energy costs for the households, but (i) due to the decarbonization until 2040 this impact from the CO_2 price increases would diminish anyway and (ii) we also believe that Austria is too small to influence global energy or resource prices, and that while Austria is implementing varying degrees of CE strategies along with a zero-emissions target, other less developed countries will not follow suit, particularly in the construction and transport sectors. We have therefore abstracted from price effects and focused on the macroeconomic rebound effects in terms of re-spending of savings from reduced capital stocks and maintenance.

[5] The expenditure structure resembles the spending on commodities (CPA01 to CPA33) in the private consumption vector in the 2018 Input-Output-Table. With the exception of energy commodities (CPA05, 06, 19) and vehicles (CPA 29).

The model results for the other economic projection 'slow recovery and zero growth' (2) are different in magnitude, but the changes follow the same direction as for the 'smooth recovery' (1) projection.

4.1.3 Impacts on SDGs

Answering the research question 2d of whether there are synergies and trade-offs with regard to Sustainable Development Goals (SDGs), it can be said that if gentrification and the financial burden for reconstructing infrastructures is fairly distributed, decarbonisation and CE measures can reduce poverty and inequalities (SDG 1 'No Poverty' and SDG 10 'Reduced Inequalities'), as improved housing for example via thermal renovation or new building standards saves fuel costs and a less car-dependent transport sector facilitates mobility for all at less costs per capita. For housing and mobility, only clean energy at affordable costs can be provided (SDG 7 'Affordable and Clean Energy'). A modal split shift in the transport sector comes with considerable health benefits due to less air pollution and more physical exercise due to increased active travel modes, thereby supporting SDG 3 'Good Health and Well-being'. By achieving net zero carbon emissions in the sectors under consideration, the goals on climate action (SDG 13) within reach. As land sealing activities are reduced significantly or completely stopped in the building and transport sectors, further land fragmentation and loss of ecosystems can be prevented, thereby enabling the renaturation of land and thus altogether contributing to life on land (SDG 15).

Regarding research question 3, which inquires as to which measures are most promising, sufficiency-based measures such as reduction in or stop of new construction of buildings (e.g., via reductions in new floor area per capita or reduction of new construction due to lifetime extension and a stop of construction on unbuilt land) and transport infrastructure were found to be the most effective in reducing overall bulk material demand. However, for scarce material consumption, sufficiency-based measures affecting personal vehicle ownership were shown to be most effective, e.g., by modal split shifts or pkm reductions.

The economic assessment shows possible positive employment and GDP effects in all three scenarios (A, B, C), with the highest growth and employment potential in the strong CE scenario (C) if a service-oriented re-spending is considered, thus CE DC contribute to SDG 8 (decent work and economic growth).

An overview of SDG Targets and their respective effect on decarbonisation and CE measures is given in Table 1.

Table 1: Effects of decarbonization and CE measures modeled that are related to specific SDG targets

SDG Goal	SDG Target	Related effects of decarbonisation and CE measures
3 Good Health and Well-being	3.6 Reduce the number of fatalities on roads	Reducing cars and road traffic (pkm & tkm) will probably also reduce the number of fatalities.
	3.a Reduce the number of deaths as a result of lung cancer/bronchial carcinomas	Eliminating all combustion engines (in all scenarios) also reduces the amount of air pollution.
7	7.1 Universal access to affordable, reliable and modern energy services	All electricity is reliable. The affordability of energy services was not assessed in this project.

Affordable and Clean Energy	7.2 Increase substantially the share of renewable energy in the energy mix	Electrification of the whole fleet and the shift to 100% renewable energy make energy services more sustainable.
	7.3 Increase energy efficiency	Green electricity, e-mobility and heat pumps are in sum an increase in efficiency
8 Decent work and economic growth	8.4 Decouple economic growth from environmental degradation	In particular scenario C has the potential to absolute decouple economic growth from resource use and GHG emissions, if freed monetary means are spent on services
9 Industry, innovation and infrastructure	9.1 Reduce energy use and GHG emissions of transport	Energy use of transport is decreasing with modal split shifts and reductions in pkm/tkm (scenario B & C), GHG emissions of transport are eliminated by electrification and reduction.
12 Responsible consumption and production	12.2 Reduce raw material consumption and domestic material consumption (total and per capita)	Domestic material consumption decreases in all scenarios (especially B and C) because of phasing out fossil energy carriers and implementing CE measures.
	12.5 Increase recycling rates of waste (without excavated material)	Recycling rates are increased as part of CE measures implementation in scenario B & C.
13 Climate action	13.2 Reduce of GHG emissions	Already in scenario A (decarbonization) GHG emissions are eliminated.
15 Life on land	15.1 Forest area as a proportion of total land area	No construction on unbuilt areas and no further road construction (scenario C) put a halt to further sealing of land, destroying biodiversity and natural habitats.
	15.4 Preserving mountain ecosystems	
	15.5 Preserving biodiversity and natural habitats	

5 Conclusions and recommendations

Scenario results for a reference, a decarbonisation and two CE scenarios provide crucial insights for the transformation process ahead. The insights are based on a combination of results from biophysical modeling (CeAT) and economic modeling (WIFO.DYNK).

Circularity, decarbonisation, and land consumption

Recycling is an already exercised and important CE strategy in Austria, which moderates resource demand and waste generation. Increased recycling efforts are beneficial in many areas, but the remaining potential provides only minor benefits compared to what is needed in the light of government strategies. Thus, its contribution to ease the decarbonisation is very low, the potential to get on a trajectory to achieve circularity targets is by far not sufficient and it does not contribute to limiting the annual land consumption which should be strongly reduced. Therefore other CE strategies in the categories reducing and slowing flows need far higher attention than improving recycling activities.

- Only a strong CE scenario (C) with a focus on reducing and slowing material flows can achieve the goals of the CE strategy and makes it much easier to achieve carbon neutrality by 2040, as in the strong CE scenario the electricity sector has to supply only 65% of final energy (green electricity) of the decarbonization scenario. Such a strong CE scenario (C) also achieves the government targets for reduced land consumption.
- These triple goals (carbon neutrality, circularity, land consumption) can be met despite the additional material needed for refurbishing buildings, electrifying heating and transport and replacing fossil-fuel based power plants with those based on renewable energy. In material terms this means that the phasing out of fossil fuels and the reducing and slowing flows in the strong CE scenario (C) outweighs the additional material demand for the decarbonisation.
- Strong CE strategies (C) can save 25% of carbon emissions in the transformation process of phasing out fossil fuels in buildings, transport, and electricity sectors in the period 2018 to 2040.
- The weak CE scenario (B) can save 12% of carbon emissions in the transformation process of phasing out fossil fuels in buildings, transport, and electricity sectors in the period 2018 to 2040. However, it fails to contribute sufficiently to the 2030 and 2050 CE strategy goals and it has only moderate reduction effects on the land consumption.
- A strong CE scenario (C) means in the transport sector a massive shift away from car mobility, an increased share of active mobility and public transport; as a consequence no new roads are needed after 2030 and a low level of car ownership through car sharing can be achieved.
- In the building sector the strong CE scenario (C) means thermal insulation of buildings, replacement of fossil fuel-based heating systems, no new buildings on unbuilt land, extended building lifetimes, and half of the replacement buildings made to be built as wood constructions. As this scenario means restricting new buildings only to replacing demolished buildings, the economy's overall wood consumption is in the strong CE scenario with a 50% share of wood buildings more or less as high as in the decarbonisation scenario (A) with further building activities as in the past.

- A strong CE scenario (C) is associated with limiting heated floor space for the sum of residential and office buildings leading to a per capita reduction by 7% while considering population growth and a drastic reduction in car ownership by 86% car ownership (car sharing is partly providing access to car mobility). Service provision in overall mobility is only reduced marginally and heating standards stay at the same level as they are now.

Scarce materials

- A strong CE scenario (C) yields beyond the reduction of total material (bulk) flows a reduction in requirements of critical materials. Thus, the scarce materials such as Neodymium would be increased by more than 760% in the decarbonisation scenario (A) and only little more than double in the strong CE scenario (C) by 2040 compared to 2018 levels. This difference results from reduced numbers of electric cars and wind turbines, as they demand scarce materials. Consequently, the strong CE scenario (C) is less vulnerable to shortages or price volatility at the world market increasing the security of supply respectively lowering the dependence on a smoothly functioning supply chain in times of geopolitical tensions.

Economic conclusions

- GDP growth is fueled by spending the freed-up monetary means from lower stock demand in the service sector, thereby solving the rebound issue and benefiting the economic value-added and employment in Austria with respect to a baseline (scenario C).
- Absolute decoupling of material consumption from economic growth is possible, both from a biophysical and an economic perspective, but it requires a shift from material-intensive sectors such as the construction sector towards investments in growing tertiary and quaternary sectors (e.g., education, healthcare, etc.).
- This would simultaneously increase net income with more capital being invested in quality products (e.g., longer-living products) or healthy and climate-friendly diets.

Sustainable development goals (SDGs)

- The changes modeled in the strong CE scenario (C) yield benefits for the following sustainable development goals (SDG):
  - SDG 3 'Good Health and Well-being': less air pollution and more exercise,
  - SDG 7 'Affordable and Clean Energy': only clean renewable energy available and refurbished buildings and public transport reduce energy demand and costs (increased disposable income),
  - SDG 8 'Sustainable economic growth and decent work"
  - SDG 9 'Industry, innovation and infrastructure': energy use and GHG emissions of transport are reduced,
  - SDG 12 'Responsible consumption and production': material consumption is reduced,
  - SDG 13 'Climate action': Reduction of carbon emissions to zero,
  - SDG 15 'Life on land': No buildings on unbuilt land and no further road construction put a halt to further sealing of land, destroying biodiversity and natural habitats.

Policy implications

The most effective individual measures are the reduction of floor space and the reduction of car traffic and the associated halt to the expansion of existing buildings and roads. If the targets set by the Austrian government, such as climate neutrality, the circular economy targets and the land consumption targets, are to be achieved, this will require new policy measures. Exemplary options for action are presented for the following fields of action, which have a key role to play:

Media relations:

- Systematic presentation of the connections between ecological goals and the expansion of buildings and roads in order to sharpen the public's perception in this area.

Regulatory measures:

- Phasing out of new land designations for buildings and roads,
- Reduction of vacancies in buildings,
- Simplifying the conversion of office space into residential space and vice versa,
- Flexibilising the change of residence between the same standards under the same conditions,
- Consistent implementation of phasing out road construction in transport planning.

Accompanying measures:

- Accompanying the reorganization of the construction industry from a focus on new construction to renovation and new, sustainable building materials.
- Preventing rebound by incentivizing the consumption of services at the expense of the consumption of material-intensive goods and services.

C) Project details

6 Methodology

6.1 Project activities and methodology

To address the research questions described in section 2.2.2, multiple consecutive working stages were necessary. In a first step, the biophysical CE model CeAT was updated to the year 2018 and further extended, which allowed to model yearly biophysical flows until the year 2040, by using material intensities and GDP projections. We used two economic projections following the COVID-19 pandemic, thereby producing two reference scenarios which served as a baseline. In order to conduct prospective scenario modeling, assigning current material stock data to their function or end-use (e.g., buildings, roads, vehicles) was necessary since material stocks are a main driver of material consumption. Consequently, three sector modules (building, transport, and electricity production) were developed, collectively covering 51% of emissions or 49% of material consumption (DMC) in Austria in 2018 (see Figure 8).

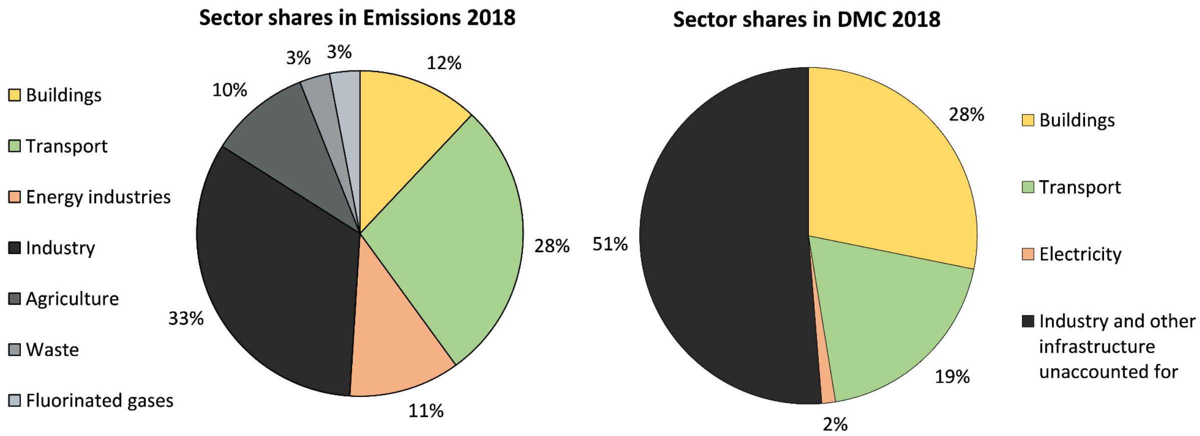


Figure 8: Sector shares in emissions and domestic material consumption (DMC)

For all three sector modules we gathered comprehensive data of the relevant societal stocks, their material and energy requirements (e.g., building types, heating systems, vehicles, roads). Based on these empirical grounds, scenarios reflecting various decarbonisation and CE strategies could be developed, with each measure altering future material stocks and consequently material and energy demand and related emissions. After completing these biophysical forecasts, an economic assessment of the different scenarios was conducted using the pre-developed macroeconomic WIFO.DYNK model, including calculations of CE driven macroeconomic rebound effects. The following section describes each working stage in more detail.

6.1.1 CeAT model

Biophysical CE model extension

The biophysical CE model (CeAT) used in our analysis has previously been developed based on the conceptual framework of economy-wide material flow accounting (MFA). It tracks flows of biomass, metals, non-metallic minerals and fossil materials from extraction and imports into the domestic economy to their processing and conversion into societal material stocks, emissions and waste outputs or recycling inputs. The model has been applied successfully to the global economy, the EU-27, Austria, and South Africa (Haas et al., 2015, 2020, 2023; Jacobi et al., 2018; Mayer et al., 2019). For detailed descriptions about the general system and assumptions behind CeAT, we refer to the listed cases. In this study, we based our work on the model for Austria (Jacobi et al., 2018) and extended it in several ways.

First, we updated input data in CeAT to calculate the base year of 2018. We used Eurostat MFA data (Eurostat, 2020a); data download 07/07/2020) on domestic extraction, imports, and exports in Austria in 2018 in kilotons for the 56 material categories reported. We added categories: (a) 4.2.1 'Crude oil' was split into five subcategories (crude oil, plastic, bitumen, lubricants, tyres), using information from other data sources and assumptions. (b) 1.7 'Cutting from public greens', which is a flow of biomass not reported in statistics, (c) 'Extractive Waste', which is a non-reported flow from metals extraction, (d) 'Asphalt', and (e) 'Concrete'. Second, we extended the model by a waste module. As the reuse and recycling of materials and the changes in these activities in different scenarios and over time are put in focus in this study, we included a detailed split of waste materials and their fate (reuse, recycling, incineration, disposal, composting). In order to do so, we used waste management data (Eurostat, 2020b) and made informed assumptions to allocate materials from 33 different waste collection categories into the predefined MFA categories. This allowed us to include different categories of waste treatment, i.e. landfills, incineration and energy recovery, recycling and backfilling, and composting, and to allocate waste flows to these.

The CE modeling, which traces the material and energy flows though the economy, makes it necessary to introduce new indicators in addition to the economy-wide material flow accounting (MFA) standard indicators. As both types of key indicators are used in the result section and they are quite similar, they need some explanation. In the MFA domestic extraction (DE), imports and exports are key indicators. Derived indicators are then the domestic material consumption (DMC), which is DE + imports – exports (European Commission. Statistical Office of the European Union., 2018; Eurostat, 2013; Fischer-Kowalski et al., 2011; Krausmann et al., 2015). As the circular economy demands amongst other strategies closing loops, economies process in addition to material from domestic extraction and imports also materials from recycling (returning material as secondary material in the production process) and backfilling (using excavated material for backfilling e.g. to level the grounds around a newly constructed building instead of using extracted materials). Thus, a new indicator, named processed material (PM), was developed that added these return flows to the DMC (PM = DMC + recycling + backfilling) (European Commission & Statistical Office of the European Union, 2018; Haas et al., 2015; Jacobi et al., 2018; Mayer et al., 2019).

Economic projections until 2040

To assess the effects of CE DC scenarios, we developed two economic reference scenarios (R1, R2), which serve as a calculatory baseline up to 2040. These reference scenarios reflect general developments, such as population growth, changes in GDP, and other variables in line with the principles of the 'With existing measures' (WEM) scenario applied by the Federal Environment Agency (UBA, 2023b) i.e., shifts in the power generation energy mix and improvements in energy efficiency at current trends. As the project started during the COVID-19 pandemic and the first lockdowns, and further development of the pandemic, the corresponding protective measures, and their economic impacts were highly uncertain, we developed two alternative reference scenarios (R1, R2), reflecting two different growth assumptions until 2040 (see Figure 9). The starting point for both scenarios is a pre-pandemic moderate economic growth of 1.5% per year, followed by an economic downturn in 2020 by -6.6% (Schiman-Vukan & Ederer, 2023). After a recovery in 2021/2022 (+4.2%/+4.8%) we assumed an average annual growth rate of 1.33% per year in the reference scenario R1, following the WEM scenario of the Federal Environment Agency (UBA, 2021), and, due to interruptions of international value chains, geopolitical tensions and resulting economic frictions, a zero growth rate in the reference scenario R2.

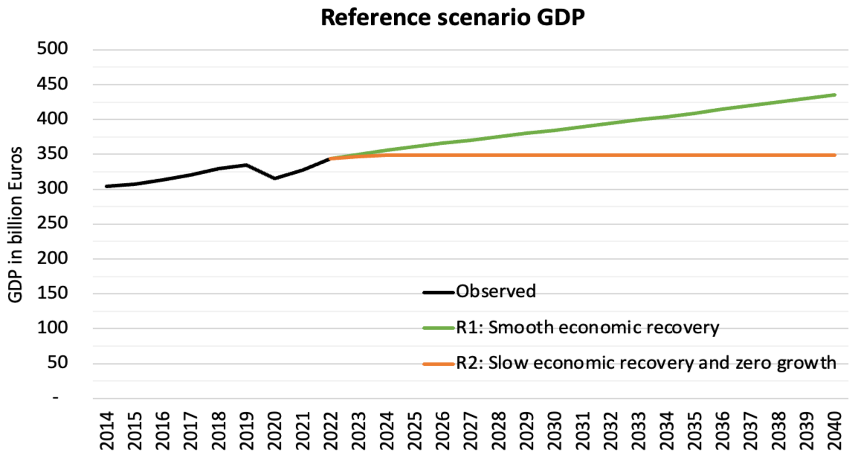


Figure 9: GDP projections for reference scenarios R1 and R2

Biophysical reference scenarios based on economic projections

To model the biophysical economy in the reference scenarios, we introduced a time dimension by using the CeAT model to forecast material stocks and flows until 2040. We did this by calculating the historical trend of material intensity of GDP over the last 15 years (2004-2018) separately for domestic extraction (DE), imports and exports for three of the four main material categories (biomass, metals, minerals). We used exponential trends for forecasting, as those functions delivered the best fit. Based on the value of the last available year (2018) we could thus forecast material intensity until 2040 for the different indicators (DE, imports, exports) and the main material groups.

By multiplying material intensity with the projected GDP, we calculated the material indicators DE, imports, and exports until 2040. Fossil materials were forecasted in the WIFO.DYNK model[6] and these figures for total fossil materials and subcategories, such as coal, oil, and gas were used as an input in CeAT. From the modeled data on material flows in DE, imports, and exports, we calculated other internal material flows of the economy (e.g., stock add) in our model for every year of the investigation period. We expressed all other material flows in the model as ration, i.e. as percentage of the forecasted values (e.g., how much of extraction and imports plus recycling is used for material use and further for stock building) and thus calculated all flows of CeAT for every year until 2040.

[6] Using energy intensity (TJ/Euro) per sector based on the sectoral energy accounts of Statistik Austria 2018 and extrapolating the historic average sectoral energy efficiency improvement of 0.8% p.a.

Sector modules

The following section describes the data compiled in the three modules and main modeling processes.

Building sector

In the building sector we considered building construction, demolition, renovation, and heating system replacement activities and the material inflows and outflows related to these. In total, four building types, eight building age cohorts, and ten heating systems were defined.

Data on annually constructed buildings was available via Statistik Austria data (Statistik Austria, 2020b), in the form of number of buildings and square meters constructed. The annually constructed area for residential and non-residential buildings was coupled with population and construction-sector GDP forecasts respectively and forecasted from 2019 to 2040.

Starting from building stock as reported in the last 2011 national census ('Registerzählung 2011': (Statistik Austria, 2011), changes in stock until 2040 were calculated by adding annual new construction and subtracting demolition flows for Vienna (Lederer et al., 2019). Per age cohort, demolition rates were gradually increased until 2040 and main material outflows were derived.

Renovation rates based on (Kranzl et al., 2018) were applied to annual building stock. Thermal renovation material intensity (MI) factors (kg/m^2) for outer walls, attic floors and basement ceilings from (Maydl, 2013) were used in combination with archetypical square meters of building elements for Austria (Austrian Energy Agency, 2011).

Final heating energy demand is calculated based on the annual renovated and unrenovated building stock area and age-cohort specific before and after renovation energy demand (kWh/m^2) (Schulter, 2013). After applying heating system shares from (Kranzl et al., 2018) and accounting for heating degree days, the derived installed capacity was multiplied with average heating system MI factors to produce annual heating system material stocks.

Embodied energy of construction materials, construction, demolition, and renovation activities were calculated based on factors reported in (Martínez-Rocamora et al., 2016) and various European LCA case studies.

Transport sector

In the transport sector we focused on vehicle fleet and transport infrastructure changes and calculated the material inflows and outflows in relation to these. Various vehicle as well as propulsion types were differentiated. Infrastructure stocks and flows comprise both road- and rail-based infrastructure, as well as bridges, tunnels, and charging stations.

For estimating fleet sizes of cars, motorcycles, trucks, and trailers, data from (Statistik Austria, 2020a) was used. For railways, data from Schienen-Control reports (Schienen Control, 2015) was used, while for buses, trams, and subways, regional data from various local transportation companies was combined. For bicycles and e-bikes, data from (BMVIT, 2013) and (VCÖ, 2020) reports were used. Historic fleet size data was coupled with (European Commission, 2020) traffic volume data. To model the vehicle fleet size until 2040, the intensity of the last available year (2018) was multiplied with annual traffic volume which in turn was forecasted by coupling passenger-kilometers (pkm) and tonne-kilometers (tkm) to future GDP. Using a simple leaching model, end-of-life (EoL) waste of vehicles was calculated based on vehicle lifetime assumptions, using average MI factors from literature.

Austrian infrastructure expansion and maintenance flows were derived from a global transport infrastructure mapping study (Virág et al., 2022; Wiedenhofer et al., 2024) that spatially maps current and future infrastructure from roads, railway to bridges and tunnels.

The fuel use of vehicles was modeled using occupancy rates (passenger/vehicle/trip) and fuel use rates (MJ/vkm or MJ/tkm) from various studies. Furthermore, the embodied energy of all materials used in the manufacturing or construction of vehicles and infrastructure was modeled based on factors from literature.

Electricity sector

Material flows of the electricity production sector are comprised of changes in installed capacity and fuel use. Electricity use changes from the building and transport modules, and energy sector consumption and transport losses based on static 15-year averages were taken into account when calculating final energy consumption. By applying the last available year's energy split as static shares, electricity generation per energy system was calculated. By accounting for full-load hours, final energy consumption was converted to installed capacity (MW).

To model future system grid expansion, energy consumption, and installed capacity were integrated with a regression model based on population-coupled household forecasts from Statistik Austria (Statistik Austria, 2020c).

In a next step, net capacity increases, as well as regular and early decommissioning for both installed capacity in MW and electricity grid system and route length in km were calculated. Regular decommissioning was calculated based on energy system-specific lifetime assumptions ranging from 25 to 50 years, while early decommissioning refers to negative net capacity changes exceeding regular decommissioning. By applying capacity-specific MI factors for steel, concrete, aluminum, and copper (Kalt et al., 2021, 2022), total installation and total decommissioning were converted to material inflows and outflows respectively. Material intensities (t/PJ) were derived from historic data and applied to future electricity generation to calculate fuel use in metric tons for coal, oil, gas, waste, and biomass.

Prospective decarbonisation and CE scenarios

The following section provides an overview of the three scenarios developed and the assumptions implemented therein. A summary of all transition measures as well as references can be found in Table 2.

<u>Decarbonisation (A)</u>: In the first scenario, future stocks needed for the decarbonisation of the three sectors were determined. These are e.g., insulated buildings, heating systems, the vehicle fleet or power plants. For the building sector, heating systems were decarbonized by replacing future reference scenario energy shares with decarbonisation scenario energy shares (Kranzl et al., 2018). The year of complete decarbonisation was shifted from 2050 to 2040 according to the government agreement agreement ("raus aus Öl und Gas"/exit from oil and gas österreich.gv.at, 2024). Compared to the reference scenario, an increased thermal renovation rate of the existing building stock was assumed, with rates of 1.60% in 2025, 1.98% in 2030 and 1.30% in 2040 (Kranzl et al., 2018). Reflecting changes in heating energy demand (kWh/m^2) (Österreichisches Institut für Bautechnik, 2007, 2019), changes rates for insulation material thicknesses were derived

and applied to insulation material MI factors, constituting an increase of 75% on average. Heating system replacement, thermal renovation rates, and an increase in insulation was kept the same for the B and C scenarios as well.

Regarding the transport sector, the vehicle fleet in 2040 was assumed to be fully electrified. Beyond fleet decarbonisation, a slight modal split shift of 10% from cars and motorcycles to public and active mobility and a 10% shift of tkm from road to rail was assumed. This is based on the target modal split share of 46% for public and active mobility as outlined in the official 'Mobilitätsmasterplan' (BMK, 2021).

The electricity sector was assumed to be fully decarbonized by 2030, reflecting the ambitious goal of the Austrian government of achieving climate-neutral electricity generation by 2030, ten years prior to EU requirements. As a starting point we used shares as they were available in different studies, albeit with some differences differences (Austrian Energy Agency, 2017; BMNT, 2019; UBA, 2016, 2023a). We assumed, in agreement with many authors and statements in official documents, that hydro power is important, but has a low potential for installing new power plants. Thus we kept hydro power (run of river and storage) at 2018 levels in terms of PJ. For the remaining energy generation, we used a split mainly between the different technologies PV and wind power in line with the above mentioned studies. However, as our scenarios have very different final energy demands for electricity depending on the building and transport sector, the final split varied depending on the final energy use in the scenario. Beyond this fossil fuel phase out in electricity generation, no further assumptions were made for the other two scenarios. Additional scenario differences in the electricity sector are instead due to varying electricity demand caused by changes in the other two sectors.

Decarbonisation and weak CE (B): The second scenario introduces moderate CE strategies. For the building sector, a 25% reduction in newly constructed per capita floor area by 2025 was assumed based on scenario assumptions described in (Kranzl et al., 2018). This corresponds to a 19% reduction in net floor area in new construction. Reduction was gradually implemented starting in 2018 and kept static after 2025.

In the transport sector, modal split shift to public transport and active mobility was increased to 20%, thereby staying within the scope of discussed transport policies (UBA, 2023a). An additional traffic volume reduction of 15% for pkm and 25% for tkm was assumed to reflect already increasing teleworking arrangements as discussed in official documents (e.g., UBA, 2023a).

Decarbonisation and strong CE (C): The third and most intense scenario reflects scenarios that go beyond those currently ratified or envisioned by official institutions. For buildings, it was assumed that no construction occurs on previously unbuilt, 'green' land. This was implemented by setting the assumption that construction can only occur on land where a building was previously demolished and limiting the annually newly constructed floor area to 50% of the annually demolished floor area. Furthermore, it was assumed that building maintenance and consequently building lifetimes increase, and demolition is reduced by 25%. Finally, it was assumed that 50% of future new construction is using timber substituting for cement/steel, thus changing the MI input and consequently the material composition of the future building stock.

Scenario assumptions for the transport sector include a 50% shift in modal split from private to public and active mobility, and a 40% tkm shift from road to rail-based transport. This was deemed legitimate given the simultaneously assumed halt of road network expansion that reduces attractivity of car and truck usage and increases attractiveness of public and rail-based transportation. Traffic volume reduction was increased to 30% for pkm based on stopping sprawl due to a stop of building construction n unbuilt land. Urban sprawl was increasing in Austria over the past three decades (Brenner et al., 2024). Likewise, increased home office use and urbanisation with urban areas in Austria having a 30% lower path length in compared to peripheral areas and 15% lower compared to central districts (BMVIT, 2016). Finally, we assume that transport might become more costly and in turn lead to private optimization of mobility. For freight, a 50% reduction in tkm was assumed based on the assumption that with reduced construction activities and a fossil fuel phase out, significantly fewer tonnes of material have to be transported. Furthermore, we assumed that car sharing was assumed to double by 2040. In regard to transport infrastructure, it was assumed that no further road network expansion occurs after 2030.

Table 2: Implemented scenario measures

Sector	Measure	A Decarbonisation	B Decarbonisation and **weak** CE	C Decarbonisation and **strong** CE	Sources
Buildings	Heating systems decarbonisation	•	•	•	österreich.gv.at, 2024 Kranzl et al., 2018
	Increased thermal renovation	•	•	•	Kranzl et al., 2018
	Increased insulation new buildings	•	•	•	Calculation based on OIB, 2019
	New floor area per capita reduced (-25%)		•		Kranzl et al., 2018
	Lifetime extension of buildings (25% fewer demolition)			•	Own assumption
	No construction on unbuilt land (construction = demolition)			•	Own assumption
	Timber construction share = 50%			•	Own assumption
Transport	Fleet electrification by 2040	•	•	•	BMK, 2022 *KW-Strategie*
	Modal split shift	-10% cars, -10% tkm road	-20% cars, -20% tkm road	-50% cars, -40% tkm road	BMK, 2024 *Mobilitätsmasterplan for scenario A; own assumptions for B+C.*
	Traffic volume (pkm) reduction		-15% pkm, -25% tkm	-30% pkm, -50% tkm	BMVIT, 2016 for scenario C; own assumptions for B.
	Car sharing doubled			•	Own assumption
	No road expansion after 2030			•	Own assumption
Electricity	- Fossil fuel phase out - Hydro capacity constant in GW in all scenarios - Bio to power slowly declines in B and C from 2018 - Installed capacities for all scenarios account for change in electricity demand for buildings and transport	Wind 23%, PV 46%, Hydro ROR 13%, Hydro-Storage 17%, Bio 1%	Wind 22%, PV 45%, Hydro ROR 14%, Hydro-Storage 18%, Bio 1%	Wind 19%, PV 40%, Hydro ROR 17%, Hydro-Storage 22%, Bio 1%	Assumption derived from (Austrian Energy Agency, 2017; BMNT, 2019; UBA, 2016, 2023a)

Soft linking of models

The biophysical model was linked to the macroeconomic model (WIFO.DYNK, see section 2.2.3.3) via two data types. On the one hand, reference scenario GDP projections were used as data inputs to the biophysical model for forecasting various biophysical activities into the future. On the other hand, both biophysical flows as mass of material used for societal activities as well as various parameters used to quantify these flows (e.g., number of buildings constructed, car fleet additions) were used as inputs in the macroeconomic model and assessed in terms of monetary value using prices per units. The monetary changes were translated to exogenous inputs in the WIFO.DYNK model. For instance the physical purchase of new vehicles per engine type is an outcome of the biophysical model. A set of prices per vehicle (type)[7] is defined and, by multiplication, a time series of monetary purchases (without inflation) was calculated. In the WIFO.DYNK model the respective inflation rate is added which results in the expenses for new vehicles by private households in nominal terms, and purchaser prices per year. The endogenous equation in WIFO.DYNK is thus replaced with the exogenous value derived from the biophysical model and price assumptions.

6.1.2 WIFO.DYNK macroeconomic model

Model type

For the quantitative scenario analysis, the macroeconomic model WIFO.DYNK (Dynamic New Keynesian) for Austria was applied. The WIFO.DYNK is an extended Input-Output model and thereby a macroeconomic model covering the monetary flows of the Austrian Economy. The main features of this model are the integration of the physical flows of the Austrian energy balance in a Supply-Use Framework, the sophisticated private consumption module which also depicts rebound-effects, wage bargaining on the labor market and the detailed price system. The term 'New Keynesian' refers to the existence of a long-run full employment equilibrium, which will not be reached in the short run, due to institutional rigidities. A detailed description of the model can be found in Kirchner et al. (2019).

Model features & modifications

In this project several expansions and modifications of the original WIFO.DYNK model have been implemented.

Sector expansion: The core of the WIFO.DYNK model is based on the official Austrian Supply- and Use tables (SUT) and contains interdependencies of 74 industries (NACE[8] and CPA[9] 2008). The numbers of sectors and commodities was expanded from 74 to 90 sectors and updated to the latest available IOT, which was 2018 at the time of project start. A focus lies on the extraction of energy commodities and transport services. This allowed a more precise linking of CeAT inputs, for instance, the consumption of coal for heat energy[10], or road bound transport services[11].

[7] Prices for Vehicles in the base year 2018 were calibrated to the expenses for “Purchase of Vehicles” in the official Input-Output-Table of Austria. This led to 22.690 € per new conventional vehicle. It was assumed that vehicles with hybrid engines are 10% and electric cars 20% more expensive.

[8] NACE (for the French term "nomenclature statistique des activités économiques dans la Communauté européenne"), is the industry standard classification system used in the European Union.

[9] CPA product categories are related to activities as defined by the Statistical classification of economic activities in the European Community (NACE)

[10] In the standard IOT the coal products are within an aggregate that comprises products of oil and gas mining, and iron ore mining (CPA B05-07)

[11] In the standard IOT all land based transport services (including pipe bound transport) is aggregated in commodity CPA49

Consumption module: In specific areas a stock-flow approach is integrated in the WIFO.DYNK model. These areas are transport (vehicle stock) and housing (building and heat system stocks) where the flow (energy demand) depends on the usage of the stock and the stocks' energy efficiency. In this project however, the model has been modified in order to allow these endogenous developments to be set exogenously. Thereby, the results of the CeAT model can be used directly as an input in the WIFO.DYNK model. The physical results of CeAT are monetarized by using costs and prices per physical unit. For instance, the building of new dwelling areas (in m^2) is monetarized by multiplication with average costs in 2018. The costs change over time according to the respective inflation rate of goods necessary for building dwellings. For the purchase of new vehicles different prices were assumed. Electric vehicles are assumed to be 20% more expensive, hybrid vehicles 10%.

Disposable income: In WIFO.DYNK the consumption of private households comprises three main blocks. Durables (dwelling, vehicles, heating systems), energy commodities (coal, oil, gas, biomass, electricity, and district heating) and non-durables as food and health services for instance. Consumption of durables and energy is determined by the results of CeAT in this project. For the consumption of non-durables the gross disposable income is the most relevant factor in WIFO.DYNK. Here two modifications have been implemented in this project. First the calculation of the net disposable income which excludes the depreciation expenses of dwellings. This is in accordance with the official data on net disposable income[12]. The second modification is, then, that the net disposable income is driving the non-durable consumption – instead of gross disposable income. This is important in the context of this project because the scenarios simulate a sharp decline of private capital stocks (C), which means an increase in net disposable income that can be spent for other goods and services or saved.

Electricity: The WIFO.DYNK model has been expanded by an electricity generation module in a previous ACRP project START2030[13]. In this module the sector that represents public supply of electricity (NACE D35.1) is modeled in more detail and disaggregated in 11 economic sub-sectors representing ten energy generation technologies and a residual sector covering trade and distribution of electricity. The composition of technologies for each year is set exogenously. In this project the development of each technology is linked to the change of the physical power plant capacity mix (in MW) provided by CeAT. Additional (w.r.t. R1 scenario) investments in power plants and grids are monetarized using costs, and integrated as additional investments of the electricity supplying sector into the model.

Fixed savings rate of private households: The scenarios state a strong reduction in expenditures for dwellings and vehicles. It is assumed that the reduced expenditures in these stocks can be used for the consumption of other commodities and services. For this purpose, a feature has been introduced, namely a constant savings rate w.r.t. each year in the reference scenario. The money freed-up by lower debt and car repair expenses can be spent on a pre-defined set of commodities and services or saved. In this project two stylized sets are defined to assess possible rebound effects from CE assumptions. One comprising material-intense commodities typically bought by private households and one comprising services only (for details refer to 2.2.4.2.1).

[12] See non-financial sectoral accounts: https://ec.europa.eu/eurostat/databrowser/view/nasa_10_nf_tr/

[13] https://start2030.wifo.ac.at/

7 Referenzen

Austrian Energy Agency. (2011). *TABULA – Eine Typologie österreichischer Wohngebäude*.

Austrian Energy Agency. (2017). *Szenarien für Strom- und Fernwärme- aufbringung im Hinblick auf Klimaziele 2030 und 2050 Endbericht zu Strom und Fernwärme in den Szenarien „WEM" und „WAM plus"*.

BMK. (2021). *Mobilitätsmasterplan 2030 für Österreich*.

BMK. (2022). *Österreich auf dem Weg zu einer nachhaltigen und zirkulären Gesellschaft.* Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. https://www.bmk.gv.at/themen/klima_umwelt/abfall/Kreislaufwirtschaft/strategie.html

BMNT. (2019). *Integrierter nationaler Energie- und Klimaplan für Österreich—Periode 2021-2030* (p. 272). https://www.bmlrt.gv.at/dam/jcr:29ba927b-d36f-4cd4-8f56-8bec97a48c76/NEKP_final%2018.12.2019.pdf

BMVIT. (2013). *Radverkehr in Zahlen: Daten, Fakten und Stimmungen*. https://www.bmk.gv.at/themen/mobilitaet/fuss_radverkehr/publikationen/riz.html

BMVIT. (2016). *Österreich unterwegs 2013/2014. Ergebnisbericht zur österreichweiten Mobilitätserhebung "Österreich unterwegs 2013/2014."* Bundesministerium für Verkehr, Innovation und Technologie.

Brenner, A.-K., Haas, W., Krüger, T., Matej, S., Haberl, H., Schug, F., Wiedenhofer, D., Behnisch, M., Jaeger, J. A. G., & Pichler, M. (2024). What drives densification and sprawl in cities? A spatially explicit assessment for Vienna, between 1984 and 2018. *Land Use Policy*, *138*, 107037. https://doi.org/10.1016/j.landusepol.2023.107037

European Commission. (2020). *EU Transport in Figures 2020. Statistical Pocketbook* (Mobility and Transport). Publications Office of the European Union. https://data.europa.eu/data/datasets/eu-transport-in-figures-2020?locale=en

European Commission & Statistical Office of the European Union. (2018). *Circular material use rate: Calculation method: 2018 edition.* http://publications.europa.eu/publication/manifestation_identifier/PUB_KSGQ18013ENN

European Commission. Statistical Office of the European Union. (2018). *Economy-wide material flow accounts handbook: 2018 edition.* Publications Office. https://data.europa.eu/doi/10.2785/158567

Eurostat. (2013). *Economy-wide Material Flow Accounts (EW-MFA)—Compilation Guide 2013* (p. 87). Eurostat.

Eurostat. (2020a). *Material flow accounts (env_ac_mfa)* [dataset]. https://ec.europa.eu/eurostat/web/main/data/database

Eurostat. (2020b). *Waste generation and treatment (env_wasgt)* [dataset]. https://ec.europa.eu/eurostat/web/main/data/database

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., & Weisz, H. (2011). Methodology and Indicators of Economy-wide Material Flow Accounting: State of the Art and Reliability Across Sources. *Journal of Industrial Ecology*, *15*(6), 855–876. https://doi.org/10.1111/j.1530-9290.2011.00366.x

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/10.1111/jiec.12244

Haas, W., Krausmann, F., Wiedenhofer, D., Lauk, C., & Mayer, A. (2020). Spaceship earth's odyssey to a circular economy—A century long perspective. *Resources, Conservation and Recycling*, *163*, 105076. https://doi.org/10.1016/j.resconrec.2020.105076

Haas, W., Virág, D., Wiedenhofer, D., & von Blottnitz, H. (2023). *How Circular is an Extractive Economy? South Africa's Export Orientation Results in Low Circularity and Insufficient Societal Stocks for Service-Provisioning* (SSRN Scholarly Paper 4386062). https://doi.org/10.2139/ssrn.4386062

Habib, K., Hansdóttir, S. T., & Habib, H. (2020). Critical metals for electromobility: Global demand scenarios for passenger vehicles, 2015–2050. *Resources, Conservation and Recycling*, *154*, 104603. https://doi.org/10.1016/j.resconrec.2019.104603

Jacobi, N., Haas, W., Wiedenhofer, D., & Mayer, A. (2018). Providing an economy-wide monitoring framework for the circular economy in Austria: Status quo and challenges. *Resources, Conservation and Recycling*, *137*, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022

Kalt, G., Thunshirn, P., Krausmann, F., & Haberl, H. (2022). Material requirements of global electricity sector pathways to 2050 and associated greenhouse gas emissions. *Journal of Cleaner Production*, *358*, 132014. https://doi.org/10.1016/j.jclepro.2022.132014

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., & Haberl, H. (2021). Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus. *Resources, Conservation and Recycling*, *173*, 105723. https://doi.org/10.1016/j.resconrec.2021.105723

Kirchengast, G., Kromp-Kolb, H., Steininger, K., Stagl, S., Kirchner, M., Ambach, C., 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)*. Climate Change Centre Austria. https://ccca.ac.at/fileadmin/00_DokumenteHauptmenue/03_Aktivitaeten/UniNEtZ_SDG13/RefNEKP/Ref-NEKP_Gesamtdokument_PublVers-9.9.2019.pdf

Kranzl, L., Müller, A., Maia, I., Büchele, R., & Hartner, M. (2018). *Wärmezukunft 2050. Erfordernisse und Konsequenzen der Dekarbonisierung von Raumwärme und Warmwasserbereitstellung in Österreich*. TU Wien.

Krausmann, F., Weisz, H., Eisenmenger, N., Schütz, H., Haas, W., & Schaffartzik, A. (2015). *Economy-wide Material Flow Accounting Introduction and Guide*. Vienna: Institute of Social Ecology.

Lederer, J., Gassner, A., Keringer, F., Mollay, U., Schremmer, C., & Fellner, J. (2019). Material Flows and Stocks in the Urban Building Sector: A Case Study from Vienna for the Years 1990–2015. *Sustainability*, *12*(1), 300. https://doi.org/10.3390/su12010300

Martínez-Rocamora, A., Solís-Guzmán, J., & Marrero, M. (2016). LCA databases focused on construction materials: A review. *Renewable and Sustainable Energy Reviews*, *58*, 565–573. https://doi.org/10.1016/j.rser.2015.12.243

Maydl, P. (2013). *Möglichkeiten und Grenzen von Gebäudesanierungen auf Plusenergiehausstandard Know-How-Plus*. BMVIT.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2019). Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. *Journal of Industrial Ecology*, *23*(1), 62–76. https://doi.org/10.1111/jiec.12809

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, 104553. https://doi.org/10.1016/j.resconrec.2019.104553 österreich.gv.at. (2024). *"raus aus Öl und Gas" 2023/2024*. https://www.oesterreich.gv.at/themen/umwelt_und_klima/energie_und_ressourcen_sparen/1/raus_aus_oel.html

Österreichisches Institut für Bautechnik. (2007). *OIB-Richtlinien 2007*. https://www.oib.or.at/de/oib-richtlinien/richtlinien/2007

Österreichisches Institut für Bautechnik. (2019). *OIB-Richtlinien 2019*. https://www.oib.or.at/oib-richtlinien/richtlinien/2019

Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). Circular Economy: Measuring Innovation in the Product Chain. *Planbureau Voor de Leefomgeving*, *2544*. https://dspace.library.uu.nl/handle/1874/358310

Schienen Control. (2015). *Jahresbericht 2015*. https://www.schienencontrol.gv.at/de/Archiv.html?file=files/1-Homepage-Schienen-Control/1f-Publikationen/

Schiman-Vukan, S., & Ederer, S. (2023). *WIFO Konjunkturprognose 3/2023, Kaufkraft steigt nach milder Rezession. Prognose für 2023 und 2024*. Österreichisches Institut für Wirtschaftsforschung.

Schulter, D. (2013). *Nachhaltige Gebäudesanierung durch lebenszyklusorientierte Bauproduktauswahl*.

Statistik Austria. (2011). *Registerzählung 2011*.

Statistik Austria. (2020a). *Kfz-Bestand* [dataset]. https://www.statistik.at/statistiken/tourismus-und-verkehr/fahrzeuge/kfz-bestand

Statistik Austria. (2020b). *Wohnungs- und Gebäudeerrichtung – Fertigstellungen* [dataset]. https://www.statistik.at/web_de/statistiken/menschen_und_gesellschaft/wohnen/wohnungs_und_gebaeudeerrichtung/fertigstellungen/index.html

Statistik Austria. (2020c). *Haushaltsprognosen*. https://www.statistik.at/statistiken/bevoelkerung-und-soziales/bevoelkerung/familien-haushalte-lebensformen/haushaltsprognosen

UBA. (2016). *Szenario erneuerbare Energie 2030 und 2050.* (REP-0576). Umweltbundesamt. https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0576.pdf

UBA. (2021). *GHG Projections and Assessment of Policies and Measures in Austria* (REP-0766). Umweltbundesamt. https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0766.pdf

UBA. (2023a). *Energie- und Treibhausgasszenarien 2023: WEM, WAM und Transition mit Zeitreihen von 2020 bis 2050* (REP-0882). Umweltbundesamt. https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0882.pdf

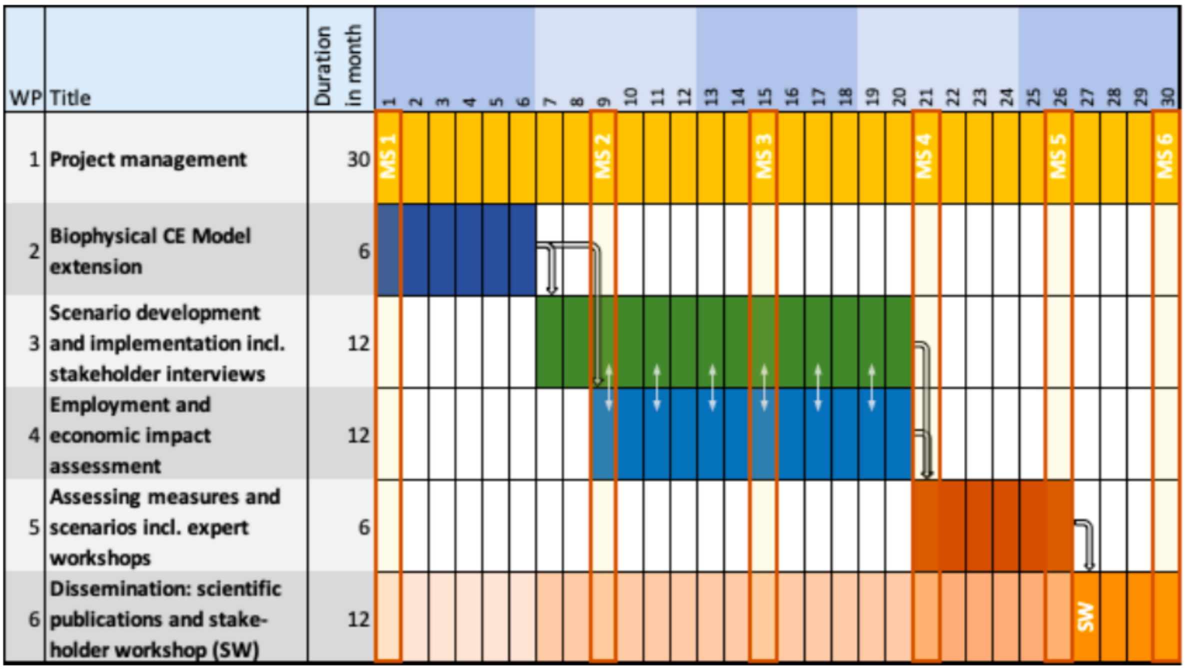
UBA. (2023b). *GHG Projections and Assessment of Policies and Measures in Austria*. Umweltbundesamt.

VCÖ. (2020). *Bereits mehr als 750.000 E-Fahrräder in Österreich – E-Fahrräder klarer Spitzenreiter unter den E-Fahrzeugen*. https://www.vcoe.at/presse/presseaussendungen/detail/vcoe-bereits-mehr-als-750-000-e-fahrraeder-in-oesterreich-e-fahrraeder-klarer-spitzenreiter-unter-den-e-fahrzeugen

Virág, D., Wiedenhofer, D., Baumgart, A., Matej, S., Krausmann, F., Min, J., Rao, N. D., & Haberl, H. (2022). How much infrastructure is required to support decent mobility for all? An exploratory assessment. *Ecological Economics*, 14. https://doi.org/10.1016/j.ecolecon.2022.107511

Wiedenhofer, D., Baumgart, A., Matej, S., Virág, D., Kalt, G., Lanau, M., Tingley, D. D., Liu, Z., Guo, J., Tanikawa, H., & Haberl, H. (2024). Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions. *Journal of Cleaner Production*, *434*, 139742. https://doi.org/10.1016/j.jclepro.2023.139742

8 Work and time schedule



9 Publications and dissemination activities

Published journal articles

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., & Haberl, H. (2021). Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus. *Resources, Conservation and Recycling*, *173*, 105723. https://doi.org/10.1016/j.resconrec.2021.105723

Journal articles in preparation

Haas, W. et al. (in preparation). Reaching decarbonisation targets and a low material footprint in Austria: What circular economy strategies can yield.

Baumgart, A. et al. (in preparation). Evaluating the impact of different CE strategies

on future bulk and scarce material demand in Austria

Sommer, M. et al. (in preparation) Economic paper to be submitted to Ecological Economics laying out the project results

Other publications

- Eisenmenger, N., Haas, W., Baumgart, A. (forthcoming). Ressourcennutzung in Österreich 2024. Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. Vienna, Austria.
- Haas, W. & Dorninger, C. (forthcoming). Wir verbrauchen in Österreich zu viele Ressourcen und Energie. In: 'Von allem genug, von nichts zu wenig'. 'Ökobüro' and 'Armutskonferenz' (eds.)
- Meyer et al., conference paper to be submitted to the International Energy Workshop in Bonn, Germany, due on 1st February 2024, accepted
- Planned publication in WIFO monthly reports ('WIFO Monatsberichte') in June 2024

Oral presentations

Haas, W. (2021). *Mit der Kreislaufwirtschaft zu Degrowth: Vision oder Illusion?* Diskussionsreihe an der Arbeiterkammer: Degrowth: Zukunftspfad oder Illusion?. 24.3.2021, Online.

Haas, W. (2021). *Mehr Recycling macht noch keine Kreislaufwirtschaft. Welche Kicks braucht eine Kreislaufschließung?* Österreichische Re-Use Konferenz 2021: Textilien & Kreislaufwirtschaft. Perspektiven – Potenziale – Strategien. 19.5.2021, Online.

Haas, W. (2021). *Photovoltaik in der Kreislaufwirtschaft: Fallstricke und Potenziale.* Österreichische Fachtagung für Photovoltaik und Stromspeicherung 2021. 13.-14.10.2021, Wien, Austria.

Haas, W., Baumgart, A., Virág, D., Eisenmenger, N. (2022). *Die Vermessung der Kreislaufwirtschaft: Voraussetzung für ein kluges Ressourcenmanagement*. Circular Economy Summit Austria. 22.3.2022, Vienna, Austria.

Klingholz, R., Haas, W. (2022). *Zu viel für diese Welt. Wie vorsorgliches Handeln künftig gehen kann und muss*. Internationales Symposium: Kindheit, Jugend & Gesellschaft X mit Fachforum jung&initiativ. 27.-29.4.2022, Bregenz, Austria.

Haas, W., Baumgart, A., Eisenmenger, N., Virág, D., Meyer, I., Sommer, M., Kratena, K. (2022). *ACeDC - Austrian Circular Economy and Decarbonisation: Synergies and trade-offs.* [Poster]. 22. Österreichischer Klimatag: Pushing Boundaries: Wissenschaft, Kunst, Klima. 20.4.2022, Vienna, Austria.

Haas, W., Baumgart, A., Eisenmenger, N., Virág, D., Meyer, I., Sommer, M., Kalt, G., Kratena, K. (2022). *How decarbonizing Austria till 2040 alters the societal metabolism and what reductions CE-strategies can yield*. 14th International Society of Industrial Ecology Socio-Economic Metabolism section conference. 19.-21.9.2022, Vienna, Austria.

Haas, W. (2022). *Vom neuen Umgang mit alten Dingen*. re:pair festival. 4.11.2022, Wien, Austria.

Haas, W., Baumgart, A., Eisenmenger, N., Virág, D., Meyer, I., Sommer, M., Naqvi, A., Kalt, G., Kratena, K. (2023). *Gegenwart und Zukunft des Ressourcenverbrauchs in Österreich.* AG Rohstoffe: "Wieviel Stoff braucht unser Wohlstand?". 27.1.2023, Vienna, Austria.

Haas, W. (2023). *Österreich: Dekarbonisierung und Kreislaufwirtschaft - Synergien, Trade-Offs und Herausforderungen*. Wachstum im Wandel - Frühstück des Bundesministeriums für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. 20.4.2023, Wien, Austria.

Eisenmenger, N. (2023). *Mit der Ressourcenwende in eine klimaneutrale und lebenswerte Zukunft für alle*. 5. Nationales Ressourcenforum: Vision 2050. Wie wir die Ressourcenwende schaffen. 2.-3.5.2023, Salzburg, Austria.

Baumgart, A., Haas, W., Virág, D., Eisenmenger, N., Meyer, I., Sommer, M., Kalt, G., Kratena, K. (2023). *Evaluating the impact of different CE strategies on future bulk and scarce material demand in Austria.* 11th International Conference on Industrial Ecology. 2.-5.7.2023, Leiden, Netherlands.

Virág, D., Haas, W., Baumgart, A., Eisenmenger, N., Meyer, I., Sommer, M., Naqvi, A., Kalt, G., Kratena, K. (2023). *Dekarbonisierung und Ressourcenschonung. Kann Circular*

Economy beides erreichen? Eine Modellierung für Österreich. Netzwerktreffen Ressourcenwende. 22.6.2023, Vienna, Austria.

Haas, W., Baumgart, A., Eisenmenger, N., Virág, D., Meyer, I., Sommer, M., Kratena, K. (2023). *A stock-flow analysis of Austria's housing system: Historic patterns and futures scenarios*. 6th Foundational Economy Conference Vienna: Exploring the Foundational Economy for a Just Transition. 14.-16.9.2023, Vienna, Austria.

Sommer, M., Haas, W., Meyer, I., Baumgart, A., Eisenmenger, N., Virág, D., Kratena, K. (2023). *The combined economic effects of decarbonization and circular economy*. 6th Foundational Economy Conference Vienna: Exploring the Foundational Economy for a Just Transition. 14.-16.9.2023, Vienna, Austria.

Haas, W. (2023). *Wie viel Stoff braucht unser Wohlstand? Gegenwart und Zukunft unseres Ressourcenverbrauchs*. Raiffeisen Nachhaltigkeitssymposium: Infrastruktur der Zukunft. 16.-17.11.2023, Vienna, Austria.

Diese Projektbeschreibung wurde von der Fördernehmerin/dem Fördernehmer erstellt. Für die Richtigkeit, Vollständigkeit und Aktualität der Inhalte sowie die barrierefreie Gestaltung der Projektbeschreibung, übernimmt der Klima- und Energiefonds keine Haftung.

Die Fördernehmerin/der Fördernehmer erklärt mit Übermittlung der Projektbeschreibung ausdrücklich über die Rechte am bereitgestellten Bildmaterial frei zu verfügen und dem Klima- und Energiefonds das unentgeltliche, nicht exklusive, zeitlich und örtlich unbeschränkte sowie unwiderrufliche Recht einräumen zu können, das Bildmaterial auf jede bekannte und zukünftig bekanntwerdende Verwertungsart zu nutzen. Für den Fall einer Inanspruchnahme des Klima- und Energiefonds durch Dritte, die die Rechtinhaberschaft am Bildmaterial behaupten, verpflichtet sich die Fördernehmerin/der Fördernehmer den Klima- und Energiefonds vollumfänglich schad- und klaglos zu halten.