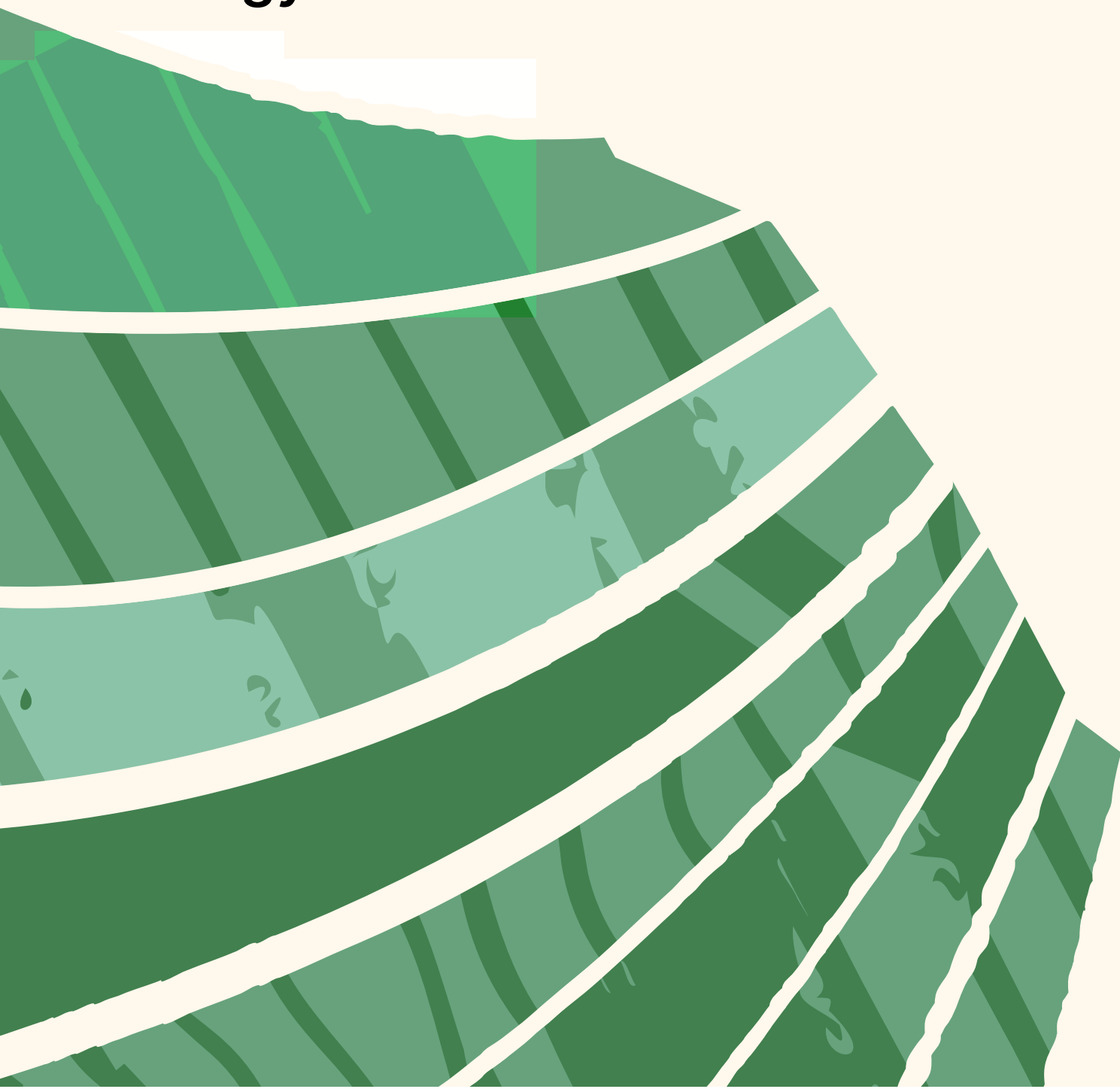


## Chapter 4

# Provision of goods and services in a climate-resilient economy via materials, energy and work



# Second Austrian Assessment Report on Climate Change | AAR2

## Chapter 4

### Provision of goods and services in a climate-resilient economy via materials, energy and work

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## EXECUTIVE SUMMARY

Several mitigation pathways are available after 2030 to reach net-zero CO<sub>2</sub>eq emissions in 2040 (*medium evidence, high agreement*). First, it is evident that the infrastructure necessary for energy storage, grids, and public transport will differ from the current infrastructure. This implies the need for swift and determined decisions today so that the necessary infrastructure is available in time, given the considerable construction time for energy and rail infrastructure. Second, the discrepancy in energy service demand, industrial output, and energy efficiency measures causes a large range of primary energy use (237–337 TWh) across the scenarios, underscoring the significance of measures reducing demand. Third, energy import dependency varies considerably (5–39 %). Fourth, wind power and solar PV constitute the backbone of the power sector in all scenarios, satisfying demand, but the respective shares differ (wind: 5–25 %; PV: 6–20 % of gross domestic consumption). Fifth, biomass remains a highly important resource in the energy sector, but to varying degrees (ranging from 14–28 % of gross domestic consumption). {4.4, 4.5}

Unabated fossil liquid fuels and gases are partly substituted by varying amounts of biogenic fuels, synthetic fuels and fossil fuels with CCS in 2040 in the scenarios (*medium evidence, high agreement*). While electrification is the most cost-effective mitigation technology in many applications, there is still a substantial need for carbon-neutral fuels and gases in 2040. Their use ranges from 91–156 TWh in 2040. These fuels are mainly used in industry (35–59 % of all liquid fuels, and gas, and solid use), in transport (8–33 %), in households, services and agriculture (20–34 %) and in power generation and district heating (4–21 %). Legacy effects cause the continued use of fossil fuels or the build-up of synthetic fuel use in land transport and heating. Due to delayed action in these sectors, a significant stock of assets based on liquids or gases may remain, causing the costly and inefficient use of these fuels in sectors where electrification could provide emission reductions at lower cost. As an example, a high proportion of liquid fuels in the transport sector will only be necessary if the electrification of land transport remains at its current low level. Sensitivity scenarios show that the phase-out of internal combustion engines in land transport is crucial if climate neutrality is to be achieved quickly. Efficient scenarios show that liquid fuels are only used for aviation and shipping, and that, after overcoming the legacy of the past, no liquid fuels or gases are used for heating. {4.4, 4.5}

The Austrian economy is already at risk due to climate change related impacts. Future climate change as well as socioeconomic development will further intensify these impacts (*limited evidence, high agreement*). International studies provide quantitative climate change impact assessments at national and supranational levels. Subnational and sector-specific assessments are rare, but needed to broaden the evidence base for potential climate change-related impacts in Austria, focusing on the Austrian energy generation and transmission infrastructure, services and industrial sectors. {4.3.3, 4.5.2}

Current provisioning of goods and services is a key driver for high levels of energy and material demand and thus domestic and upstream greenhouse gas emissions (*high confidence*). The Austrian economy rests on growing infrastructure and building stocks to provide services in transport, housing, communication, and finance (*high confidence*). The continued accumulation of infrastructure and buildings and the increased service and activity levels have largely offset technological efficiency gains and inhibited structural shifts towards a service economy (*high confidence*). {4.2.1}

A needs-oriented circular economy that focuses on reducing energy and material use through optimized space and building use, improved spatial planning that halts urban sprawl, shifting motorized private transport to public and active modes of transport, sharing, eco-design, increasing durability, reuse, and repair provides multiple benefits (*high confidence*). Shifting from material-intensive production and construction processes to services (e.g., rental, sharing) has the potential to avoid rebound effects and increase value-added and employment (*medium confidence*). The provisioning of goods and services thereby can become significantly more climate-friendly and -resilient while maintaining high levels of service quality and well-being (*high confidence*). {4.2.2}

Achieving a net-zero-emissions and resilient provisioning system requires changes at multiple levels: End-use technologies, the infrastructures that underpin everyday life, and in the local provisioning systems that shape people's modes of living (*high confidence*). Important decarbonization technologies such as electric vehicles and photovoltaics increase demand for electricity and critical raw materials, which need to be compensated by energy and material ef-

efficiency measures that reduce both the volume of material stocks in use and their energy requirements (*high confidence*). This aids decarbonization across all sectors, reduces dependencies on critical raw materials, reduces land consumption, and aligns with the government's circular economy targets (*medium evidence, high agreement*). {4.2.3}

**Tourism is of high economic significance for Austria and is associated with substantial emissions (*high confidence*).** With about 4.15 % of CO<sub>2</sub> emissions in Austria originating from tourism, and up to 34.1 % when transport-related emissions between origin and destination of foreign and domestic visitors to Austria are included, the sector is a relevant driver of emissions (*medium confidence*). Due to the economic significance of tourism in Austria (7.5 % of GDP in 2019), tourism is an important sector to be considered on the path to a carbon-neutral economy (*high confidence*). {4.3.2}

**The impacts of climate change will substantially alter some of the supply and demand in the tourism sector (*high confidence*).** Changing overall climate conditions (e.g., increase in average temperatures, shift in precipitation, shorter snow cover duration) and increasing extreme weather events (e.g., number of heat days, precipitation intensity, storm frequencies/intensity) will change the supply conditions for tourism services and thus require an adaptation of tourism (*high confidence*). The adjustment will need to take place along several dimensions and include seasonal adjustment of supply and demand, changes in the type of products offered and a reduction in the frequency of travel combined with longer stays (*high confidence*). {4.3.3}

**A modal shift to public transport and the greening of the destination transport systems are key in mitigating emissions in tourism (*high confidence*).** The largest share (75 %) of global total tourism-induced greenhouse gas (GHG) emissions is generated by transport to, from and at the destination (mostly by air and road) (*high confidence*). In Austria, too, the single most important source of GHG emissions related to tourism is personal transport, which makes up 92.2 % of the sector's GHG emissions (*medium confidence*). Consequently, to reduce tourism-related GHG emissions, a higher share of transport to and from as well as at the destination must be carried out by trains and busses and, as public transport capacities are limited, in particular in sub-urban and rural regions, by low (zero-) emission private vehicles (*high confidence*). {4.3.4}

**The industry and manufacturing sector is particularly emission intensive, contributing 18 % to GDP and 35 % (26 MtCO<sub>2</sub>eq) to emissions in 2020 (*high confidence*).** Emissions are highly concentrated in the iron and steel, chemicals, pulp and paper, and non-metallic minerals industries, which account for 82 % (21 Mt) of the sector's and 29 % of national emissions. From 2014–2020 emissions of this sector fell by 1 % per year, while value added has grown by a rate of 2 % per year (*high confidence*). {4.4.1}

**Many technological options are already available to support the defossilization of Austria's industry and manufacturing sector, but key technologies such as hydrogen-based steelmaking and the integration of CCUS require further research and development. Future systems will heavily rely on electricity; thus, the availability of low-carbon electricity is key to prevent outsourcing emissions to the energy sector (*high confidence*).** If current production levels are maintained, electricity demand for the direct use in emission-intensive industries will more than double (*high confidence*). {4.4.2}

**The defossilization of industry and manufacturing requires an integrated and coordinated economy-wide strategy, as individual incremental improvements are insufficient (*high confidence*).** In addition to sufficiency measures (avoid), the key levers are fuel switching (shift), energy/material efficiency and carbon capture (improve). These changes involve new investments and will generate major new challenges, such as securing sufficient renewable energy supply and restructuring global value chains (*medium confidence*). {4.4.4}

**The Austrian energy system is mainly based on fossil fuels and is a large emitter of greenhouse gas emissions (*high confidence*).** The Austrian energy system (serving various economic sectors) was responsible for 70 % (44.5 MtCO<sub>2</sub>eq) of all greenhouse gas emissions in Austria in 2023 and fossil fuels had a share of 62 % in energy supply. A major share of fossil fuels is imported (96 % in 2023), implying a high import dependency in terms of primary energy. {4.5.1}

**A carbon-neutral and climate-resilient energy system is electrified, hosts high shares of renewables, and is prepared for climate change impacts to maintain system security (*medium evidence, high agreement*).** A future carbon-neutral energy system will show significantly higher shares of electricity in end use and larger shares of renew-

ables (*medium evidence, high agreement*), but many different technology mixes allow carbon neutrality to be achieved, e.g., focusing on wind power or on solar PV, or allowing for higher shares of carbon capture and storage versus using green hydrogen (*medium evidence, high agreement*). Systems with high shares of wind and/or solar PV will have a higher degree of exposure and vulnerability to weather-related variability and hazards (*limited evidence, medium agreement*). Therefore, the design of energy systems needs to consider long-term climate trends in addition to weather variability, exposure, and vulnerability to reduce future risks (*limited evidence, medium agreement*). {4.5.2}

**The net costs of transitioning to a carbon-neutral energy system are low to negative (*limited evidence, medium agreement*), most of the necessary technologies are available, and there are in principle sufficient land resources for most pathways to successfully transition to a carbon-neutral energy system (*medium confidence*).** However, major barriers in terms of infrastructure development, including flexibility options to balance intermittent renewable supply and coupling energy-demanding sectors, policy design, technology acceptance and supply-chain bottlenecks, need to be overcome to implement a carbon-neutral energy system (*medium evidence, high agreement*). In all scenarios, import dependency on energy carriers is reduced, but reductions vary and depend on assumptions about the development of energy demand, in particular in the industrial sector, on assumptions about domestic renewable energy potential and on the expansion of fossil fuels with carbon capture and storage. {4.5.3}

**Carbon Capture, Utilization, and Storage (CCUS) technology chains are mature and can be employed to bind CO<sub>2</sub> and thus prevent the release of emissions into the atmosphere (*high confidence*).** CCUS refers to technology chains for reducing CO<sub>2</sub> emissions on a relevant scale through geological storage underground or through utilization in industrial processes and products. While geological CO<sub>2</sub> storage (CCS) is a large-scale and permanent-reduction option, CO<sub>2</sub> utilization (CCU) is limited by demand and final product lifetime. {4.6.1}

**During the transition to a climate-neutral society, especially regarding hard-to-abate industrial emissions, CCUS will play a crucial role in decarbonizing the Austrian economy (*high confidence*).** CCUS can enable emission-critical industries in Austria to achieve CO<sub>2</sub> reduction goals. This requires

a national and European transportation network of CO<sub>2</sub> sources and sinks. Combined with bioenergy and direct air capture, geological CO<sub>2</sub> storage can contribute to achieving negative emissions (Carbon Dioxide Removal, CDR) (*medium confidence*). Mineral carbonation and closed CO<sub>2</sub> utilization loops can contribute to the CO<sub>2</sub> reduction goals in the transition to climate neutrality (*medium confidence*). CCUS also comes with new challenges, as it is energy and water intensive and puts pressure on the supply systems. {4.6.2}

**The development of CCUS in Austria requires overcoming geological, technological, and societal challenges (*high confidence*).** Using the geological subsurface for permanent storage requires public acceptance based on relevant information and a broad societal consensus. Technological feasibility requires that CO<sub>2</sub> emitters and sinks are connected by a transport network, that geological fields are developed while minimizing risks, and that innovative solutions for utilizing CO<sub>2</sub> are found that permanently remove CO<sub>2</sub>. With Austria's estimated capacity, CCUS can contribute to national decarbonization on a relevant scale (*high confidence*). {4.6.3}

**Work, including unpaid care and paid employment, dominates daily life in Austria, and the structural dependence of persons and welfare systems on paid work currently tends to impede climate-neutral provisioning as well as climate-friendly living (*high confidence*).** High-productive, energy-intensive work is well-paid and structurally linked to low-productive, energy-light, unpaid or low-paid, very essential work (including care) (*limited evidence, medium agreement*). The work-mode of living poses a structural barrier for climate-friendly mobility, food, housing and leisure practices, and encourages energy- and fossil-fuel-intensive practices (*medium confidence*). 46 % of Austrians believe that their current job does not contribute to the green transition (*limited evidence, high agreement*). {4.7.1}

**A transition to a climate-friendly society will end the requirement for greenhouse gas emissions from paid employment or unpaid care (*limited evidence, high agreement*).** The greening and sharing of paid employment and unpaid care will ensure a high quality of life, good work and climate-friendly living, work-life balance and adequate provisioning of care (*medium confidence*). Under the current business-as-usual scenario, work will be severely affected by the unfolding of the climate crisis, requiring sectoral shifts towards the provisioning of basic goods such as health, care, food, and housing (*limited evidence, medium agreement*). {4.7.2}

To avoid climate-damaging production and to overcome labor supply constraints, climate-friendly regulation of labor markets can enable a shift from excess production to climate-friendly provision of essential services (*medium confidence*). A redistribution of paid work and unpaid care and the relocation of jobs to people's living place through eco-

nomic and labor market policies, can enable climate-friendly work-life patterns (*medium confidence*). More equal distribution of wealth and income, job guarantee and public provision of basic goods (e.g., housing, food and health care) can increase economic security and thus enable green labor market transformations (*medium confidence*). {4.7.3}

## 4.1. Chapter introduction

Chapter 4 of the AAR2 discusses the role of the Austrian economy in a climate-neutral ‘Provisioning System’, with the objective of satisfying anticipated human needs and fostering human well-being (see, e.g., Fanning et al., 2020). In conjunction with the Avoid-Shift-Improve framework (see [Cross-Chapter Box 4](#)), this demand and service-provisioning perspective (see [Cross-Chapter Box 3](#)) allows to identify leverage points, such as a Circular Economy (see [Cross-Chapter Box 5](#)), to achieve a climate-neutral and low material footprint economy along the resource conversion chain.

### 4.1.1. The provisioning system

Here, in Chapter 4, we focus on the provision of goods and services (capital and consumer goods and from other sectors including tourism) and of energy to meet diverse human needs. [Figure 4.1](#) illustrates this understanding of the economy as a provisioning system and how specific elements of it are represented in the AAR2. The provisioning system is

embedded in the broader societal sphere and fulfills the ultimate goal of satisfying human needs and thereby generating human well-being, which requires appropriate governance and financial arrangements. The provision of goods and services, for example through manufacturing processes, involves a certain demand for resources (for materials, energy, and work). In doing so, the provisioning system interacts closely with the ecological sphere through the demand for natural resources and as a source of greenhouse gas (GHG) emissions (with mitigation potential through Carbon Capture Storage and Utilization, CCS/CCU, see [Section 4.6](#)) and other pollution and impacts on ecosystem health (which plays a key role in land-based Carbon Dioxide Removal, CDR, see [Cross-Chapter Box 4](#)). In addition, the provisioning system is affected by climate and global change, presenting opportunities and challenges for adaptation to climate change.

Other chapters of the AAR2 discuss other aspects of the Austrian provisioning system in the context of a climate neutral economy, in particular [Chapter 2](#) (agriculture, land use, ecosystem services) and [Chapter 3](#) (buildings and mobility), [Chapter 5](#) (human needs and wellbeing and individ-

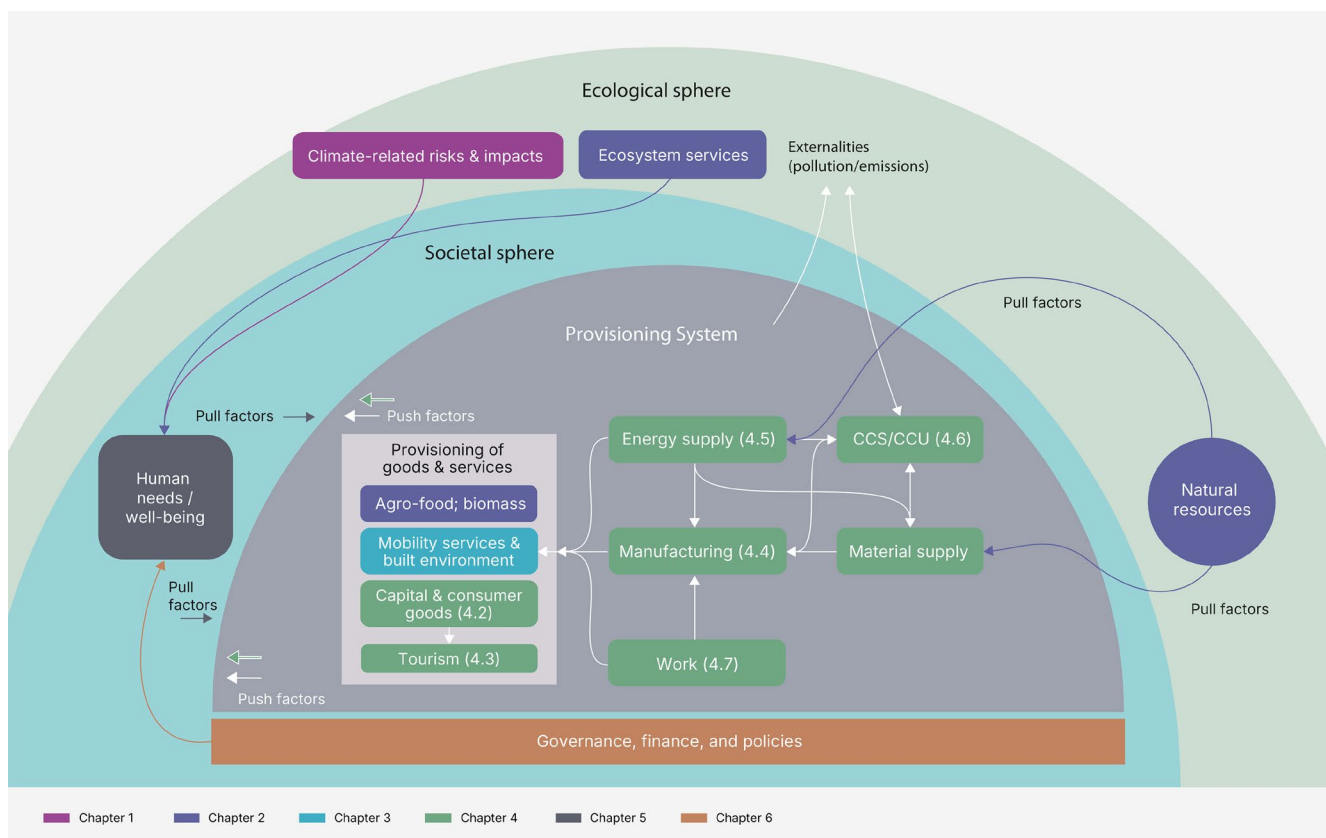


Figure 4.1 The economy as a 'Provisioning System' as represented in the AAR2.

ual decision making at household and company level) and Chapter 6 (governance, finance and policy).

After a brief presentation of Austria's historical GHG emissions at the sectoral level (Section 4.1.2), the provisioning of goods and services (Section 4.2) is the starting point of this chapter. As tourism is an important sector within the Austrian economy, we assess tourism as a driver of climate change but also as a highly affected sector, with significant adaptation needs in the future (Section 4.3). We assess the industrial and manufacturing sectors that provide goods and services for final demand (Section 4.4), with a particular focus on Austria's hard-to-abate industrial sectors and the opportunities and challenges of a more circular economy for material supply. In addition, we assess the scientific evidence on energy supply (Section 4.5) and focus on decarbonization through the storage and use of CO<sub>2</sub> from carbon-intensive industries (Section 4.6). We also review the literature

on the framework conditions for work, which are not only shaped by economic development, but are also crucial for the development of low-carbon pathways in production and consumption. Both paid work and unpaid but socially necessary work and activities are important for climate-friendly livelihoods (Section 4.7). Each of these sub-chapters reflects on the respective status quo, the constitution of a potential future climate-resilient and carbon-neutral sub-system, and the transformations needed to get there.

### 4.1.2. Sectoral emissions

GHG emissions in Austria have been fairly stable over the last five decades at 80 MtCO<sub>2</sub>eq/yr, excluding sinks such as land-use, land-use change and forestry (LULUCF). Looking at Austrian sectoral emissions, the transport sector and industry are the largest contributors, with the latter's emissions

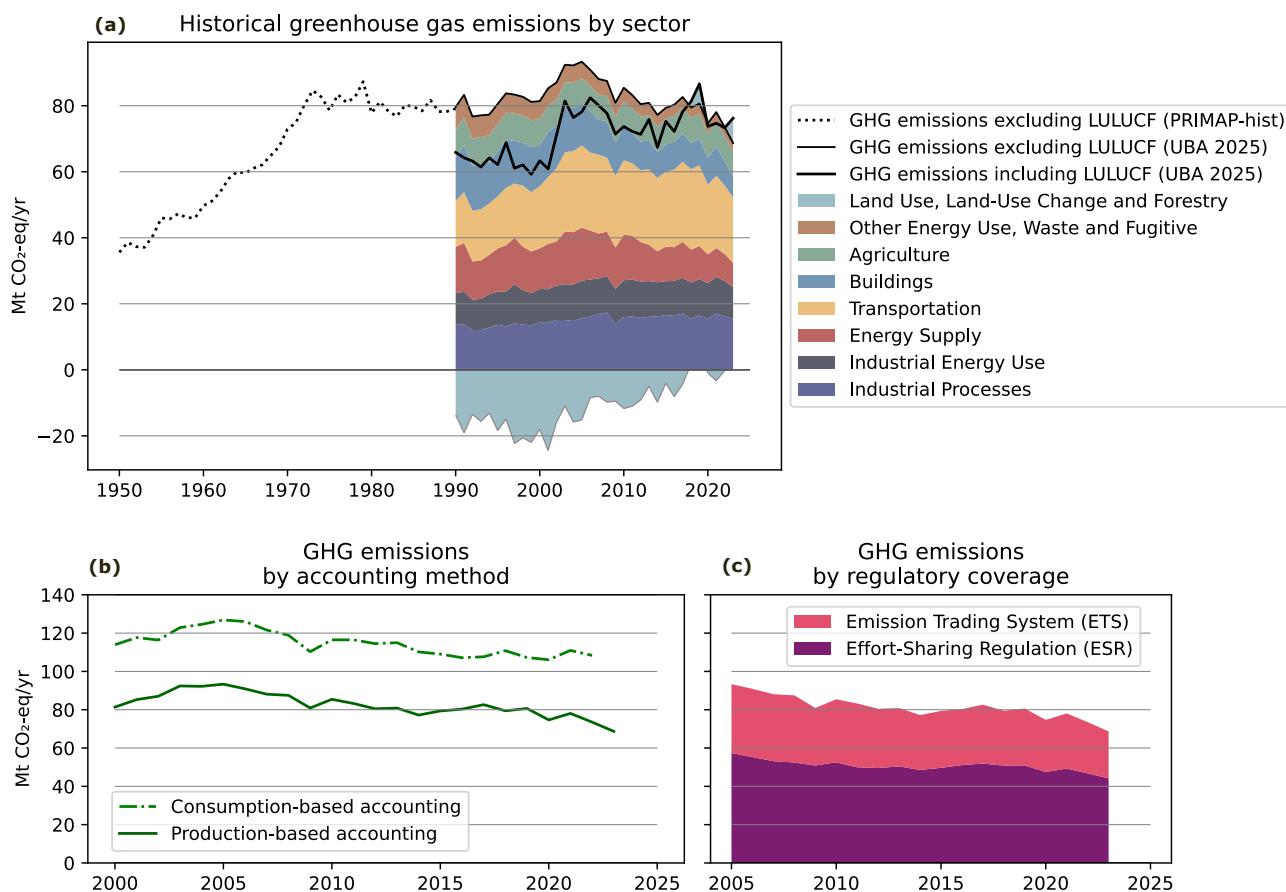


**Figure 4.2** Panel (a) Greenhouse gas emissions in Austria by sector (production-based accounting) since 1990 (Umweltbundesamt, 2025) (solid thick line including LULUCF; solid thin line excluding LULUCF; GHG emissions excluding LULUCF since 1950 (dotted line, Gütschow et al., 2016, 2024). Panel (b) Production- vs. consumption-based accounting of GHG emissions excluding sources and sinks from LULUCF (Dörninger et al., 2025). Panel (c) GHG emissions in Austria by regulatory coverage, excluding sources and sinks from LULUCF (Umweltbundesamt, 2024c, 2025). The reference data shown in this figure is available at [aar2.ccca.ac.at/explorer](http://aar2.ccca.ac.at/explorer).

split into those from industrial processes (the larger share) and those from energy use in industry (Figure 4.2).

When carbon emissions are adjusted for emissions associated with foreign trade in goods and services, Austrian imports are much more carbon-intensive than Austrian exports, making these so-called ‘consumption-based’ emissions about 50 % higher than the emissions generated within Austrian borders, so-called ‘territorial’ or ‘production-based’ emissions. Per-capita emissions in Austria are 10 % higher than the EU27 average and more than 50 % higher than the global average (Ritchie et al., 2024).

Only the last few years show a noticeable decrease in GHG emissions (Nowcast 2024, Umweltbundesamt, 2024b). This reduction of emissions was at first mainly due to effects of the COVID-19 pandemic-induced lockdowns, and in 2022 and 2023 due to a combination of the fossil fuel price increases due to the war of aggression by Russia against Ukraine and climate policy measures by the Austrian government (see Chapter 6) (Eibinger et al., 2024).

## 4.2. Provisioning of goods and services

This section considers the GHG intensity and climate resilience of the goods and services provided to meet individual and societal needs. Provisioning systems define the range of options available to individuals to meet their needs and thus have a significant influence on the adopted technologies, daily routines, and lifestyles (Plank et al., 2021b; Wieser and Kaufmann, 2023). The provisioning of goods and services contributes to well-being, but it requires both human labor and material stocks such as buildings, transportation infrastructure, and the energy production system, the expansion and maintenance of which can consume large amounts of energy (i.e., fossil fuels) and materials. In addition, access to services, such as thermal comfort in a living space or access to a particular destination, generally requires energy (Haberl, 2018; Kalt et al., 2019).

The goods and services that are made available for final consumption and use, and the way in which they are provided, thus have a major impact on resource demand and the climate footprint of a society. Furthermore, goods and services are essential for meeting needs that are distributed across space, time, and society (Chapter 5). Transforming goods and services to be climate-neutral and adapting them to changing climate conditions is therefore critical to ensuring adequate levels of service for all. In addition to decarbonization measures in ‘supply-side’ energy and manu-

facturing systems, which will be discussed below, changes in the volume (avoid), composition (shift), and quality (improve) of goods and services offer a wide range of options for ‘demand-side’ reductions in GHG emissions (Creutzig et al., 2022b) (see Cross-Chapter Box 4).

### 4.2.1. Status quo in the provisioning of goods and services

Material flow analyses provide a comprehensive overview of the number of resources that have to be extracted each year for the provisioning of goods and services. In Austria, the annual demand for processed materials amounts to 242 Mt, of which 51.2 % are extracted domestically, 40.5 % are imported, and 8.3 % are derived from secondary materials (see Figure 4.3) (BMK, 2024b). Nearly half of these processed materials (46 %) are used for durable goods and infrastructures, following their continued expansion in the recent decades (Jacobi et al., 2018; Wiedenhofer et al., 2021; Schug et al., 2023). The processed materials consist of 74 Mt of biomass, 27 Mt of metals (incl. extractive waste), 105 Mt of non-metallic minerals, and 37 Mt of fossil energy carriers. The expansion, replacement, and maintenance of the *built environment* in particular has become a major source of material demand (101 Mt), overshadowing the material requirements for technical equipment (4 Mt), transport vehicles (3 Mt), and non-technical products (3 Mt) used by households and firms. Today, the total mass of infrastructures and buildings in Austria is estimated at 540 t/capita, compared to 450 t/capita in Germany (Haberl et al., 2021), and per capita stocks are particularly high in sparsely populated areas (Schug et al., 2023). Important drivers of the expansion of infrastructures and buildings include the growth of the service economy (Deetman et al., 2021; Plank et al., 2021b), their significance for contemporary financial investments (Schaffartzik et al., 2021; Pineault, 2023; Wieser et al., 2023), and spatial development (see Chapter 3).

Increasing material demand for building and maintaining materials stocks (Wiedenhofer et al., 2021; Schug et al., 2023) and high growth rates in some service sectors (especially real estate, information and communication technologies, finance) (Plank et al., 2021b) have largely offset positive contributions to the decarbonization of provisioning systems made possible by structural shifts towards a more service-oriented economy. As a result, the total material footprint decreased only marginally between 2000 and 2015 in Austria (Plank et al., 2021b). A study found that out of 11 high-income countries that were able to reduce consump-

## Austria 2020

Material flows in Mt

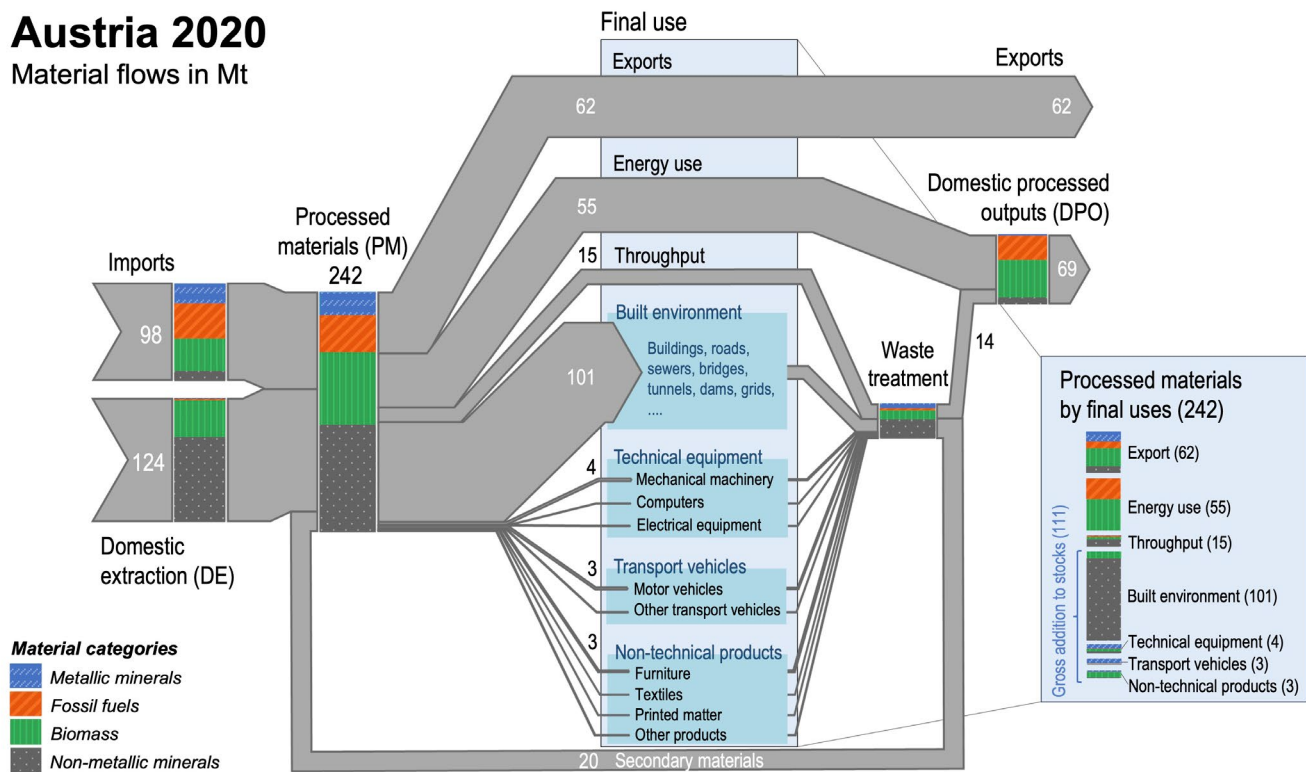


**Figure 4.3** The material flows through the economy of Austria from inputs (extraction and imports) to final use (stock building) to outflows of exports and domestic processed outputs (DPO) (waste and emissions excluding oxygen from air) in 2020 (BMK, 2024b).

tion-based CO<sub>2</sub> emissions between 2013 and 2019 (achieving absolute decoupling from their GDP), Austria had the second slowest rate of reduction in consumption-based CO<sub>2</sub> emissions (-0.87 %/yr), which, when extrapolated into the future, is far from sufficient to stay below the temperature limit of the Paris Agreement (Vogel and Hickel, 2023).

Despite the importance of material stocks such as buildings, infrastructure, and machinery in driving material demand and GHG emissions, their expansion has received little attention in Austrian climate policy and discourse to date (cf. Theine et al., 2023) (see [Chapter 6](#)). Instead, efforts towards more climate-friendly goods and services have traditionally focused on the development and diffusion of technologies (Aigner et al., 2023b; Haas et al., 2023) (see [Chapter 6](#)). Today, 4.6 % of Austria's GDP is related to the production of environmental goods and services. Since 2008, this sector has grown largely in line with the Austrian economy, with comparatively high growth rates in export products, especially in renewable technologies, industrial products (chemical, machinery, information and communications technologies), and waste management. The Austrian economy has been shown to be particularly competitive in

the provision of technologies for low-carbon buildings and rail transport (Steininger et al., 2021). However, most firms have so far focused on process innovations, with less attention being paid to the climate-friendliness of goods and services and how they are delivered to customers (Schögggl et al., 2022). The portfolios of Austrian manufacturing firms remain predominantly product-centric, with complementary services (e.g., repair, maintenance) and alternative, service-oriented business models (e.g., contracting, rental) making up only a small share of company revenues and added value to date (Dachs et al., 2014; Mastrogiamomo et al., 2019; Friesenbichler and Kügler, 2022; Wieser et al., 2023). The provisioning of energy-efficient technologies has thus been largely detached from wider concerns about material demand.

Public and non-governmental organizations are core pillars of the provisioning of goods and services in Austria. Public provisioning tends to be significantly more energy and material efficient due to a stronger focus on services and collective needs (Giljum et al., 2016; Vogel et al., 2021; in relation to public transport, see Virág et al., 2022). However, in the private sector, the focus has so far been on improving

procurement and internal processes for resource efficiency (see Klien et al., 2023), rather than on the implications of public infrastructures and services for climate-friendly living (Aigner et al., 2023b; Haas et al., 2023). Significant decarbonization potential exists in several areas of public provisioning, including transport, housing, energy, and land use (Bröthaler et al., 2023).

In addition to challenges in cutting material demand, it has proven difficult to reduce the demand for energy needed to process and utilize goods and services. Energy demand is a key driver of GHG emissions in Austria, stabilizing at a level of around 1,280 PJ final energy (BMK, 2023b). The residential, industrial, and transport sector (Chapter 3) each account for around 30 % of final energy demand (Section 4.5). Despite improvements in energy efficiency, so far only *relative* decoupling (resource use grows more slowly than GDP) has been achieved for energy to date (BMK, 2023b). *Absolute* decoupling (declining energy use independent of GDP growth), which would be necessary to achieve ambitious climate goals with the current energy mix and without negative emission technologies, has not yet been achieved in Austria (Figure 4.4a). Reasons for this can be found in the residential and transport sectors and include the rebound effect (Seebauer, 2018), increasing activity and service levels, and the expansion of material stocks in buildings, infrastructure, and vehicle fleet which have outpaced energy efficiency improvements (see Chapter 3). In Austria, for example, higher heating energy demand (Figure 4.4b) is associated with behavior (Kulmer and Seebauer, 2019; Venturi et al., 2023) and an increase in floor area (Holzmann et al., 2013; Narula et al., 2022), despite recent climate- and price-induced reductions in energy demand for heating (WIFO, 2024). Heterogeneous effects across income groups have been observed (Kulmer and Seebauer, 2019), with, for example, energy-poor households compensating for previous-

ly unmet thermal comfort needs when insulation leads to lower energy bills for heating (Berger and Hörtl, 2019). Similarly, the number of kilometers traveled in passenger cars, which are still predominantly powered by fossil fuels, has increased almost twice as much in Austria (+11.3 %) compared to the EU average (+6 %), while some EU countries have managed to achieve a decrease since 2010 (e.g., The Netherlands -3.8 %) (Eurostat, VCÖ, 2019) (Section 3.4.2). With their high dependence on fossil fuels and increasing demand for thermal comfort (mainly heating) and mobility, these sectors pose challenges for Austria's decarbonization, but several Avoid-Shift-Improve options are available (see Cross-Chapter Box 4 and Chapter 3).

Both private and public provisioning systems are exposed to extreme weather events, particularly floods and droughts, which can cause significant economic damage (Steininger et al., 2016; Unterberger et al., 2019). Empirical evidence on climate adaptation in the private sector is scarce but indicates that levels of awareness are low (Balas et al., 2021) and that the implementation of climate risk management measures is underdeveloped (Meinel and Höferl, 2017; Mitter et al., 2019; Hanger-Kopp and Palka, 2022), with public authorities considered as responsible for the management of physical climate-related risks (Rauter et al., 2020).

#### 4.2.2. Future systems for the provisioning of goods and services using circular economy principles

Provisioning systems can become significantly more climate-friendly and -resilient while maintaining high levels of service quality and well-being (Barrett et al., 2022; Creutzig et al., 2022a). Energy services needed for a decent life (Grubler et al., 2018; Rao and Min, 2018; Kikstra et al., 2021) (Section 5.2.1) are substantially lower than the ener-

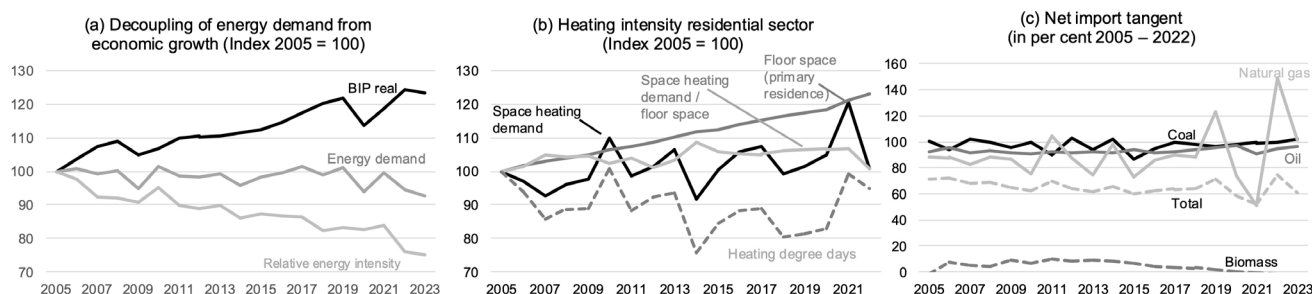


**Figure 4.4** (a) No absolute decoupling of energy demand from GDP growth in Austria as service levels increase; (b) heating demand (example), linked to energy; (c) import dependency. Source: Redrawn Figures 34, 36, 43 (BMK, 2023b).

gy footprint of the current provisioning system. For example, the carbon footprint of the Austrian healthcare system (0.8 tCO<sub>2</sub>/capita) is significantly higher than in most European countries (0.52 tCO<sub>2</sub>/capita in France or 0.42 tCO<sub>2</sub>/capita in Sweden), suggesting significant GHG mitigation opportunities in the provision of high-quality healthcare services (Pichler et al., 2019; Weisz et al., 2020) (see [Cross-Chapter Box 2](#) and [Section 5.2](#)). Reducing energy and material demand through changes in provisioning systems can deliver multiple co-benefits, most notably with respect to health and clean air (Creutzig et al., 2022a, 2022b), and system security and import dependence (see [Figure 4.4c](#)) (Bento et al., 2024), and enable low-carbon transformations of upstream supply systems (Grubler et al., 2018; Barrett et al., 2022; Creutzig et al., 2022b).

The recent decades have seen a sharp increase in material extraction from the environment, which has multiplied by a factor of 12 from 1900 to 2015. This acceleration of material use can be observed for all major material categories: Biomass, metals, non-metallic minerals, and fossil fuels (Krausmann et al., 2018). This unprecedented growth in resource use has implications for the climate, the environment, and the global supply chain. In this context, the Global Resource Outlook (UNEP IRP, 2024, p. 46) states prominently: “Given that resource use is driving the triple planetary crisis, sustainable resource management is urgently needed”.

To mitigate the increase in resource use, the concept of the circular economy has become increasingly popular in recent years (see [Cross-Chapter Box 5](#) and [Cross-Chapter Box 4](#), for more details on circular economy principles). Material Economics (2018) investigated the climate potential of the circular economy in relation to industries in the European Union for 2050. They model (a) the material recirculation opportunity and assume that 75 % of steel, 50 % of aluminum and 56 % of plastics could be recirculated, saving 33 % of CO<sub>2</sub> emissions. Next, (b) their model results show that materials efficiency increases through avoiding losses in production processes (e.g., for aluminum or building materials) could save another 11 % of CO<sub>2</sub> emissions. Finally, (c) circular economy business models are identified as another lever that could reduce 12 % of emissions, particularly through sharing of vehicles (utilization of cars is currently about 2 % in the EU) and buildings (European offices’ utilization is only about 40 %). Overall, 56 % of CO<sub>2</sub> emissions in heavy industries can be saved by these circular economy strategies.

A review article (Cantzler et al., 2020) screened more than 300 English-language papers in the fields of industry,

waste, energy, buildings, transport, and agriculture that explicitly referred to both circular economy or closely related concepts and climate change mitigation potential. Only 10 % of the studies provided insights into how the circular economy can support climate change mitigation. The highest abatement potentials are found in industry, energy, and transport, medium abatement potentials in waste and buildings, and the lowest abatement potentials in agriculture. In conclusion, substitution of material and process substitution in cement, steel, and vehicle production, together with a shift to renewable energies, are core and essential strategies to decarbonize economies. This study shows that the existing literature provides a rather fragmented picture. Circular economy strategies of lower priority seem to be favored, while refuse, reduce, and rethink strategies are only poorly represented in the applied literature (see [Cross-Chapter Box 5](#)).

The most recent Global Resource Outlook (UNEP IRP, 2024) developed scenarios for a sustainability transition to 2060. It focuses on four policy packages, including (1) resource efficiency measures, (2) climate and energy, (3) food and land, and (4) a just transition. The packages address, for example, a resource tax, efficient and sustainable settlements with a compact urban form, and sustainable transport modes (ad. 1), carbon pricing, electrification, and renewable energy (ad. 2), nature protection and restoration, healthy diets, and less food waste (ad. 3), and net carbon revenues to provide a carbon dividend payment that supports reduced inequalities and no net economic loss due to the transition (ad. 4). These policy packages achieve a 30 % reduction in resource use and a 90 % reduction of GHG emissions by 2060 compared to a continuation of historical trends.

For Austria, a recent study models the biophysical economy for the period 2018 to 2040 to investigate how circular economy strategies in the building, transport (passenger and freight) and electricity sectors interact with decarbonization (Haas et al., 2025). For this purpose, two economic projections (moderate growth (1) and no growth (2)) are used in combination with four scenarios. One scenario (R) is a continuation of historical trends with no clear decarbonization, while the second scenario (A) is a decarbonization in the three sectors with strong recycling activities and a weak modal split shift representing circular economy strategies by 2040 (see details for all scenarios in [Figure 4.5](#)). A third scenario (B) adds to the decarbonization weak circular economy strategies, which are mainly a moderate reduction of passenger kilometers (p-km) and ton kilometers (t-km) and a moderate reduction of per capita floor area in new build-

ing construction. The strong circular economy scenario (C) includes a strong modal split shift and strong reduction in traffic volume, increased car sharing, a complete halt to the expansion of the road network, a halt to new construction on unbuilt land, and a higher share of wood construction in new buildings. The reduction in construction activity allows for a significant reduction in ton kilometers as, in addition to eliminating the transportation of fossil fuels, a large proportion of construction materials no longer need to be transported.

The weak circular economy scenario is based on assumptions found in official documents and studies during the modeling exercise (e.g., Kranzl et al., 2018; BMNT, 2019; Krutzler et al., 2023). The strong circular economy scenario is designed to achieve decarbonization and the targets set out by the Austrian government's circular economy strategy (BMK, 2022).

Methodologically, this research is based on international predecessor studies (Haas et al., 2015; Mayer et al., 2019a; Haas et al., 2020; Wang et al., 2020; Miatto et al., 2024) but goes beyond them in modeling all stocks in the building, transport and electricity sectors. End-use explicit material stocks are essential in modeling, as a transition will sooner or later need to replace societal stocks from heating systems, vehicles, to power plants.

The results in Figure 4.5 are presented for a smooth economic recovery projection after the crises since 2019 (COVID-19 pandemic, Russian war on Ukraine, assuming an annual GDP growth of 1.6 %, projection indexed 1) and a slow recovery with zero GDP growth (projection indexed 2). Reducing domestic material consumption (DMC) from 18.4 t/capita in 2018 to the targeted 14 t/capita in 2030 and about 6 t/capita in 2050 (based on the proclaimed 7 t/capita material footprint target of the government's circular economy strategy) (BMK, 2022) is unachievable with pure decarbonization (yellow line, A1). A combination of decarbonization and weak circular economy (B1) measures based on loop-closing (blue line), would still lead to a material consumption significantly above the official target and much closer to the reference value with continued trends (see Figure 4.5a). The strong circular economy scenario (C1) can contribute its share of the buildings, transport, and electricity sectors to government's circular economy targets. It should be emphasized that the measures needed to achieve these targets are highly controversial amongst policymakers. A halt to new building construction on unbuilt land is highly debated, as is a significant reduction in car use (derStandard, 2024).

The phasing out of fossil fuels through fleet electrification and non-fossil fuel heating systems (e.g., heat pumps), as well as the decarbonization of the electricity sector (green power), will contribute significantly to the achievement of the targets. The combination of a phase-out of new constructions of buildings in the period until 2030 and a strong modal split shift assists to reduce both processed materials and final energy use. While some measures have a strong impact on reducing both energy and material demand (e.g., no construction on unbuilt land), others mainly reduce final energy (fleet electrification) or materials (no new roads). Collectively, they contribute to a reduction in final energy of more than 50 %. The direct final energy use in these three sectors is completely based on renewable energy sources (mainly wind, solar and hydro at present levels). The reduction of material of more than 70 % by 2040 is in line with a reduction of the material footprint of Austria from 22 t/capita in 2018 to 7 t/capita in 2050.

The transition to a carbon-neutral economy can be facilitated if accompanied by strong circular economy strategies (Creutzig et al., 2024). The electrification of transport and, to some extent, heating (especially through heat pumps) is increasing demand for electricity. In 2018, electricity generation was 244 PJ, of which 158 PJ was based on renewable energy sources. In 2040, when all electricity generation is to be based on renewable sources, the demand is 378 PJ in the decarbonization scenario A1 (2.4 times the demand in 2018). The weak circular economy scenario (B1) requires 354 PJ of renewables (2.2x), while the strong circular economy scenario (C1) requires 308 PJ (2.0x). At the same time, as renewable energy sources increase, the demand for rare earth elements (REEs) increases from 84 t in 2018 to 722 t in the decarbonization scenario (A1) in 2040 and 181 t in the strong circular economy scenario in 2040. In particular, the transition will require REEs for electric vehicles and wind turbines. The availability of REEs is potentially challenging, depending on the global increase in renewable energy (Valero et al., 2018; Li et al., 2020; Klimenko et al., 2021) and potentially complicated by geopolitical tensions and negative social impacts in extraction locations (Creutzig et al., 2024). Similarly, a strong increase in electricity demand, as seen in the decarbonization scenario (A1), will require a significant increase in storage capacity, for example in the transport sector, associated with batteries containing scarce raw materials such as lithium (Diouf and Pode, 2015). This material demand can be mitigated by the strong circular economy scenario (C1), as it significantly reduces the number of battery-driven vehicles, for example through less road transport and car sharing.

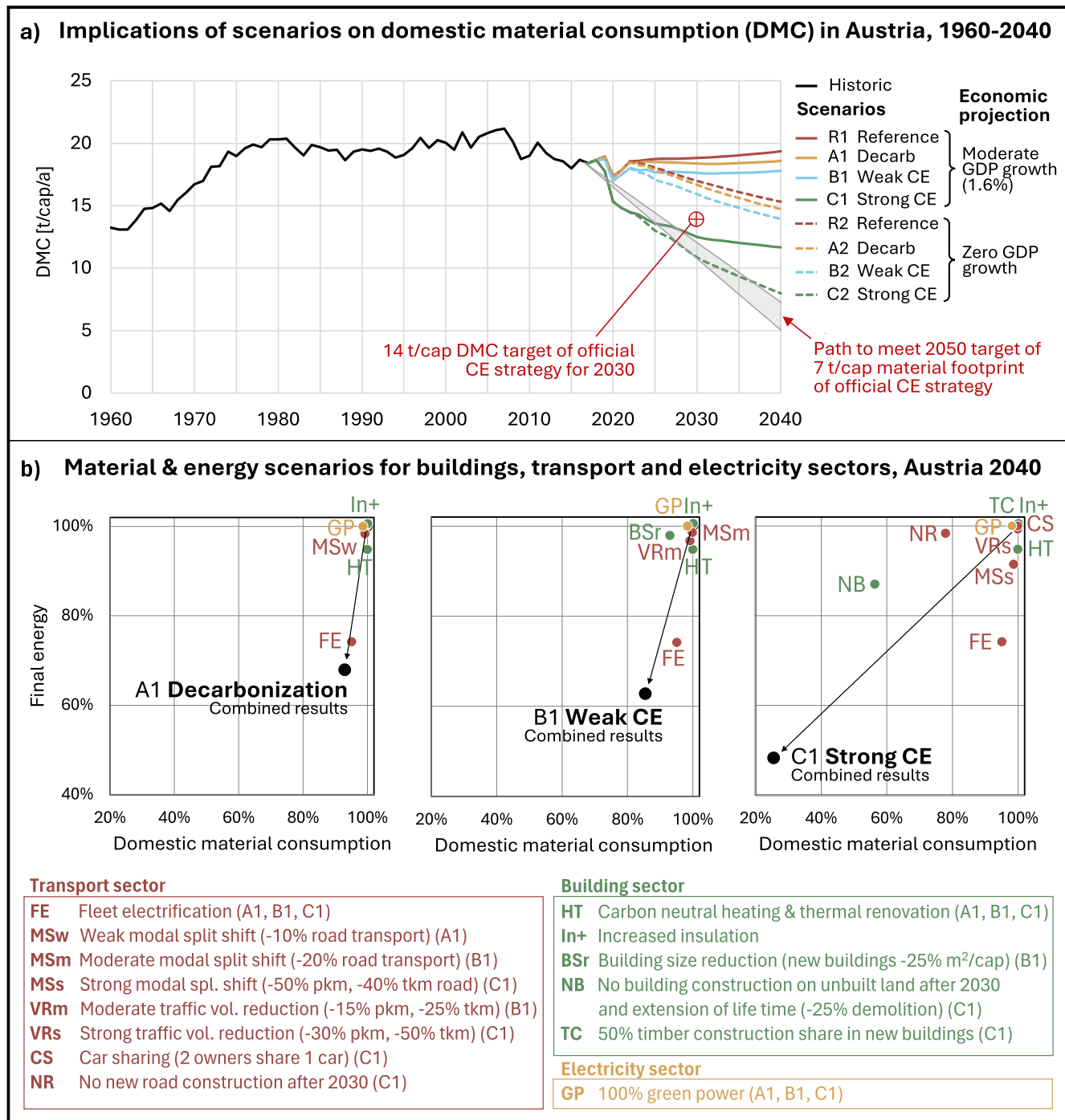


**Figure 4.5** (a) Domestic material consumption (DMC, all material extraction + imports – exports) for different decarbonization and circular economy scenarios towards the 2030 and 2050 targets of the Austrian Circular Economy Strategy. Scenarios were applied for two different economic projections, a moderate growth (GDP growth after recovery of 1.6 %) and a slow recovery and growth of 0 %. (b) Below, a list of measures for decarbonization and circular economy is presented. These measures were applied in a decarbonization and loop closing (material recovery through recycling) scenario (A1), a decarbonization and weak circular economy scenario (applying officially reported measures) and a decarbonization and strong circular economy scenario (C1) that aims for contributing to the government's circular economy targets, which is summarized in processed materials (PM = DMC + secondary materials) but also reduces the demand for final energy. See assumptions for measures in the legend (Haas et al., 2025).

Although some circular economy measures in scenario C1 may seem extensive, the actual impact on quality of life will be rather low. While the car ownership rate is drastically reduced in a strong circular economy scenario (due to modal split shifts and an increase in car sharing), the distance traveled per capita would be reduced by 6 % compared to 2018. This is reasonable given the recent increase in the popularity of teleworking arrangements that reduce the need for work-related car-based commuting (Hartwig et al., 2022), and since the phasing out of new buildings in the C1 scenario stops further urban sprawl.

Another impact of the transition can be seen on floor space and land consumption. The decarbonization scenario (A1) would imply a continuation and thus an increase in land consumption from 11.5 to 12.4 ha/d in 2040. However, such an increase could be mitigated in the C1 scenario because no new roads and no new buildings on unbuilt land have the potential to stabilize land use without further land-consuming stock additions. In terms of floor space, this means that while we have 72 m<sup>2</sup>/capita for residential and office space in 2018, this would increase to 78 m<sup>2</sup>/capita in 2040 in the decarbonization scenario (A1), but decrease to 67 m<sup>2</sup>/capita in the strong circular economy scenario (C1). Among the older population (60 years and older), there is an openness to reducing per capita floor space. For example, a German study found that 29 % of homeowners and 11 % of tenants are overburdened and assess their housing conditions as too spacious (Kitzmann, 2023). The Global Resource Outlook estimates a utilization rate of 40 % for office buildings (UNEP IRP, 2024). Numerous non-representative case studies show that office, public and educational buildings stand empty for between 90 to 95 % of their service life (including non-working time like weekends or holidays). Factors like low occupancy of seminar rooms, home office, part-time jobs and high proportion of field service can play a significant role here (Wiegand, 2012) (see also [Section 3.3](#)). Another Swedish study finds in a specific case a utilization rate of meeting rooms between 14 and 36 %, with meeting rooms mostly larger than needed, and an office attendance of less than 50 % on weekdays and during working hours, with no overcrowding up to 68 % office attendance (Holmin et al., 2015). Thus, a 7 % reduction in heated floor space for residential buildings and offices does not seem unrealistic. Further potential can be found in improved spatial planning that counteracts urban sprawl (Brenner et al., 2024).

From an economic point of view, an assessment of these scenarios shows that the average GDP growth rate for the period 2018–2040 would increase from 1.35 % in the reference scenario to 1.44 % in the C1 scenario. This change is due to the re-investment of savings from reduced construction activity in services, as services have a relatively low import intensity and high domestic wage intensity. For the same reason, employment also shows positive effects (Meyer et al., 2024).

An investigation of 18 individual measures with the overall aim of reducing the consumption of mineral raw materials in line with the sustainability strategies (consistency, efficiency, and sufficiency) from exploration through material processing to semi-finished production finds many positive effects for SDG 12 and its targets (Trummer et al., 2022) (see also [Chapter 3](#)). An interaction assessment of the measures related to the individual SDGs to better understand the many synergies and trade-offs between SDGs/targets was not conducted and is still lacking. The Global Resource Outlook finds that 13 SDGs are directly, and 4 are indirectly linked to natural resource use (out of 17 SDGs) (UNEP IRP, 2024).

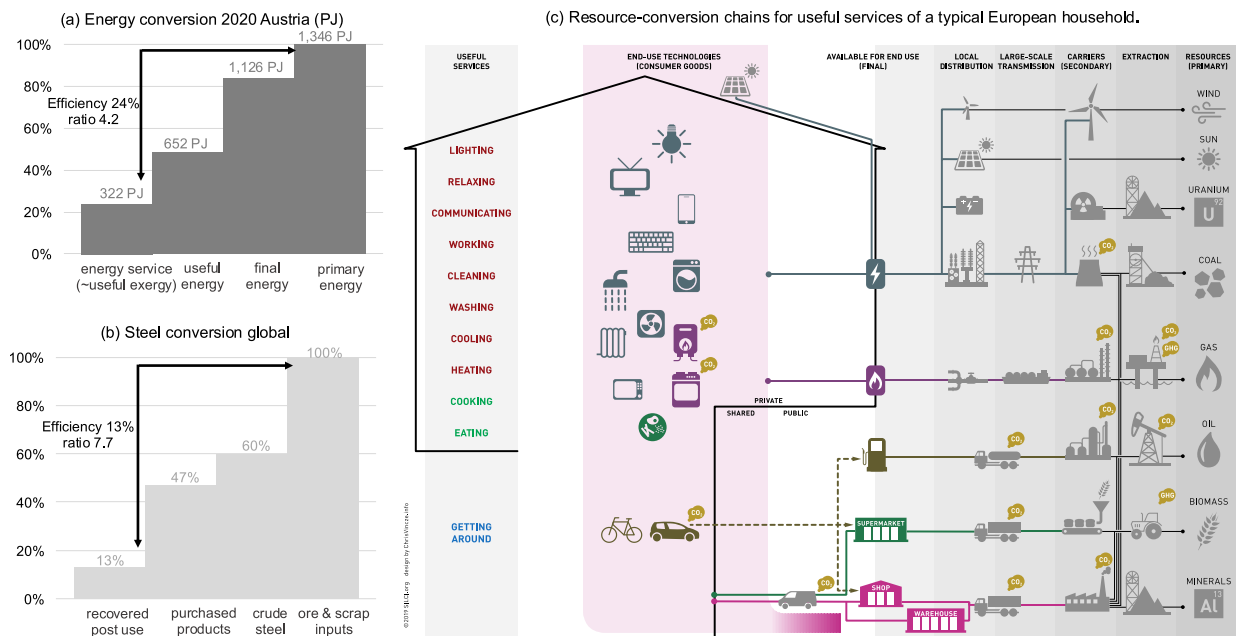
The transition to a carbon-neutral economy offers both benefits and transition risks, depending on how it is implemented. A narrow implementation of measures for buildings, transport, and electricity sector, as in the A1 decarbonization scenario, could risk being highly vulnerable to supply chain disruptions, as REE demand would steeply increase. In addition, the high demand for electricity from renewable energy sources carries the risk that it is highly dependent on the smooth approval of projects, with little room to participate and respond constructively to public opposition and the availability of a sufficiently skilled workforce. Such a scenario would imply further land consumption, exceeding the long-discussed target of 2.5 ha of land consumption per day. It would fail to meet the targets set out in the government's circular economy strategy and to address the triple planetary crisis of climate change, biodiversity loss, and pollution. In contrast, the strong circular economy scenario (C1) has great potential to achieve circular economy goals, reduce land consumption, and facilitate the transition to renewable energy sources, as energy consumption and demand for REE are significantly lower. In summary, especially if a strong circular economy strategy in combination with demand-side measures is implemented, both the magnitude of the climate challenge and the need for material resources relevant to biodiversity and pollution will be reduced (see Creutzig et al., 2024; Haas et al., 2025).

### Cross-Chapter Box 3. Needs orientation in provisioning systems

Caroline Zimm; Benigna Boza-Kiss

A demand-side perspective that focuses on the provisioning of services can help (i) identifying large leverage opportunities along the resource conversion chain and (ii) shifting focus on human needs and well-being.

Conversion losses occur, for example, when energy is transformed from one form to another, such as from primary energy (e.g., crude oil) via final energy (e.g., gasoline) to useful energy (e.g., power to the wheel of the car) to the energy service level (e.g., mobility for a certain distance). First, in the current energy system dominated by thermal combustion (e.g., internal combustion engines, boilers), service energy (i.e., useful energy as a proxy) accounts for 24 % of primary energy input in Austria (CCBox 3 Figure 1a), up from 11 % in 1960 (Marshall et al., 2024). This means that each unit of energy that is avoided or not needed at end-use levels translates to around four units of primary energy that do not need to be provided (Marshall et al., 2024). When we move towards more (renewable) electricity-based systems, these conversion losses will be reduced substantially. The conversion losses also occur in materials processing, where Austria is connected to global material chains (Section 4.2). Globally, steel production from primary ore shows high conversion efficiency losses (CCBox 3 Figure 1b), even though steel is one of the easier-to-recycle materials and a respective market exists. Challenges related to materials will increase with the need for high-quality materials, which are often not available through recycling, and increasing shares of compound materials used, which cannot be recycled easily. Actions reducing demand have great potential in terms of overall resource implications and other co-benefits, e.g., for energy, GHG reduction potential, costs, well-being, reduced air pollution, supply security, flexibility, positive impact on the trade balance of energy importers (Finn and Brockway, 2023; Bento et al., 2024) (see Figure 4.4c and Cross-Chapter Box 2).



**CCBox 3 Figure 1** (a) Resource efficiency cascades throughout the provisioning system for energy in Austria and (b) for steel globally. Each step of the cascade shows the percentage of the extracted primary resource remaining after conversion losses, starting from primary energy on the right. Arrows indicate the efficiency ratio between primary input and the last conversion step. (c) Resource conversion chains (gray shades) linking energy services (e.g., heating, cooking, and mobility) with primary energy for a typical European household (Source: Adapted from Wilson et al. (2023) based on TWI2050 (2018). Estimates for energy in Austria from Marshall et al. (2024), for global steel from De Sterck (2014)).

Moreover, demand for goods and services can be met with different levels of energy or material input. By shifting the focus away from primary resource inputs (e.g., tons of oil) to services that meet human needs and enable human well-being (e.g., thermal comfort), diverse provisioning opportunities of different resource intensities arise. Energy or materials are not demanded for their own sake, but for the goods and services they enable (CCBox 3 Figure 1c). The design of services and the associated user experience is highly relevant to managing demand (Lovins, 2010; Polaine et al., 2013). This is critical for just energy transitions, as human well-being should not be compromised, or at least maintained, but ideally be improved in the transition process. Focusing on service levels rather than on energy or material inputs can facilitate the achievement of decarbonization and distributional objectives, such as those related to affordability (Sections 5.6, 6.7), energy poverty (Sections 5.3.4, 6.8) and decent living (Sections 5.2.1, 6.8), but a focus on the demand side also helps to achieve improvements in health (see Cross-Chapter Box 2), jobs, and energy security (Bento et al., 2024).

#### Cross-Chapter Box 4. Avoid – Shift – Improve: The ASI-framework

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Avoiding, shifting and improving are different entry points for achieving **reductions in emissions and resource use** which have been systematized in the so-called A(void)-S(hift)-I(mprove)-framework (Creutzig et al., 2018). In many ways, the ASI-framework is complementary to a framework based on efficiency, consistency and sufficiency. Here, efficiency (i.e., improve) refers to ‘doing things better’, consistency (i.e., shift) refers to ‘doing things differently’ and sufficiency (i.e., avoid) to ‘doing less’ (Fuchs et al., 2023). The ASI-framework represents a hierarchy, with concerns for ‘Avoid’ and ‘Shift’ preceding those of ‘Improve’ (Arnz et al., 2024), as improve strategies so far have not led to the required GHG emissions reductions (Haberl et al., 2020), while national climate action plans in the EU still hardly use sufficiency-oriented measures (Fuchs et al., 2023).

**Avoid** refers to mitigation options that aim at **reducing or refraining from activities** that are using products and services that are unnecessary in meeting basic human needs (see Cross-Chapter Box 5) (Fuchs et al., 2023). ‘Avoid’ refers to the reduction of energy and materials either through behavioral change and/or through the redesign of associated *service provisioning systems*, such as the redesign of infrastructures and institutions by means of laws, regulations, nudging, etc. (Aigner et al., 2023b). Sometimes structures enable needs satisfaction without producing goods or using energy and materials (e.g., a compact city) (Aigner et al., 2023b). Examples of mitigation options of ‘Avoid’ comprise reducing unused living space, calory consumption or transport needs by working from home (or remotely), thereby avoiding the production and consumption of energy and material-intensive harmful and unhealthy food (Lampl et al., 2024).

**Shift** describes a change through substitution of one option for another. This entails a **switch to another cleaner option or service provisioning system**. This could be the switch from car to public transport due to new infrastructural arrangements or price incentives (e.g., climate and repair bonus), replacing fossil fuels by renewables in the energy mix (e.g., gas boiler to heat pump), or moving towards a more plant-based diet.

**Improve** refers to enhancing the efficiency of existing technologies or practices improving their environmental performance. This often means optimizing the efficiency of existing products, services and production processes. Examples are better building insulation, reducing food losses, or higher efficiency in internal combustion engines.

In line with multi-perspectivity, avoid, shift, and improve measures are not mutually exclusive, but **need to be combined in portfolios of measures**, to increase their effectiveness (Fuchs et al., 2023; Novy et al., 2023) (see Sections 6.5.4,

8.6.1). Transport systems that provide the service of accessibility and mobility can combine compact cities with a shift to public transport and ridesharing (see [Section 3.4.2](#), [CCBox 4 Table 1](#)).

As all ASI mitigation options entail synergies and trade-offs (e.g., rebound effects), a careful approach is required that takes into account the interactions between ASI options in order to utilize synergies and mitigate trade-offs (Haas et al. (2023); for a discussion on digitalization, see Santarius et al. (2020)) (see [Section 8.3](#), [8.6](#)).

The ASI-framework is also relevant for GHG-emissions stemming from consumption in general (e.g., GHG emissions from process emissions in the concrete production as part of housing provisioning) (Aigner et al., 2023a, 2023b).

While avoid and shift measures often depend on **changes in infrastructure, institutions and prices**, improve measures are often compatible with incumbent habits and practices and can therefore be implemented more quickly. However, improve options alone often bear a small mitigation potential compared to avoid and shift measures to achieve decarbonization. They may also lead to rebound effects when efficiency gains induce an increase in production and consumption (Alcott, 2008; Sachverständigenrat für Umweltfragen, 2024).

The ASI-framework aims at reducing environmental pressures rather than solely favoring efficiency gains, acknowledging the absolute biophysical limits of the Earth system and the non-substitutability between different dimensions of sustainability. It is grounded in theories of provisioning, exploring the interplay between production, consumption and distribution. While a ‘provisioning system approach’ does not examine the material throughputs (Fine, 1994; Bayliss and Fine, 2020), a ‘social provisioning perspective’ studies the organization of livelihoods and places provisioning at the center of feminist and (social) ecological economics, investigating who provides services (paid and unpaid), by what means, and with what material impacts (Nelson, 1993; Jo, 2011; Jo and Todorova, 2019; Spash, 2024). Human well-being depends on the specific institutional-normative organization of the socio-economic system embedded in biophysical systems with diverse planetary boundaries (O’Neill et al., 2018). Therefore, gender, inequality and power relations affect the potential to mitigate emissions and resource use (Brand-Correa et al., 2018; O’Neill et al., 2018; Schaffartzik et al., 2021). In such a broad understanding of provisioning, actors including households, business, civil society and (semi-)public institutions form provisioning systems (Plank et al., 2021b). They evaluate, judge, and decide on whether and how to modify framework conditions of service-provisioning systems – and in consequence – forms of life (Creutzig et al., 2022a). Structures of supply (e.g., available portfolio of goods) and infrastructures (e.g., village centers with a high quality of livability) interact with social and cultural norms for service choices (i.e., diet choice, modal split).

The ASI framework encourages a more systematic way of thinking about different measures by **directly targeting well-being** and needs satisfaction when formulating and comparing mitigation strategies. The underlying eudaimonic understanding of a good life puts human needs at the center, including thermal comfort, nutrition, or mobility (Creutzig et al., 2016, 2018) (see [Cross-Chapter Box 3](#)). It aims to change supply structures and modify infrastructures and choice architectures to change demand for goods and services, thereby differentiating between the overall amount of resource use (e.g., liters of fuel), the required *service level* (e.g., the use of energy for heating or cooking) and the related *provisioning systems* (e.g., the energy, food or mobility system covering production, consumption and distribution) that are available to provide the different services (Creutzig et al., 2022a).

The ASI framework, interested in what people need for a good life, has labeled its policy proposals as demand-side solutions, i.e., service provisioning systems with the specific objective to conceptualize **demand, preferences and choices not as given but as malleable** (Creutzig et al., 2018). Globally, demand-side solutions could collectively reduce emissions by 40–70 % by 2050 (IPCC, 2023a). Demand-side solutions widen the available portfolio of measures. First, they nudge behavioral changes within given infrastructures and institutions by exploring consumer preferences and deriving feasible (often incremental) solutions under given framework conditions (see [Chapter 5](#)). Second, they aim at deeper transformations of norms and objectives due to different infrastructures, institutions and prices (Meadows, 1999; Abson et al., 2017; Aigner et al., 2023a) (see [Section 8.6.3](#)).

Some examples to guide the categorization of options are provided in CCBox 4 Table 1.

**CCBox 4 Table 1** Selected examples of measures across sectors categorized according to the ASI framework (assessment by authors based on Creutzig et al., 2018, 2022a, 2024; Aigner et al., 2023; Arnz et al., 2024). For a systematic list of measures and their assessment, see the respective chapters, as well as [Table 6.2](#).

|                                    | Service                   | Avoid                                                                                                           | Shift                                                                              | Improve                                       |
|------------------------------------|---------------------------|-----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------|
| Transport                          | Accessibility<br>Mobility | Compact cities                                                                                                  | Electric two-, three- and four-wheelers                                            | Eco-driving                                   |
|                                    |                           | Integration of transport and land-use planning                                                                  | Mode shift from car to cycling, walking, or public transit                         | Light-weight vehicles                         |
|                                    |                           | Teleworking                                                                                                     |                                                                                    | More efficient gasoline engines               |
|                                    |                           | Workplace near to place of residence                                                                            |                                                                                    | Ride sharing                                  |
| Buildings                          | Shelter                   | Avoid empty living space                                                                                        | Combined heat and power                                                            | Building insulation                           |
|                                    |                           | Change temperature set-points                                                                                   | Heat pumps, district heating and cooling                                           | Improved raw materials sourcing practices     |
|                                    |                           | Efficient floor space allocation and reuse of existing buildings                                                | Inverter air conditioning                                                          | Condensing boilers                            |
|                                    |                           | Passive house (avoiding demand for heating/cooling)                                                             | Solar thermal                                                                      | Incremental insulation options                |
|                                    |                           | Shading and solar radiation aware architecture                                                                  |                                                                                    | Energy-efficient appliances                   |
|                                    |                           | Smaller houses                                                                                                  |                                                                                    | Other building materials                      |
| Manufactured products and services | Clothing<br>Appliances    | Prohibition of certain fast fashion business practices (e.g., throwing away non-used goods in on-line-shopping) | Shift to recycled materials, low-carbon materials for buildings and infrastructure | Long-lasting fabric, appliances               |
|                                    |                           | Reuse and repair (that is: Not producing new goods, thereby avoiding emissions and material)                    |                                                                                    | New manufacturing processes and equipment use |
|                                    |                           | Sharing economy                                                                                                 |                                                                                    | Use of low-carbon fabrics                     |
|                                    |                           |                                                                                                                 |                                                                                    |                                               |
| Food                               | Nutrition                 | Calories in line with daily needs                                                                               | Healthy fresh (seasonal) food to replace processed food                            | More efficient fridges and freezers           |
|                                    |                           | Smaller fridges and freezers                                                                                    | Shift from ruminant meat to other protein sources where appropriate                | Reuse food waste and food waste reduction     |
|                                    |                           |                                                                                                                 |                                                                                    |                                               |
| Work                               | Commuting                 | Limit the availability of car parking lots                                                                      | Provide sharing options at workplace                                               | Shift to electric mobility for commuting      |
|                                    |                           | Reduce the number of days worked per week to avoid non-needed commuting                                         | Shift to public transport or cycling                                               | Subsize the electrification of company cars   |
|                                    |                           | Work-places nearby the living places                                                                            |                                                                                    |                                               |

## Cross-Chapter Box 5. Circular economy

*Willi Haas, André Baumgart*

Steadily increasing extraction and processing of material resources (fossil fuels, minerals, non-metallic minerals and biomass) are the main drivers of the three planetary crises climate change, biodiversity loss and pollution (Geissdoerfer et al., 2017; UNEP IRP, 2024). To better deal with these increasing resource flows, the concept of circular economy has gained popularity in the past two decades and is being continuously developed (Kirchherr et al., 2023). The importance of and interest in circular economy concepts derive primarily from the fact that they can be used as a basis for developing solutions to environmental and climate policy concerns that will also provide economic opportunities, while relying on key economic principles such as the efficient use of resources. Increased resource efficiency through a circular economy essentially means striving for higher value creation with lower use of natural resources (Geng et al., 2019). The definition of the circular economy matters for circularity assessments and prioritizing measures. In the last two decades, according to Korhonen et al. (2018), practitioners have been the dominant driving force behind the circular economy concept. Thus, policymakers, businesses, business consultants, business associations, and business foundations play a key role in this field (People's Republic of China, 2008; Ellen Macarthur Foundation, 2013, 2015; COM/2015/0614 final; McKinsey & Company, 2016; Japanese Ministry of the Environment, 2018; de Wit et al., 2019). Consequently, these actors promote definitions that serve their interests with little attention to consistency across products, supply chains, materials, or scales, and in the worst case risk greenwashing and image loss (Nobre and Tavares, 2021). But also within the scientific community, circular economy “means many different things to different people” (Kirchherr et al., 2017, p. 229). In a follow-up article, Kirchherr et al. (2023) found 221 definitions in 6,566 studies in a review of circular economy conceptualization.

A definition that received broad recognition (more than 3,800 citations) comes from Korhonen et al. (2018, p. 39): “Circular economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading-type energy flows. Successful circular economy contributes to all the three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilizes ecosystem cycles in economic cycles by respecting their natural reproduction rates”.

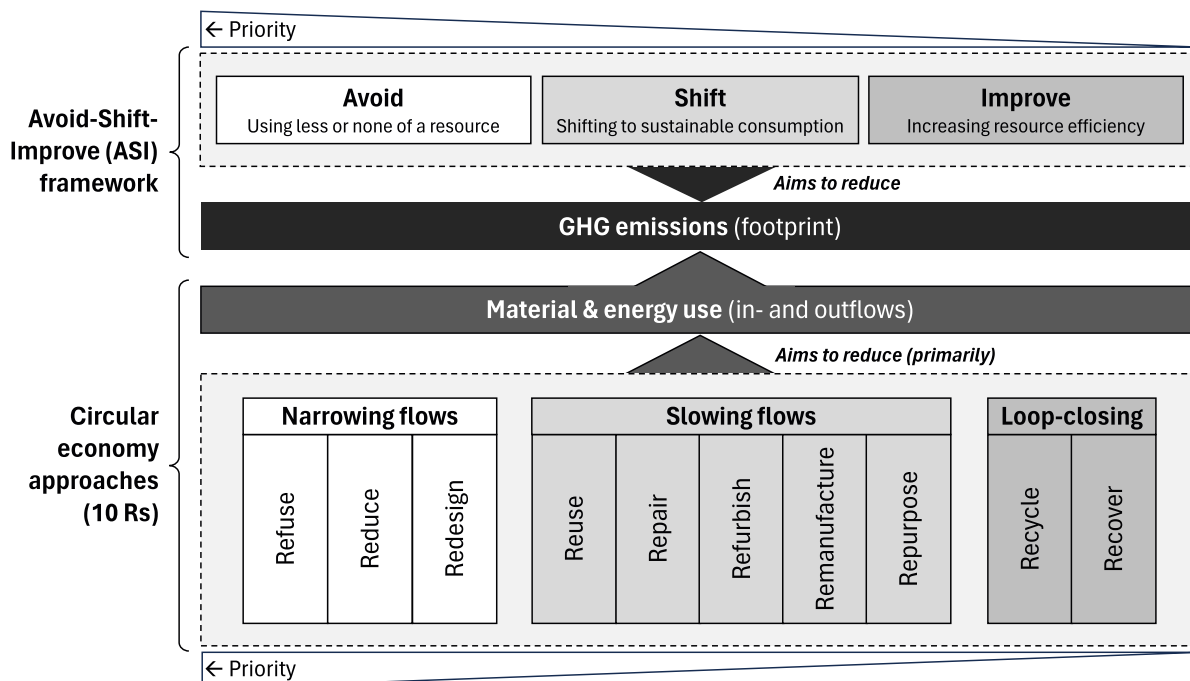
In line with this definition, there are several circularity strategy frameworks, often referred to as 10R (Potting et al., 2017; Blomsma et al., 2019; Morsetto, 2020) – because of the ten strategies all starting with an ‘R’ – which aim to minimize the consumption of raw materials and the generation of waste and emissions. The 10R strategies (sometimes referred to as 9Rs due to different counting) range from narrowing (refuse, reduce, redesign), slowing (reuse, repair, refurbish, remanufacture, repurpose), to closing loops (recycle, recover) of material flows. Strategies are prioritized according to their levels of circularity, with smarter product manufacturing and use, such as product sharing, generally being preferred over extending product lifetime because more users can be served by one product (narrowing strategy with high circularity). Next in order is lifetime extension (slowing), followed by material recycling (closing loops), in which product integrity is lost. Last is incineration, in which energy is recovered with the highest quality material reduction (Potting et al., 2017).

Thus, the 10R strategies follow the same guiding principle as the Avoid-Shift-Improve framework (Muñoz et al., 2024). While Avoid-Shift-Improve is primarily focused on reducing GHG emissions, the 10R strategies are focused on reducing raw material inputs from nature and waste (Reike et al., 2018). However, the two concepts are inherently linked, as the material perspective of the 10R framework, which includes energy materials (fossil and biomass fuels) and the extraction, processing, and use of materials as products and infrastructure, is a major cause for energy use and GHG emissions (see [CCBox 5 Figure 1](#)). As a direct result of material and energy use reduction, the circular economy approach also reduces land consumption and biodiversity loss.

The circular economy is thought to contribute to resource security and resilient value chains by redirecting resource flows from waste management to the productive economy (IEA, 2022). However, there is a risk that circular economy strategies focus too narrowly on closing loops, respectively recycling, as this promises a zero-waste world and thus allows unrestrained growth of stocks and flows, rendering circular economy impossible and failing to address the enormous strain to reduce and slow material and energy use (Haas et al., 2025).

While circular economy offers strategies to reduce material and energy use as well as waste and emissions, it encounters surmountable thermodynamic limits. According to the first law of thermodynamics, mass and energy are constant in a closed system (Fischer-Kowalski et al., 2011). Therefore, if the global socio-economic system is a circular economy that does not draw on the resources of the biosphere, this is not feasible with growing stocks of materials. Materials cannot be created out of nothing, so any system with growing stocks will need inputs of primary materials, even if it were possible to completely reuse or recycle all old materials and waste. As stocks, even if constant, have to be maintained due to deterioration, wear and losses, a fully circular economy is impossible. The second law of thermodynamics on entropy means that material qualitative characteristics are altered in irreversible production processes (Giampietro, 2022). Further, energy and material requirements for recovery, processing and recycling rise disproportionately the more dispersed and mixed end-of-life wastes are. This is because waste materials of all households for example need to be returned to the specialized production sites and have to comply with quality and purity requirements of high-tech production processes or for performance reasons, e.g., in construction (Ayres, 1999; Reck and Graedel, 2012; Cullen, 2017).

All these limitations need to be seriously considered when discussing circular economy potentials against the backdrop of material and energy use dynamics at different levels. According to the latest Global Resources Outlook report (UNEP IRP, 2024), global domestic material consumption (DMC) amounted to 96 Gt/yr in 2019. With 9.5 Gt/yr of secondary materials having re-entered the production chain, global input circularity was about 9 % (UNEP IRP, 2024). Since 1900, non-circular input flows have increased 16-fold, while the global input cycling rate has decreased from 43 to 27 % (Haas et al., 2020). At EU level, with a DMC of 6.4 Gt/yr and a recycling of 0.8 Gt/yr in 2022, the circularity rate was about 11 % (Eurostat, 2023).



**CCBox 5 Figure 1** Comparison of two overlapping but different frameworks: The Avoid-Shift-Improve framework sets priorities between three strategies to reduce GHG emissions while the circular economy approaches set priorities for 10R strategies to reduce material and energy in terms of their related inflows of raw materials from and outflows wastes and emissions to nature. Source: Own visualization.

To increase circularity, circular economy concepts have been integrated into various international policies and strategies, including the Sustainable Development Goals (SDGs), where SDG 12 ‘Responsible consumption and production’ is primary concerned with sustainable use of natural resources and waste reduction. Likewise, the European Union adopted the ‘EU Action Plan for the Circular Economy’ in 2015 (COM/2015/0614 final), which has gained new impetus in the wake of the Green Deal to achieve climate neutrality (COM/2019/640 final), but has also been criticized for being holistic in words but ‘end-of-pipe’ in action (Calisto Friant et al., 2021), with fragmented and competing goals reducing effectiveness (Domenech and Bahn-Walkowiak, 2019), and finally for a lack of high-quality data to assess progress towards a far-reaching circular economy (Morseletto and Haas, 2023). The Austrian government has set the ambitious goal to achieve climate neutrality by 2040 at the latest (BMK, 2023a). The ‘Austrian Circularity Strategy’ aims to reduce resource use and waste by promoting circular economy strategies (BMK, 2022). The strategy envisions an annual per capita DMC of 14 t in 2030 and a per capita material footprint (MF=DMC including upstream material requirements) of 7 t/yr in 2040, which corresponds to a DMC of roughly 5–6 t/capita. However, Austria, as a country with a high per capita stock level (Haberl et al., 2021), had a DMC of around 18 t/capita in 2018, of which 28 % was used in the building sector, 19 % in the transport sector, and 2 % in the electricity sector (Haas et al., 2025). This leaves more than half for other sectors, including manufacturing and agriculture (see [Section 4.2.2](#) and [Chapter 5](#)).

Circular economy can support climate policy and the transition to carbon neutrality, as the accumulation of material in societal stocks in particular is key to energy reduction, since the expansion, maintenance and operation of stocks are major drivers of energy use. Since green energy will remain a bottleneck for at least the next decades (see challenges discussed in Ang et al., 2022), the circular economy’s reduction potential is urgently needed.

The goals of the Austrian Circularity Strategy are interwoven with goals from other national strategies: Soil sealing remains an issue in Austria, with the average daily increase in hectares of land taken being significantly above the official 2.5 ha/d target formulated as part of the Master Plan Rural Development 2017 (Prokop, 2019). Reducing the amount of land sealing implies a reduction in newly constructed houses or a slowdown in further transport network expansion and consequently puts a restraint on resource use. Reductions in material and energy use lead to reductions in GHG emissions. Together, a reduction in land sealing and associated land fragmentation and mitigation of GHG emissions benefit biodiversity and the climate (Wiedenhofer et al., 2015; Koemle et al., 2018).

### 4.2.3. Necessary transformation in the provisioning of goods and services

Considering the large stocks of materials in use in infrastructures, buildings, and appliances, major investments are required to reduce fossil fuel consumption needed for their use and to adapt these stocks to changing climatic conditions (Bachner, 2017; Bachner et al., 2019a; Bröthaler et al., 2023). At the same time, the modernization and replacement of existing material provisioning structures, alongside necessary investments in new manufacturing facilities (see [Section 4.4](#)) and energy supply infrastructures (see [Section 4.5](#)), would significantly increase electricity and material demand in the short- to medium-term. Furthermore, an overemphasis on the diffusion of low-carbon technologies can create long-term dependencies on critical raw materials such as lithium. This calls for a balanced approach to trans-

formation that accounts for the different timeframes within which net reductions in GHG emissions can be achieved. Energy and material efficiency measures in the provisioning of goods and services with high potential for short-term reductions in demand, thus play a vital role in the transformation process (Barrett et al., 2022; Creutzig et al., 2022a; Langevin et al., 2023). Avoid measures come with both short- and long-term potential, thus focusing on them offers great transformation opportunities. Within all Avoid-Shift-Improve options, the interplay between individual actions and existing structures can hamper the potential (see [Chapters 5 and 6](#); [Cross-Chapter Box 4](#)).

To realize the potential for reductions in energy and material demand outlined in the previous section, and to improve the resilience of provisioning systems to climate-related shocks, provisioning systems would need to undergo transformative change at multiple levels: Shifting to local

provisioning systems that enable climate-friendly modes of living, establishing infrastructures and buildings that facilitate climate-friendly practices in everyday life, and deploying more climate-friendly end-use technologies. To date, the latter have received most attention in climate mitigation strategies (see [Section 4.2.1](#)). Integrative frameworks such as the circular economy can support actions across all three levels and thereby contribute to more systemic and needs-oriented responses (see [Cross-Chapter Box 5](#) and [Cross-Chapter Box 4](#)) to climate mitigation.

**Local provisioning systems for climate-friendly modes of living:** Provisioning systems can play an important role in giving rise to daily needs in the first place. The quality, design, and spatial organization of provisioning systems can influence decisions as diverse as starting a family, relocating, or choosing a certain lifestyle – decisions that can have long-term repercussions for both climate mitigation and adaptation (Schäfer et al., 2012; Greene, 2018). Compact city design, polycentric provisioning systems, and multifunctional areas can reduce dependencies on unsustainable technologies and practices (e.g., car dependency) (Svanda and Zech, 2023). Design aspects need to go beyond spatial planning to include institutional arrangements with regards to, for example, work or decision making ([Sections 4.7](#) and [8.5.4](#)). Within the design of systems that cater to certain needs lies the largest power for avoid and shift activities that reduce the overall system size (see [Cross-Chapter Box 4](#)).

**Infrastructures and buildings for everyday life:** At the level of everyday practices, the circular economy, the sharing economy, and digitalization are three interrelated ‘megatrends’ that offer cross-sectoral opportunities to improve more infrastructures and buildings more efficiently (Creutzig et al., 2022b). Synergies may exist between the circular economy and resilience, but evidence is limited to date (Kennedy and Linnenluecke, 2022). New, digitally-enabled and more service-oriented business models are at the center of many circular economy and sharing economy initiatives, although assessments of their mitigation potential still remain fragmented. Despite the greater service orientation, there is still a significant gap between the focus on business models and specific product lifecycles in these economic models on the one hand, and the broader solution space considered in energy and material services perspectives on the other (Carmona et al., 2017; Whiting et al., 2022; Wieser et al., 2023). Less attention is paid, for example, to public provisioning and inequalities in access to goods and services. The mitigation potential of circular and sharing business models

is therefore contingent on the careful management of rebound effects (Kjaer et al., 2019; Castro et al., 2022; Metc and Pigosso, 2022). As a regulator, procurer, and owner of large infrastructure providers, the public sector can play a key role in supporting the transition to climate-neutral and -resilient infrastructures and buildings (Kubeczko and Krisch, 2023). It has been shown that policies to meet Austria’s circular economy strategy (BMK, 2022) and the formulated targets for land take (Prokop, 2019), have to limit the construction of road infrastructure and buildings, as they are major consumers of materials and are related to increasing energy consumption (see [Figure 4.5](#)). Thus, a strong circular economy strategy focused on narrowing material resource flows and essentially targeting infrastructures and buildings in the transport, building and electricity sectors, can reduce material consumption in these sectors by more than 60 % and their energy consumption by more than 50 % (Haas et al., 2025).

**Environmental end-use technologies:** The diffusion of climate-friendly end-use technologies has been critical to climate mitigation to date (Geels, 2023). As the development of important end-use technologies such as electric cars, heat pumps, photovoltaics, and biomass district heating in Austria shows, innovation and diffusion processes typically take several decades, frequently have an infrastructure component, and involve significant changes in user practices (Geels and Johnson, 2018; Kulmer et al., 2022). Supporting such non-incremental innovation requires a balanced combination of supply-side ‘technology-push’, demand-side ‘market-pull’, and systemic intervention measures (Pitelis et al., 2020; Aflaki et al., 2021). Where technologies have reached a high level of maturity and become available in markets, coordinated efforts to improve cost-performance ratios, coalition building, and market shaping can create self-reinforcing positive feedback effects to accelerate technology diffusion (Roberts et al., 2018; Victor et al., 2019; Kulmer et al., 2022; Andersen et al., 2023; Geels and Ayoub, 2023). Cost-performance improvements can be achieved through economies of scale, learning-by-doing, and increased availability of complementary technologies (Victor et al., 2019). Shared visions and targets, public procurement, empowerment of actor coalitions, visibility of frontrunners, and economic incentives for adoption can increase support for climate-friendly technologies (Roberts et al., 2018; Termeer and Dewulf, 2019). End-use technologies lie at the core of improve and also shift activities ([Cross-Chapter Box 4](#)).

### 4.3. The case of tourism and climate change

#### 4.3.1. Overview of the Austrian tourism sector

The Austrian tourism sector is of considerable importance to the Austrian economy. Prior to the COVID-19 pandemic, Austria recorded more than 46.2 million guests with around 152.7 million overnight stays in 2019 (Statistik Austria, 2022). In 2019, the direct value-added effects of tourism amounted to EUR<sub>2023</sub> 26.45 billion according to the Tourism Satellite Account (TSA), which corresponds to a share of 5.5 % of the gross domestic product in 2019 and EUR<sub>2023</sub> 36.2 billion (7.5 % of GDP in 2019) if the indirect value-added effects of tourism are also included; direct tourism employment in 2019 accounted for 6.2 % of total nationwide employment (Fritz et al., 2021).

As peripheral Alpine regions in particular are economically dependent on the tourism sector, a failure to successfully implement adaptation and mitigation strategies to climate change in the immediate future will pose significant economic risks (Pröbstl-Haider et al., 2020).

#### 4.3.2. The contribution of tourism to GHG emissions

Tourism is a significant contributor to global warming. According to Lenzen et al. (2018), global tourism emitted approximately 4.5 GtCO<sub>2</sub>eq in 2013, accounting for about 8 % of total GHG emissions. This includes direct emissions from visitor consumption (2.9 GtCO<sub>2</sub>eq) and indirect emissions from the upstream supply chain (1–2 GtCO<sub>2</sub>eq). Notably, about half of the emissions are attributed to transport, with a higher share originating from high-income countries due to increased air travel consumption. Gössling et al. (2023, p. 2) note that “adding aviation’s non-CO<sub>2</sub> contribution to climate change ... increases tourism’s contribution to global warming to 10 % in 2013”.

For Austria, estimates of tourism-induced emissions are provided by three sources: Lenzen et al. (2018), Neger et al. (2021), and Prettenthaler et al. (2021).

- **Lenzen et al. (2018):** The authors provide (so far unpublished) estimates indicating that GHG emissions from the Austrian tourism sector amounted to 12.85 MtCO<sub>2</sub>eq in 2013. The accounting relies on Tourism Satellite Account data and is destination-based (DBA), i.e., it includes

emissions from domestic tourism, inbound tourism, and local services for outbound travel (e.g., travel from home to the airport). For international air transport, only emissions from national carriers for inbound, outbound, and stop-over services are included, as well as emissions from other transport providers registered in Austria.

Additionally, Lenzen et al. (2018) apply a residence-based accounting (RBA) approach that considers all direct and indirect travel-related emissions (transport, accommodation, food, etc.) generated by Austrian residents. These emissions are estimated at 15.63 MtCO<sub>2</sub>eq, indicating that Austria is a ‘net origin’ country: Emissions caused by Austrian residents traveling abroad exceed those induced by international travelers visiting Austria by 2.78 MtCO<sub>2</sub>eq (21.7 %).

- **Neger et al. (2021):** This study uses a destination-based accounting (DBA) approach. They estimate that the Austrian tourism sector directly emitted 4.3 MtCO<sub>2</sub>eq in 2016, which corresponds to 4.15 % of total Austrian CO<sub>2</sub>eq emissions. Notably, this estimate does not include indirect emissions from tourism activities (scope 2 and 3 emissions). Thus, the reported direct emissions are significantly lower than the estimates of Lenzen et al. (2018).

For the year 2018, the authors also calculate transport-related emissions from foreign visitors to Austria which amount to 35 MtCO<sub>2</sub>eq (and thus more than eight times the DBA emissions, corresponding to a share in total CO<sub>2</sub>eq emissions of 34.1 %). Almost 95 % of these emissions are generated by visitors arriving in Austria by air from outside Europe. Together with the DBA estimates of 4.3 MtCO<sub>2</sub>eq for 2016, this implies that about 99 % of all emissions directly caused by visitors to Austrian destinations are related to transport. However, such a high share of transport-related emissions may depend on the estimation method used (e.g., if international air carriers are included), but also on the share of international visitors arriving mainly by car or air. Other studies have found much lower shares: For Norway, Sun et al. (2022) estimate that 56 % of total carbon emissions are transport-related, the same share was reported by Kitamura et al. (2020) for Japan.

- **Prettenthaler et al. (2021):** This study reports direct transport-related emissions from residents traveling to destinations within and outside Austria (RBA) at 11.5 Mt CO<sub>2</sub>eq for 2016, with 95 % of these emissions concerning travel abroad. However, as this estimate does not include emissions from accommodation and food, it is not directly comparable with the estimates from other studies.

As the estimates by Lenzen et al. (2018) and by Neger et al. (2021) differ not only in scope (direct and indirect emissions for the former, only direct emissions for the latter), but also in magnitude, a high degree of uncertainty regarding tourism-induced emissions for Austria is evident. The challenges of estimating tourism emissions' footprint are also highlighted by Gössling et al. (2023). An emissions inventory for Austrian tourism is needed, which must shed light on tourism-induced emissions from different perspectives (DBA, RBA, producer-based accounting) and the emission sources.

### 4.3.3. Future systems: Impact of climate change on tourism

Austria's tourism industry is particularly vulnerable to climate change due to its dependence on the natural environment, which is one of the most important factors motivating international tourists to visit the country (Nature Reloaded, 2015). Rising temperatures, shifting weather patterns, and extreme weather events are reshaping tourism offerings and demand. This will consequently change tourism employment, both in terms of regionality and seasonal shifts, which may require different skill sets, training and education (Scott et al., 2019). Shifts in tourism employment will depend on changes in tourism product offerings. A detailed analysis of the impacts of climate change on the Austrian tourism industry is provided in the *Austrian Special Report 2019 'Tourismus und Klimawandel'* (Pröbstl-Haider et al., 2020), which discusses the demand- and supply-side effects of climate change.

Higher temperatures could make summer vacations in the Austrian alpine regions more attractive for both domestic and international visitors seeking cooler destinations, thus shifting their choice of destinations away from southern European destinations suffering from intense heat waves, rising sea temperatures, wildfires and water scarcity. In addition, more moderate temperatures in the shoulder months of the summer season will extend the season. On the other hand, winter tourism in the Alps is expected to lose demand due to higher average temperatures and less precipitation in the form of snow (Steiger et al., 2021). Consequently, the main adaptation strategy will be to at least partially compensate for the loss of income from alpine snow-related winter tourism by increasing tourism revenue from spring to fall (Pröbstl-Haider et al., 2020).

Austrian cities and rural, non-alpine tourism regions are also experiencing various impacts of climate change, particularly rising temperatures, but also extreme weather events.

These changes affect the environment, local economies, and overall quality of life for residents and visitors alike.

- More frequent and intense heat waves in cities can exacerbate the urban heat island effect, making them significantly warmer than surrounding rural areas (Loibl et al., 2014). This can lead to increased energy demand for cooling, higher health risks for vulnerable populations, and a greater strain on infrastructure. Additionally, higher temperatures can worsen air quality by increasing the formation of ground-level ozone, which poses health risks, particularly for individuals with pre-existing health conditions (European Climate and Health Observatory, 2021; Mayer et al., 2022; Umweltbundesamt, 2024a).
- Rising temperatures may initially appear to benefit rural tourism, but extreme heat may deter visitors. Rising air temperatures lead to higher water temperatures in lakes, which can negatively affect aquatic ecosystems (Dokulil et al., 2021). Warmer temperatures can disrupt local ecosystems, leading to changes in species composition and loss of biodiversity. Further, changes in water quality and levels can affect recreational activities such as swimming, boating, and fishing; thereby reducing the attractiveness of tourist destinations. Rising temperatures can lead to more intense and frequent precipitation events, increasing the risk of flooding that damages infrastructure, homes and businesses, and deters tourists.

In winter, the Austrian ski industry is expected to be negatively affected by rising temperatures (see [Section 1.3](#) on snow coverage). Studies on the impacts of climate change on ski tourism show a significant shortening of the ski season, less precipitation, lower snow depth, increased need and difficulty for artificial snowmaking, and a decrease in glaciers in Austria (Olefs et al., 2017; Helfricht et al., 2019; Steiger et al., 2020; Steiger and Scott, 2020; Abegg and Mayer, 2023; François et al., 2023a; Salim et al., 2023; Mayer and Abegg, 2024) (see [Section 7.4](#) for details on climate change impacts on ski destinations). Visitors may also be deterred by the lack of snow-covered landscapes. In this respect, guest numbers in ski resorts fluctuate more than the number of overnight stays (Steiger, 2010; Falk, 2013), presumably because day visitors can react more spontaneously to weather and snowfall than vacation guests (Steiger, 2011). Many Austrian ski resorts, especially those at lower altitudes, will therefore have to find alternative solutions for increasingly difficult winter operations, as it may no longer be technically possible, economically viable, or preferable/acceptable to guests

and local communities to provide sufficient snow cover in some places (see [Section 7.4](#)). However, there are also challenges in high-altitude ski resorts, particularly related to the retreat of permafrost and glaciers (Mayer and Abegg, 2024).

Furthermore, the climate crisis could significantly reduce the importance of the tourism industry in the context of a general loss of prosperity (Scott and Gössling, 2022).

#### 4.3.4. Needed transitions in the Austrian tourism sector

##### Avoid

A reduction in the **number of trips** would decrease overall GHG emissions. In the case of business trips, digitization facilitates such a reduction, as meetings are increasingly organized online (Kagermann, 2015). The COVID-19 pandemic provided incentives for firms to invest in equipment for online videoconferencing, thereby saving on travel costs. Furthermore, an increasing number of conferences are organized online or in a hybrid mode (Lenzen et al., 2018; Hanaei et al., 2022). A reduction in the number of holiday trips, accompanied by an increase in vacation duration to compensate for the loss of recreational value, could help to curb tourism-induced emissions (Pröbstl-Haider et al., 2020; Gössling and Higham, 2021).

Furthermore, as the largest share of emissions originates from mobility (Dubois et al., 2011; Pröbstl-Haider et al., 2020), visitors from **long-distance markets** traveling by air could be discouraged to spend their holidays in Austria, e.g., by refraining from marketing activities in these countries. However, global net emissions benefits are only achieved if long distance trips to (Austrian) destinations are not substituted by long distance trips to other destinations outside Austria.

##### Shift

In line with the above, climate change mitigation efforts may take the form of a shift in the target groups of the Austrian tourism industry, for example by focusing on guests that have more opportunities to travel by sustainable means of transport. This is essential, as air traveling produces 31 times more CO<sub>2</sub> emissions than train travel, and traveling with a combustion engine car produces about 15 times more CO<sub>2</sub>/km compared to the train alternative (VCÖ, 2022). Touristic service providers and tourism operators may encourage the proposed shifts by guiding guest behavior, for example by

introducing price or convenience incentives (Gössling and Higham, 2021; Bursa et al., 2022; Blättler et al., 2024). Such substitution could also be incentivized by internalizing the environmental costs of carbon emissions.

Public transportation networks, active mobility options (including bike and e-bike rental systems) or car sharing systems can be an attractive and more sustainable option for mobility within destinations (Pisoni et al., 2022; Edberg, 2024) (see [Chapter 3](#) on spatial planning and mobility). However, this can only be achieved through infrastructure investments.

A shift in the mode of transport is also key to reducing emissions from outgoing tourism: Reducing the number of long-haul trips by plane and increasing domestic travel by train, for example, already drastically reduces GHG emissions (Umweltbundesamt, 2018; VCÖ, 2022, vacation in Austria by train: 15 kg CO<sub>2</sub>/capita/d vs long-haul trip by plane: 454 kg CO<sub>2</sub>/capita/d).

##### Improve

In addition to avoiding emission-intensive tourism and shifting to a less carbon-intensive mode of the tourism production function, the current supply of tourism services, including transport to and from the destination, needs to be improved to reduce emissions (Gössling and Higham, 2021; Gössling et al., 2023). If individual travel cannot be fully shifted to public transport (both because of the mobility preferences of the travelers and insufficient rail transport capacities), the use of electric cars should be promoted by investing in charging infrastructure. If, at the same time, electricity generation is shifted to renewable energy, CO<sub>2</sub> emissions will be reduced (Holmberg and Erdemir, 2019). Numerous other transition measures have been listed and discussed for the different segments of the tourism industry (accommodation, restaurants, transport, summer and winter outdoor activities, events etc.).

Suggested improvements focus on energy efficiency (related to tourism buildings and infrastructure), waste reduction and recycling concepts, water management, intensification of natural planting to limit ground erosion, and greening of buildings to create natural shade and cooling systems (see, e.g., Pröbstl-Haider et al., 2020; Gössling and Higham, 2021). In the accommodation sector, building insulation can be improved and measures can be taken to increase energy efficiency in terms of room temperature, hot water use, and lighting (Energieinstitut der Wirtschaft GmbH, 2012). This is particularly important in city destinations, as energy demand for cooling buildings will increase as climate change

continues (Prettenthaler et al., 2008; Dowling, 2013; Berger et al., 2014a, 2014b). In addition, measures such as increasing green spaces, creating green roofs, and improving urban planning can be proposed to reduce the urban heat island effect (Aram et al., 2019).

In recent years, the Austrian tourism industry has already made a considerable shift away from non-renewable energy sources (Umweltbundesamt, 2023b): Between 2008 and 2019, the share of renewable energy in the accommodation and restaurants sector has increased from 36 to 54 %, which is above both the Austrian average of 34 % and the Austrian government's target of 50 % for 2030 (Pröbstl-Haider et al., 2020). This ongoing shift to renewable energy is necessary at the expense of non-renewable sources (see Federal Statistics Office, 2023, for where this is not the case). In Austria, several federal government programs offer financial support for companies to encourage this shift.

In winter tourism destinations, technological innovations are needed to find new ways to intensify snowmaking due to lower precipitation and higher winter temperatures, while improving the efficiency of water storage and other processes to reduce the growing demand for energy. The economic benefits should be carefully weighed against potential ecological impacts and problems associated with snowmaking, such as energy consumption, resource scarcity, and biological degradation (Aigner et al., 2024) (also see [Section 2.2](#) on ecosystem services).

However, the potential for adaptation is limited. Due to regional climate conditions, businesses and skiing resorts, especially at lower altitudes (Marty, 2013), have already closed due to economic unviability (Falk, 2013). As climate change progresses, regional 'tipping points' will be crossed, making alpine skiing impossible in certain (mostly lower-lying) alpine regions (Ginkel et al., 2020). The exact point at which skiing becomes impossible depends on several factors, including the intensity and pace of warming, the availability of technological adaptations, local geography, and snowmaking capacity (Damm et al., 2014; François et al., 2023a).

## 4.4. Industry and manufacturing

### 4.4.1. Status quo

The industry and manufacturing sector<sup>1</sup> covers a wide range of production processes needed for the transformation of

materials and energy into intermediate and finished goods. Manufacturing firms in Austria tend to use state-of-the-art technology, but energy intensity is relatively high compared to other Western European countries due to the high share of energy-intensive metal and paper industries (Diendorfer et al., 2021). Between 2014–2020, the sector contributed 18 % to Austria's value added, growing by 2 %/yr. Due to its high emission intensity, the sector's share of Austrian emissions was significantly higher over the same period, but stable (fluctuating between 32–35 %), with absolute emissions of 26 MtCO<sub>2</sub>eq in 2020 (Statistik Austria, 2023a, 2023c). Despite increasing output, absolute emissions in industry have remained relatively stable since 2005, mainly because of energy efficiency improvements (Umweltbundesamt, 2023a), indicating a relative decoupling from economic growth.

Emissions are highly concentrated in a small number of sectors and firms. In 2020, more than 80 % of the sector's emissions (or 29 % of total national emissions) came from four groups of products (see [Figure 4.6](#)): Basic metals (12 MtCO<sub>2</sub>eq, 16 % of national emissions), other non-metallic mineral products (5 MtCO<sub>2</sub>eq, 7 %), chemicals and chemical products (2.2 MtCO<sub>2</sub>eq, 3 %), and paper and paper products (1.9 MtCO<sub>2</sub>eq, 2 %) (Statistik Austria, 2023f, 2023e, 2023c).

### 4.4.2. Current and future systems

The following sections present sectoral perspectives and economy-wide effects in the Austrian context. More details on mitigation options and emission reduction potentials per sector are given in [Table 4.A.1](#). Global trends for each sector can be found in the [appendix](#) as well.

#### Steel

In Austria, the metal sector is relatively large, with steel being the most important product. In 2020, the sector 'manufacture of basic metals' generated 1.1 % of the economy's value added (EUR<sub>2023</sub> 4.45 billion) and employed more than 37,000 people (Statistik Austria, 2023a, 2023b). Emissions come mainly from the use of coal/coke as a reducing agent and from the high temperatures required for steel production (see [Figure 4.6](#) for details). Steel output has been stable since 2018, between 7–8 Mt/yr (WSA, 2023a), of which 90 % is produced via the blast furnace-basic oxygen furnace (BF-BOF) route (WSA, 2023b). The specific energy demand of crude steel in Austria is 4.9 MWh/t, its emission factor is 1.7 tCO<sub>2</sub>eq/t which is below the global and EU averages

<sup>1</sup> In this section the industry and manufacturing sector is defined as NACE sectors 10–32, if not stated differently.

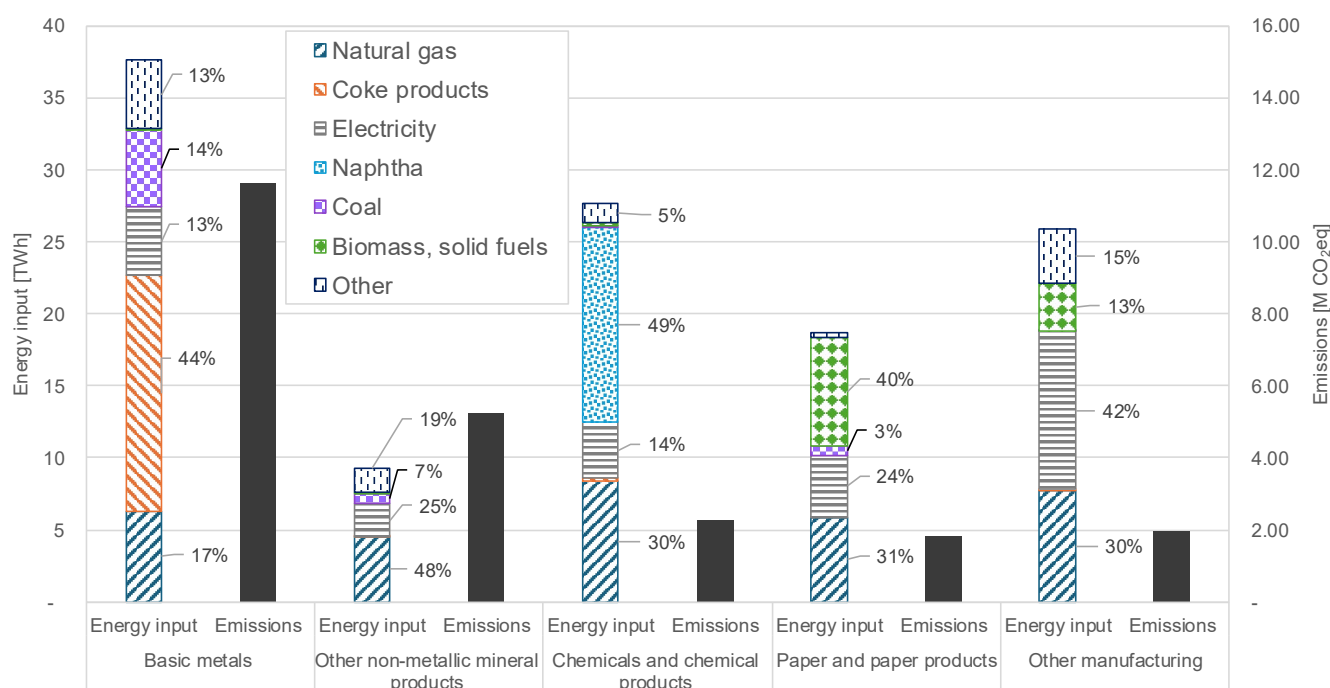


**Figure 4.6** Production-based direct GHG emissions and energy inputs by energy product (covering also feedstocks) and sector. The sector ‘manufacture of coke and refined petroleum products’ was excluded from ‘other manufacturing’. Sources: Physical Energy Flow Accounts (Statistik Austria, 2023f) and Air Emissions Accounts (Statistik Austria, 2023c).

(5.5 and 1.9 respectively) (Alton et al., 2022; Rahnama Mobarakeh and Kienberger, 2022). 88 % of emissions are process-related and 12 % are combustion-based (Rahnama Mobarakeh and Kienberger, 2022).

Emissions can be reduced by increasing circularity, especially by increasing the proportion of secondary steel (avoid). It is estimated that scrap-based steel production emits only one-eighth of the carbon compared to the conventional BF-BOF route (Wang et al., 2021). In the long term, the Austrian steel sector plans to switch to a hydrogen-based direct reduced iron-electric arc furnace (DRI-EAF) route (using natural gas as a bridging fuel until hydrogen becomes economical; shift). At constant output, this would require an additional 30–33 TWh of electricity (50 % of today’s demand in Austria) (Mayer et al., 2019b; Alton et al., 2022). Efficiency improvements (improve) can further reduce emissions, but emissions are already close to the best available technology (BAT) of 1.6 tCO<sub>2</sub>eq/t (Material Economics, 2019).

Mayer et al. (2019b) derive Austria-specific unit costs of EUR<sub>2023</sub> 551/t of steel for a low-cost specification (Plasma Direct Reduction) and EUR<sub>2023</sub> 760/t for a high-cost specification (H<sub>2</sub> based DRI), compared to the current BF-BOF route at EUR<sub>2023</sub> 500/t. However, these figures are highly sensitive to electricity price assumptions. Other estimates range between EUR<sub>2023</sub> 460–1,020/t, covering (in order of increas-

ing cost): Recycling via EAF, gas-based DRI-EAF, gas-based DRI-EAF with carbon capture and storage (CCS), hydrogen-based DRI-EAF, smelting reduction with CCS as well as material efficiency and circularity (Material Economics, 2019; IEA, 2020).

Austria-specific ‘greenfield’ investment requirements for carbon-neutral steel production technologies are about EUR<sub>2023</sub> 1,340/t of annual capacity (corresponding to capital expenditures (CAPEX) of about EUR<sub>2023</sub> 120/t) (Mayer et al., 2019b). In the international literature, the range is EUR<sub>2023</sub> 670–1,050/t (Chiappinelli et al., 2021). Investment requirements are estimated to be 60–65 % higher for the implementation of new processes or CCS, but only 25 % higher (or even below baseline levels in the long term) for a circular economy pathway (Material Economics, 2019).

## Cement

In Austria, the sector ‘manufacture of other non-metallic mineral products’ directly generated 0.8 % of the value added in 2020 (EUR<sub>2023</sub> 3.1 billion), employing 30,500 people (Statistik Austria, 2023a, 2023b). Emissions come mainly from geogenic process-emissions and the combustion of gas and waste for high-temperature heat in cement production (Rahnama Mobarakeh and Kienberger, 2022) (see Figure

4.6). In 2020, Austria produced 5.2 Mt of cement and is equipped with highly efficient dry kiln factories, producing at 0.84 MWh/t of cement, generating 0.5 tCO<sub>2</sub>/t cement (Rahnama Mobarakeh and Kienberger, 2022).

In the Austrian context, short/medium term solutions are improve-measures such as circular economy (including recycling) and material efficiency increases, further increases in energy efficiency, the use of waste fuel with higher heating value content as well as biomass. Specifically, the share of biomass in alternative waste fuels (AWFs) could be increased (depending on availability; see Section 2.3.2) until AWFs are replaced by biomethane or hydrogen (fuels with higher calorific values) by mid-century. However, this would only reduce heat-related emissions. Since a large share (60 %) of CO<sub>2</sub> emissions are process-related (coming from the chemical reaction to decompose limestone (CaCO<sub>3</sub>) into lime (CaO) and CO<sub>2</sub>), CCS/CCU (improve) is currently seen as an option to reach carbon neutrality in the long term (Plaza et al., 2020; Bashmakov et al., 2022; Rahnama Mobarakeh and Kienberger, 2022) (see also Section 4.6). Specifically, ‘cement electrolysis’ with CCUS is currently being researched (mostly in the US), indicating both technical and economic viability (Mowbray et al., 2023). Energy demand for the non-metallic minerals sector in Austria is expected to increase by 25–90 % (2–9 TWh), mainly due to higher electricity demand for CCS. Natural gas and coal are expected to be replaced by hydrogen (Alton et al., 2022).

Production costs of carbon-neutral cement are estimated to be 70–115 % higher than the reference technology when using CCS (Material Economics, 2019). The cheapest alternative technology is oxyfuel CCS with cost estimates between EUR<sub>2023</sub> 100–110/t clinker. Other technologies range between EUR<sub>2023</sub> 130–150/t clinker. In general, higher CAPEX, higher fixed operating costs, and the higher electricity and steam requirements drive the cost increase (Gardarsdottir et al., 2019). Investment requirements are estimated to increase by 22–49 %, with a circular economy pathway demanding the lowest additional investment (Material Economics, 2019).

## Chemicals

In Austria, the sector ‘manufacture of chemicals and chemical products’ contributed with 0.9 % (EUR<sub>2023</sub> 3.85 billion) to total value added, employing 18,600 people in 2020 (Statistik Austria, 2023a, 2023b). Energy demand and emissions are mainly driven by low and high temperature heat provision via natural gas (for details, see Figure 4.6).

Specifically for Austria, the methanol-to-olefin (MTO) process appears to be a promising option (Alton et al., 2022), which could replace naphtha (i.e., a fossil resource) as feedstock (improve). However, this requires methanol, which could be produced from biomass (depending on availability; see Section 2.3.2 on a sufficiency oriented bio-economy) or hydrogen and captured CO<sub>2</sub> from other sectors (e.g., cement). Such production of the feedstock would increase energy intensity, but (within the system boundaries of the chemicals industry) the process could become a carbon sink, by absorbing captured carbon from other sectors. Ammonia could be completely synthesized from hydrogen. Following the decarbonization pathways described in (Alton et al., 2022), the total energy demand of the Austrian chemicals sector (28 TWh in 2020) is projected to increase strongly, reaching between 53–63 TWh in 2050, of which 8–9 TWh will be electricity, the rest hydrogen and biofuels as feedstock. This is due to the higher energy intensity of the processes compared to the status quo (particularly the MTO process). Taking into account the electricity required for hydrogen production, electricity demand would increase by 42 TWh.

Switching to low-carbon production routes in the chemicals sector is estimated to increase costs as the feedstock has to be synthesized. For plastics, cost increases are estimated at 20–43 % (Material Economics, 2019). For ammonia and methanol, cost increases are expected to range from 25–90 % depending on the technology and feedstock, with electrification options being the most expensive and CCU-based options less so (IEA, 2020). Investment requirements in the plastics industry are estimated to increase by 122–199 % (Material Economics, 2019).

## Pulp and paper

In Austria, the sector ‘manufacture of paper and paper products’ accounted for 0.7 % (EUR<sub>2023</sub> 2.76 billion) of national value added in 2020 and employed 17,000 people (Statistik Austria, 2023a, 2023b). Direct emissions mainly come from natural gas combustion for low-temperature heat for drying processes (Figure 4.6 gives details). In 2020, 1.6 Mt of pulp and 5.6 Mt of paper and board were produced in Austria (CEPI, 2023).

Short to medium term mitigation options in Austria are efficiency improvements and fuel switching (to electricity) (improve). The emission intensity can still be decreased, which is currently 0.38 tCO<sub>2</sub>/t paper (compared to the EU average of 0.33). In addition, heat management (recovery of

waste heat) can be further improved and alternative drying technologies used. Natural gas in boilers could be replaced by biofuels (depending on availability, see [Section 2.3.2](#) on a sufficiency oriented bioeconomy), or non-electric boilers could be replaced by electric boilers (improve). In the long term, further electrification and installation of heat pumps and an increase in the share of biofuels in combined heat and power (CHP) can replace natural gas (the only source of direct emissions). The low process emissions from lime kiln (3 %) could be phased out through CCS/CCU (Rahnama Mobarakeh and Kienberger, 2022) (improve). In terms of

energy demand, electricity demand could increase significantly from 2 to 7 TWh if heat pumps are used on a large scale, replacing 6 TWh of natural gas (Alton et al., 2022).

Cost estimates for decarbonizing the pulp and paper industry are scarce. Abatement costs from full biomass firing are estimated to be around EUR<sub>2023</sub> 54/tCO<sub>2</sub>eq (Bashmakov et al., 2022). Economy-wide estimates of investment requirements for decarbonizing low-temperature heat range from EUR<sub>2023</sub> 320–570 million (with the cheapest option being heat pumps) and the conversion of CHP plants is estimated to require EUR<sub>2023</sub> 140–230 million (Diendorfer et al., 2021).

### Chapter Box 4.1. Integrated scenarios for industry decarbonization in Austria

The study by Alton et al. (2022) presents two mitigation pathways for the industry and manufacturing sector in Austria up to 2050, with the goal of achieving full decarbonization. The results for the four energy-intensive sectors steel, cement, chemicals, and pulp and paper are summarized in [Table 4.1](#). The first scenario, called ‘Pathway of Industry’ (POI), was developed based on an intensive stakeholder dialogue and represents their expected developments until 2030, with extrapolations until 2050. The second scenario, called ‘Zero Emission’ (ZEM), is based on a back-casting approach and reaches carbon neutrality by 2050, assuming breakthrough technologies. In the **steel** sector, both scenarios assume a shift to direct reduction (at constant steel output), using mainly (natural-, bio- and synthetic) gas in the POI scenario and mainly hydrogen in the ZEM scenario. In the **chemicals** sector, a shift from fossil resources to hydrogen, biofuels, biomass, and electricity is assumed. Due to the assumed methanol-to-olefins process, the production of methanol increases strongly, which also implies a higher energy demand for synthesizing feedstocks. The **cement** industry (included in non-metallic minerals) is assumed to deploy CCS technologies (amine scrubbing in POI and oxyfuel in ZEM), which increases electricity demand. In the **pulp and paper** sector, emissions are reduced by increasing the share of biofuels and using hydrogen in POI, whereas in ZEM electrification through heat pumps leads to zero emissions and lower energy demand. Overall, emissions from industry and manufacturing are reduced by 98 % (to 0.6 Mt in POI) and 106 % (to -1.6 Mt in ZEM). Compared to 2020, energy demand increases by 47 % in POI and 50 % in ZEM, with the largest increases in the chemicals sector (+227 % in POI and +294 % in ZEM).

**Table 4.1** Current (2020) and future (2050) energy demand, emissions for the four sectors steel, chemicals, non-metallic minerals, and pulp and paper, as well as for rest of manufacturing in Austria for two scenarios (POI and ZEM) (Source: Alton et al., 2022; Nagovnak et al., 2024). Note that numbers do not match Figure 4.7 due to differences in system boundaries.

|                                     | 2020                |          |                                |                            |       |                         | 2050 POI            |          |                                |                            |       |                         |                | 2050 ZEM            |          |                                |                            |       |                         |                |
|-------------------------------------|---------------------|----------|--------------------------------|----------------------------|-------|-------------------------|---------------------|----------|--------------------------------|----------------------------|-------|-------------------------|----------------|---------------------|----------|--------------------------------|----------------------------|-------|-------------------------|----------------|
|                                     | Energy demand [TWh] |          |                                |                            |       | [Mt CO <sub>2</sub> eq] | Energy demand [TWh] |          |                                |                            |       | [Mt CO <sub>2</sub> eq] |                | Energy demand [TWh] |          |                                |                            |       | [Mt CO <sub>2</sub> eq] |                |
|                                     | Electricity         | Hydrogen | Hydrogen transformation losses | Other fuels and feedstocks | Total | Emissions               | Electricity         | Hydrogen | Hydrogen transformation losses | Other fuels and feedstocks | Total | Excl. hydrogen          | Incl. hydrogen | Electricity         | Hydrogen | Hydrogen transformation losses | Other fuels and feedstocks | Total | Excl. hydrogen          | Incl. hydrogen |
| Steel                               | 2.6                 | -        | -                              | 34.2                       | 36.8  | 12.8                    | 4.8                 | 7.1      | 3.0                            | 15.6                       | 30.5  | 0.7                     | 0.8            | 4.8                 | 19.6     | 8.4                            | 4.3                        | 37.1  | 0.8                     | 1.2            |
| Chemicals                           | 4.4                 | -        | -                              | 11.5                       | 15.9  | 3.9                     | 9.3                 | 19.2     | 8.2                            | 15.3                       | 51.9  | -2.4                    | -2.0           | 8.3                 | 23.2     | 10.0                           | 21.1                       | 62.6  | -4.8                    | -4.3           |
| Non-metallic minerals               | 1.9                 | -        | -                              | 7.8                        | 9.7   | 5.2                     | 7.2                 | 2.3      | 1.0                            | 6.0                        | 16.5  | 1.0                     | 1.0            | 4.9                 | 1.3      | 0.6                            | 5.3                        | 12.1  | 0.8                     | 0.9            |
| Pulp and paper                      | 2.3                 | -        | -                              | 19.5                       | 21.7  | 2.2                     | 2.3                 | 4.1      | 1.8                            | 16.0                       | 24.3  | 0.0                     | 0.1            | 7.1                 | 0.0      | 0.0                            | 12.2                       | 19.3  | 0.1                     | 0.1            |
| Rest of manufacturing               | 12.7                | -        | -                              | 17.4                       | 30.1  | 5.4                     | 24.9                | 6.4      | 2.7                            | 10.2                       | 44.3  | 0.6                     | 0.7            | 23.4                | 3.4      | 1.4                            | 12.2                       | 40.4  | 0.4                     | 0.5            |
| <b>All manufacturing industries</b> | 23.8                | 0.0      | 0.0                            | 90.4                       | 114.2 | 29.5                    | 48.6                | 39.1     | 16.7                           | 63.1                       | 167.5 | -0.2                    | 0.6            | 48.5                | 47.5     | 20.4                           | 55.2                       | 171.5 | -2.6                    | -1.6           |
| 2050 POI/2020                       | +104 %              |          |                                | -30 %                      | +47 % | -98 %                   |                     |          |                                |                            |       |                         |                |                     |          |                                |                            |       |                         |                |
| 2050 ZEM/2020                       | +104 %              |          |                                | -39 %                      | +50 % | -106 %                  |                     |          |                                |                            |       |                         |                |                     |          |                                |                            |       |                         |                |

## Other manufacturing sectors

The GHG emissions from the remaining manufacturing sub-sectors (2 MtCO<sub>2</sub>eq) account for 8 % of emissions from industry and manufacturing (Diendorfer et al., 2021) (see Figure 4.6). The emissions can be attributed to a large and heterogeneous number of manufacturing firms, mostly operating in the construction industry, followed by mechanical engineering, food and beverages, and woodworking industries. The same sectors are also the main emitters of GHG emissions, although other relevant processes include mining, the processing of non-ferrous metals, vehicle construction, and textiles. Due to the lower energy intensity of these sectors, only nine manufacturing plants are covered by the EU-ETS.

Although relatively less energy intensive overall, a significant share of the energy demand in the ‘other manufacturing’ sector is due to energy-intensive processes, requiring targeted mitigation measures. In the construction sector, by far the largest technical decarbonization potential rests in the electrification of engines or the switch to carbon-neutral gas for the operation of machinery and off-road vehicles (improve). In other sectors, significant reductions in GHG emissions could be achieved by installing heat pumps (shift) to meet the energy demand for process heat (<200°C), which is particularly high in the food and mining industries, and for room heating, for which natural gas remains a common energy source in machine engineering and the woodworking industries (Diendorfer et al., 2021).

## Economy-wide effects

Production costs and prices of carbon-neutral materials and goods are expected to be higher, yet the direct impact on consumers is estimated to be small. Price increases for typical final demand goods (such as plastic bottles, cars or houses) are estimated at 1–5 %, despite large price increases for materials (cement: 35–115 %, steel: 10–50 %, and primary chemicals: 15–115 %) (Bataille et al., 2018; Material Economics, 2019; Bashmakov et al., 2022). The effects on consumption possibilities (welfare) could be stronger if changes in income or employment are included. Bachner et al. (2020a), analyzing the transition of the European steel sector, show income (GDP) effects for Austria between +0.5 % and -1.5 %, depending on the assumption of production factor availability (idle or not). In particular, capital owners could benefit from distributional effects due to higher capital intensities (Bachner et al., 2020b). Regarding the timing of decarbonization, early action may be less costly in

terms of foregone GDP per avoided ton of CO<sub>2</sub> (Bachner et al., 2020b; Steininger et al., 2021). For labor-market implications, see Section 4.7.

### 4.4.3. Climate related risks and adaptation of industry and manufacturing

Industry and manufacturing are affected by physical risks related to climate (change). Energy-intensive firms are often located along rivers for access to water and waterways, making them vulnerable to water scarcity and fluvial flood risk (Bashmakov et al., 2022). For Austria, Bachner et al. (2023) estimate the current direct flood risk via sectoral capital stock damages for the whole economy, represented by 72 sectors. Out of a total of 18 manufacturing sectors, 12 are among the top 30 sectoral losers, with the highest direct risks in the ‘fabricated metal products’, ‘chemicals and chemical products’, ‘basic metals’ and ‘food products’. As the flood risk in Austria is expected to increase (see Cross-Chapter Box 1), a sectoral analysis of the future flood risk in Austria is necessary. Heat-induced labor productivity losses are also an important risk, both globally (Dasgupta et al., 2021) and for Austria (Urban and Steininger, 2015). Next to direct risks, indirect risks via supply chains are also a concern for industry (Bednar-Friedl et al., 2022b). Extreme weather events abroad (e.g., floods), but also gradual climate change (e.g., rising temperatures and resulting losses in labor productivity) can trigger negative economic effects domestically (Knittel et al., 2020, 2024).

In terms of adaptation, European industry has been found to have a low level of adaptation, with SMEs often lacking sufficient knowledge (Bednar-Friedl et al., 2022a). Little is known about adaptation in Austria’s industry sector. Key adaptation options for industry are knowledge creation, research and development (R&D), and risk management, with governments and international communities seen as key actors for adaptation (Bednar-Friedl et al., 2022b). Some industries could benefit from adaptation, as demand for materials such as concrete or steel could increase, for example for flood protection or sea walls (Bashmakov et al., 2022). Relocation could also change exposure to natural hazards.

### 4.4.4. Necessary transformation of industry and manufacturing

Direct and indirect electricity demand is expected to grow strongly (Lechtenböhrer et al., 2016; Geyer et al., 2021; Nagovnak et al., 2024). Direct demand is estimated to in-

crease by 110–130 % at constant production levels (Geyer et al., 2021; Alton et al., 2022). Thus, in addition to avoid measures, material efficiency (i.e., reducing material demand), and energy efficiency improvements, the transition to a fully renewable electricity supply is key to a system-wide decarbonization (Material Economics, 2019; Rissman et al., 2020; Geyer et al., 2021; Edelenbosch et al., 2024). Under insufficient domestic supply (see Table 4.A.3 for the range of estimates), imports could be a complementary strategy. However, uncertainties regarding the stability of the electricity grid and the flexibility of the energy system have been identified as key concerns (Bachner et al., 2020b). Due to these uncertainties, industries could relocate to regions with high renewable energy availability at low prices (Samadi et al., 2023; Verpoort et al., 2024) and high potential for CCS (Bashmakov et al., 2022), thus requiring a societal debate on this ‘renewables pull’ effect (Verpoort et al., 2024).

Estimated investment requirements for decarbonizing steel, plastics, ammonia, and cement in the EU are 0.2 % of gross fixed capital formation, but for individual firms, investment in (often costlier) low-carbon technologies might be too risky due to high uncertainties (see Section 4.4.2 for sectoral investment requirements). A particular feature is the high share of ‘process emissions’ (emissions from non-combustion processes in production), which require fundamentally new tailor-made processes and equipment (Odelenbosch et al., 2022). These are mostly available at relatively high levels of technological readiness (Alton et al., 2022), but some key technologies and their integration into existing process chains require further R&D (Gailani et al., 2024). Crucially, investment incentives are often weak due to the characteristics of these industries, the risk of asset obsolescence, and uncertainties about future technological and commercial viability (Wesseling et al., 2017; Bataille et al., 2018; Material Economics, 2019; Zhang et al., 2022). However, there are opportunities for first-movers to gain competitive advantages if the appropriate market framework is established (Karkatsoulis et al., 2016; Bachner et al., 2020b; Zhang et al., 2022). To achieve a decarbonized industry, a mix of measures is needed, in particular investment support schemes, contracts-for-difference, market-based instruments (CO<sub>2</sub> pricing, border carbon adjustment) and a strengthening of circular economy principles (Edelenbosch et al., 2024) (see also Chapter 6).

In industrial SMEs, where the energy intensity of core production processes is low, support processes (e.g., lighting, ventilation, heating) can account for a significant share of energy demand and have been found to be the most promising intervention points for achieving reductions

in energy use (Johansson et al., 2019). The main firm-level barriers in industrial SMEs relate to lack of information and the insufficient financial viability of investments and alternative procurement models such as energy contracting (Fresner et al., 2017; Johansson et al., 2019; Hrovatin et al., 2021). A cost-effective policy mix to reduce energy demand in industrial SMEs provides tailored support through a combination of subsidized energy audits and subsidies for investments in technologies (Johansson et al., 2019). For more energy-intensive medium-sized enterprises, supporting the implementation of energy management systems, facilitating learning networks, and regulatory policies can increase the adoption rate of energy efficiency measures (Thollander et al., 2015; Paramonova and Thollander, 2016; Jalo et al., 2021; Johansson et al., 2022).

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## 4.5. Energy supply systems

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### 4.5.1. Characteristics of the current energy system/status quo

Although fossil fuel use declined from 75 to 66 % of total primary energy consumption when comparing the period 2003–2007 to 2019–2023, the Austrian energy system is still largely based on fossil fuels (Statistik Austria, 2024a) (see Figure 4.7a). Coal use shows the strongest decline (-35 %), followed by fossil oil use (-18 %). Gas consumption decreases slightly over the whole period (-6 %). The decline in fossil fuel use is made possible by a stabilization of gross energy use (improve measures), and a switch from fossil fuels to biomass (53 % increase), ambient heat (216 % increase), wind and solar PV (707 % increase), and hydropower (10 % increase) (shift measures) (see Figure 4.7a). As a consequence of the high use of fossil fuels, about 58 % of primary energy was imported on average in the period 2019–2023 (see Figure 4.7b). This affects Austria’s energy trade balance and comes with several other challenges related to, inter alia energy security, affordability, and flexibility (see Section 4.2). At the pace of the energy transition until 2021, it is impossible to achieve a carbon-neutral Austria by 2040 (Auel and Schmidt, 2023).

The sector ‘production’ slightly increased its final energy consumption (+4 %), ‘households’, ‘services’ and ‘other’ decreased final energy consumption by 1 %, and ‘transport’ slightly decreased by 2 % when comparing 2003–2007 with 2019–2023 (see Figure 4.7c and d).

In 2019–2023, natural gas was mainly used in ‘production’ (58 %), followed by ‘households’, ‘services’ and ‘other’ (39 %). Natural gas use in the ‘transport’ sector was low (at around 3 %). Compared to the period 2003–2007, ‘industry’ and ‘production’ increased their share by 8 % at the cost of ‘households’, ‘services’ and ‘others’.

Fossil oil is mainly used in transport (82 %), and this share even increased from 72 % in the period 2003–2007. ‘Households’, ‘services’, and ‘other’ have reduced their use of fossil oil for heating (the share decreased from 21 to 14 %). Overall, fossil oil consumption in the ‘transport’ sector decreased slightly from 96 TWh (2003–2007) to 89 TWh (2019–2023), taking into account the very weak years in terms of transportation consumption due to COVID-19 restrictions (Hartwig et al., 2022; Staehle et al., 2022).

Coal is mainly used in the ‘production’ sector (97 %), mainly for steel production. Compared to the period 2003–2007, this share increased by 17 %, as ‘households’, ‘services’, and ‘other’ have significantly reduced their coal consumption, mainly due to the fading out of coal as a heating fuel (shift measure). Coal use in the ‘transport’ sector has virtually disappeared.

The use of renewables has increased in absolute terms in all sectors, but the share of the ‘transport’ sector in all renewables increased from about 5 % in the period 2003–2007 to 10 % in the period 2019–2023, and it decreased in the ‘production’ sector from 34 to 30 %, while the sector ‘other’ remained constant.

As a consequence of the slow pace of the energy transition, fossil fuel combustion is still by far the largest emitter

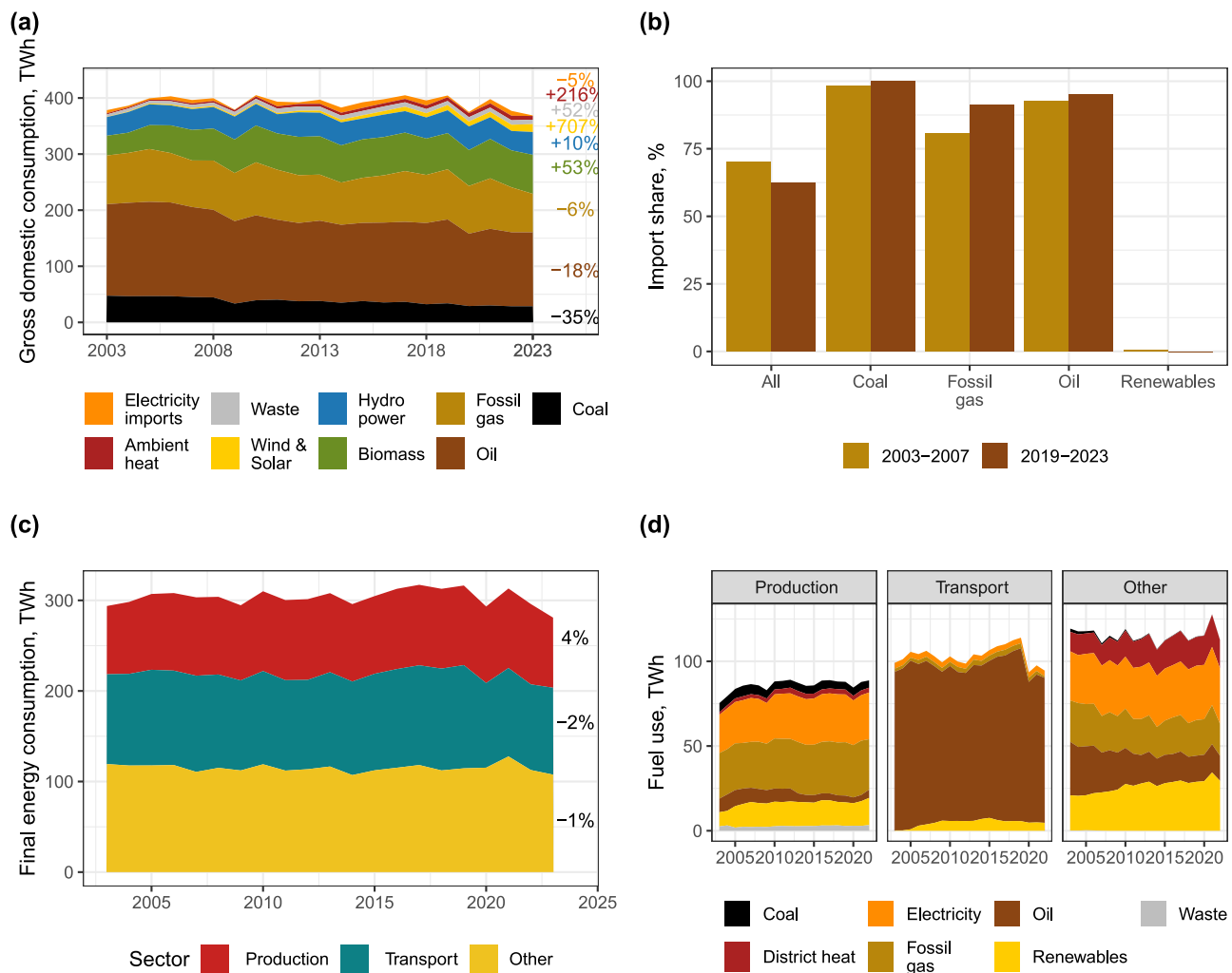


**Figure 4.7** (a) Gross domestic energy consumption by fuel in Austria for 2003–2023 based on Austrian energy balance. (b) Import shares by fuel. (c) Structure of final energy demand by sector. (d) Final energy use by fuel and sector. The numbers on the right side of (a) and (c) show the growth rate in percent from the period 2003–2007 to 2019–2023, e.g., coal use has declined by 35 % in the period. The category ‘other’ includes households, services and agriculture. (Source: Energiebilanzen, Statistik Austria, 2024a).

of greenhouse gases in Austria (66 % in 2018–2022, compared to 71 % in 2003–2007) (Umweltbundesamt, 2025).

Austria's energy infrastructure is characterized by geographical and technological peculiarities. In the electricity sector, hydropower accounts for a large share of electricity generation in most of the federal provinces, with the exception of Burgenland and Vienna; wind power plants are located mainly in Burgenland and Lower Austria, and to a lesser extent in Styria. The Austrian electricity grid has a length of about 250,000 km. As far as the gas infrastructure is concerned, there are currently 47,000 km of gas network in Austria. In both cases, the vast majority is at the distribution network level. The Austrian gas storage facilities are located in Upper Austria and Salzburg (about 75 %) and in the east of Lower Austria (about 25 % of the total Austrian storage volume). Due to its location in Central Europe, Austria is an important energy transit country and the related infrastructure is also relevant for neighboring countries (BMK, 2024a).

#### 4.5.2. Characteristics of the future energy system

A future carbon-neutral energy system can rely on a combination of domestic energy supply technologies and imported

energy carriers, i.e., wind power, solar PV, biomass, geothermal energy, hydropower and imported hydrogen, other synthetic fuels and fossil fuels with carbon capture and storage (shift measures, strong co-benefits between these mitigation options and SDG 7) (see Table 4.A.3). However, there is little agreement on the best mix of these technologies, as many different technological pathways allow achieving climate neutrality in the Austrian energy system, and the underlying scenario processes make significantly different assumptions about the potentials of different technologies (see Figure 4.8). However, there is a consensus that renewable energies, especially wind power and solar PV, need to be strongly expanded, and that the electrification of land transport and heat supply is crucial. Both measures are a common driver of decarbonization in all available scenarios up to 2030, but the scenarios differ more after 2030. Electrification causes a substantial decrease of gross domestic energy consumption of 50–100 TWh by 2040 (BMK, 2024a; Schmidt et al., 2025). Under the assumption of unlimited potentials and from an energy system perspective, wind power fits seasonal demand and hydropower supply patterns better than solar PV. Systems with a higher share of wind power therefore have a higher level of reliability at the same cost or the same level of reliability at a lower cost (Scholz et al., 2017; Maeder et al.,

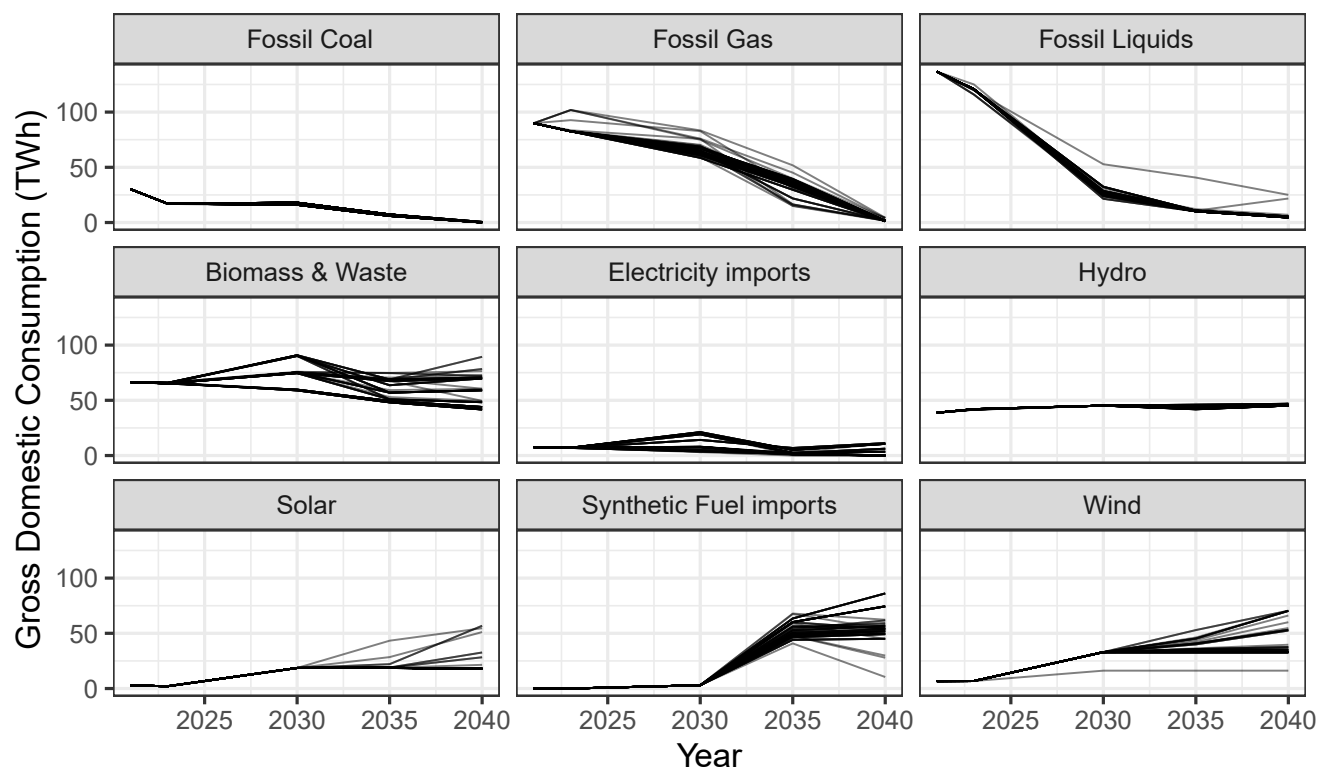


**Figure 4.8** Gross domestic energy use by energy carrier in Austrian net-zero scenarios. The reference data shown in this figure is available at [aar2.ccca.ac.at/explorer](https://aarr2.ccca.ac.at/explorer).

2021; Wehrle et al., 2021; Schmidt et al., 2025). Furthermore, if synthetic fuels are available as imports, domestic electricity generation can be reduced, as the production of these fuels, especially for use in hard-to-abate industries, is electricity intensive (Schmidt et al., 2025). Similarly, biomass is a versatile fuel that can replace the use of synthetic fuels, but sustainable potentials are limited in Austria (Schmidt et al., 2025). Notably, in climate neutrality scenarios, biomass will be used in different sectors than today: Its use will be reduced in domestic heating as it is replaced by heat pumps and thermal insulation, while biomass will be instead upgraded to biogenic methane for use in high-temperature processes in industry (the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](https://aar2.ccca.ac.at/explorer)).

The electrification of energy services supports the achievement of mitigation goals, as it allows for highly efficient delivery of energy services and the direct use of variable renewable electricity generation (Luderer et al., 2022; Sejkora et al., 2022; Schmidt et al., 2025) (the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](https://aar2.ccca.ac.at/explorer)). Therefore, final consumption of electricity increases in all scenarios. Electrification means that sectors that previously operated in isolation will become much more integrated (Brown et al., 2018), such as the power sector, mobility, and heating and cooling, as formerly fossil-fueled processes in these sectors are electrified, for instance using heat pumps and electric cars (Schmidt et al., 2025). Further energy efficiency measures such as high insulation rates and building standards for new construction, as well as measures to reduce the level of energy services on the demand side, such as a reduction in heated area or driven distances, will help limit the necessary infrastructure expansion on the supply side (avoid measures) (the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](https://aar2.ccca.ac.at/explorer)) (see Sections 4.2, 3.3, 3.4). In the transportation sector, demand-side measures are generally very important, especially if a very rapid electrification of cars and trucks, far beyond current penetration rates, is not achieved (Schmidt et al., 2025) (see Section 3.4). However, changes in demand for land transport services in a fully electrified land transportation sector will only have a limited impact on total gross domestic energy consumption due to the high efficiency of electric drives (Schmidt et al., 2025). In contrast, a major reduction in energy demand by industry is the most important driver of reductions in gross domestic energy use in decarbonization scenarios (Schmidt et al., 2025).

Scenarios of a climate neutral Austrian energy system indicate that **hydrogen, synthetic gases and fuels** will be used

primarily in industry, air and ship transportation, and partly to balance the power grid (see Figure 4.9; the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](https://aar2.ccca.ac.at/explorer)), as other uses are too costly (Ueckerdt et al., 2021). Hydrogen and synthetic methane play an important role in industry, where their use can only be avoided by expanding carbon capture and storage in combination with fossil fuels. As intensive carbon capture and storage pathways have not been extensively assessed in integrated energy system scenarios in Austria, the use of hydrogen, synthetic gases and fuels in industry is high in the available scenarios (Schmidt et al., 2025) (the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](https://aar2.ccca.ac.at/explorer)). However, there are significant differences between the scenarios: First, if Austria does not produce raw iron, but uses either scrap steel or imports direct reduced iron pellets (shift and avoid measure), the demand for hydrogen in the industry sector decreases significantly (Sections 4.2 and 4.4). Second, if the availability of these fuels is limited or if they are expensive, the scenarios instead show increased electrification of industry, higher utilization of hydrogen than synthetic methane, and increased use of biomass upgraded to biomethane. Furthermore, synfuels are relevant for replacing fossil fuels in air and ship transport (see Section 3.4). In district heating and power generation, the use of hydrogen or synthetic methane depends on the scenario assumptions and the variability between scenarios is high. In land transport, synthetic fuels are used extensively only in scenarios where uptake of electrification is exogenously limited. For households and services, synthetic gas is exclusively used because of the lock-in of gas-based infrastructure for heating, i.e., the long lifespan of today's heating infrastructure requires the use of some synthetic gas as a substitute for fossil gas. Hydrogen, synthetic fuels, and gas are either imported or produced domestically, depending on relative cost assumptions and assumptions about the expansion of domestic renewables. In all scenarios, how-

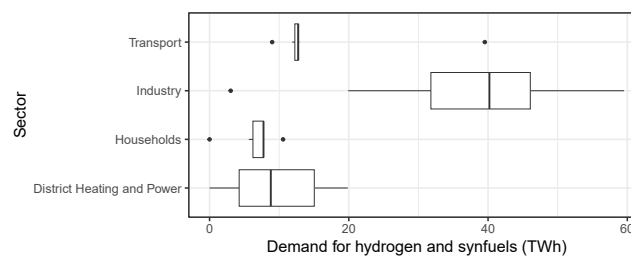


**Figure 4.9** Use of hydrogen, synthetic gas and synthetic fuels in different applications in the energy system (74 scenarios of a climate neutral Austrian energy system; the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](https://aar2.ccca.ac.at/explorer)).

ever, dependence on imports of energy carriers is reduced compared to today because the use of hydrogen, synthetic gases and fuels is less than today's fossil fuel consumption. At the same time, material dependencies may arise in the renewable energy sector (see [Cross-Chapter Box 5](#)). A further reduction in demand also leads to a further reduction in import dependency (Schmidt et al., 2025).

In terms of **infrastructure**, the expansion of the electricity grid is seen of high importance for the integration of increasing shares of renewable electricity in the energy system. Costs for this are estimated at EUR<sub>2023</sub> 8.75 billion by 2034 (BMK, 2024a). In the gas sector, a parallel infrastructure for renewable methane and hydrogen is planned and associated with costs of EUR<sub>2023</sub> 1.9 billion until 2050 (BMK, 2024a).

### Energy supply security and resilience of systems and infrastructure

A central question is how the Austrian decarbonized energy system has to be designed while maintaining security of

supply and resilience, considering all aspects of mitigation and adaptation. Current energy systems have relatively large buffers as fossil fuels are easily storable. Renewables-based energy systems show a reduction in these buffers and an increased demand for flexibility (Kondziella and Bruckner, 2016; Suna et al., 2022). In electrified systems with large shares of variable renewables, the size of buffers and associated costs may increase due to higher variability of supply. At the same time, the acceptable risk of electricity system failure may decrease, as electrification will interconnect many different sectors.

Flexibility options in the carbon-neutral electricity system can be provided by (a) sector coupling (for more detailed information on energy storage in buildings and mobility, see [Chapter Boxes 3.2](#) and [3.3](#)), (b) short- and long-term storage, (c) carbon-neutral firm capacity, (d) demand-side management (e.g., industrial or residential load shifting) (Märkle-Huß et al., 2018; Christensen et al., 2020; Mascherbauer et al., 2022; Schwaiger et al., 2023), and (e) exports/imports (Resch et al., 2020; Haas et al., 2022; Suna

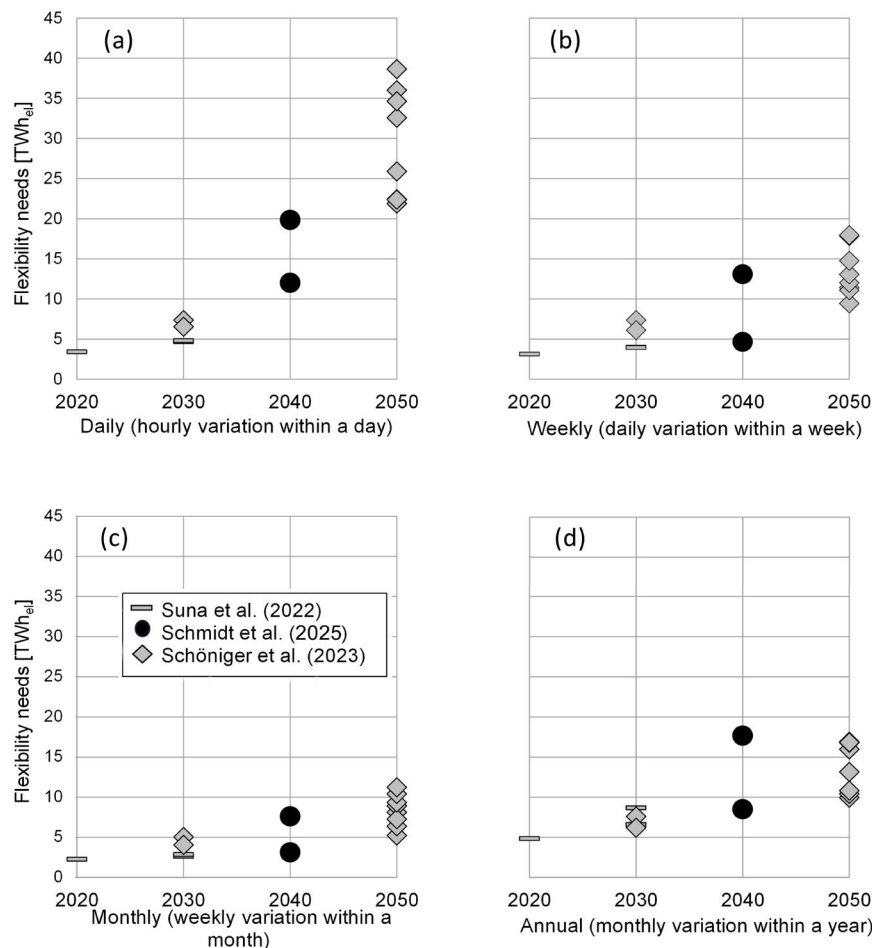


**Figure 4.10** Flexibility/storage needs in the power sector in different scenarios with increasing shares of variable renewable energy. The values are based on 14 scenarios and different years and depicted for daily (a), weekly (b), monthly (c), and annual (d) flexibility needs. The status quo (2020) is based on Suna et al. (2022), 2030 is based on Suna et al. (2022) and Schöniger et al. (2023), 2040 is based on Schmidt et al. (2025), 2050 is based on Schöniger et al. (2023). Source: Own illustration.

et al., 2022; Lienhard et al., 2023; López Prol et al., 2023). There are different timescales for flexibility needs and options (see Figure 4.10), which will have different dynamics in the future. Scenarios with a higher solar PV generation share show higher daily (hourly fluctuations within a day) and annual (monthly fluctuations within a year) flexibility demand than scenarios with a higher wind generation share due to the strong intra-day and seasonal characteristic of solar PV generation. Scenarios with a higher wind share show more fluctuations of the renewable electricity generation on a weekly and monthly timescale (Suna et al., 2022; Schöniger et al., 2023; Schmidt et al., 2025).

Harnessing the synergies of seasonal compatibilities of different energy demand and supply components can increase system stability (Jerez et al., 2013; Ramsebner et al., 2021; López Prol et al., 2024). Reducing energy demand in the building sector (see Section 3.3), for instance, reduces the need for seasonal storage, as there is a natural seasonal mismatch between heating demand (peak in winter) and renewable energy supply (surplus in summer) in Austria, which can be reduced in this way. Climate change impacts on demand and supply patterns might improve the seasonal correlation of renewable energy supply and the stability of energy demand due to reduced heating demand.

The transition to a more decentralized electricity system implies changes in system vulnerability that need to be further understood. Reducing energy demand is a no-regret measure to reduce the necessity of energy infrastructure and related risks (Kranzl et al., 2015) (see Section 4.2). Electricity systems with higher shares of renewable energies show lower sensitivity to fuel price shocks in Austria (Totschnig et al., 2017) and lower fuel import dependency (see scenario descriptions in Section 4.5.2).

In sectors where they can be used efficiently, fuels such as hydrogen, renewable gases, and other e-fuels might play a role and have to be domestically generated or imported as well as stored in the future energy system (see Sections 3.4, 4.2, 4.4). The efficient use of available renewable energy sources requires the use of e-fuels in hard-to-electrify sectors (Sections 4.6 and 3.4) and the use of synergies provided by electrolysis, for example the provision of electricity system flexibility (Reiter and Lindorfer, 2015; Greiml et al., 2021) and waste heat (Böhm et al., 2021).

### Climate change impacts on energy systems

The energy supply system will become increasingly linked to the climate system due to higher electrification and large

shares of weather-dependent renewable energy (Cronin et al., 2018; Emodi et al., 2019; Yalew et al., 2020; Simoes et al., 2021; De Felice et al., 2023; Kapica et al., 2024). Climate change impacts the energy system in the fields of (i) energy supply, (ii) energy demand, and (iii) energy infrastructure due to natural hazards (Kranzl et al., 2015). Long investment cycles of energy infrastructure assets require timely adaptation of planning, building and operation to avoid lock-in effects (Seto et al., 2016; Fisch-Romito et al., 2021).

Climate change is expected to increase hazards that impact different parts of the energy system on both the supply and demand side: While heat waves and droughts particularly impact thermal electricity generation (cooling requirements) (Kranzl et al., 2010) and hydropower, transmission and other renewable generation technologies are more risk-sensitive to cold waves, wildfires, flooding, heavy snow, ice storms, and windstorms (Yalew et al., 2020). If energy infrastructure is not designed to be resilient, supply risks can increase, as higher weather dependence and more infrastructure damage from extreme events can lead to a stressed system (Mikellidou et al., 2018; Perera et al., 2020; Doss-Gollin et al., 2023). Climate change impacts on energy demand, supply, and infrastructure through extreme events (e.g., wind, droughts, cold waves, heat waves, floodings, wildfires, storms, and compound effects thereof) (Brás et al., 2023) or changes in long-term trends can lead to cascading effects and energy supply disruptions (Rübbelke and Vögele, 2011; Hossain et al., 2021). Energy systems, especially the increasingly important electricity system, are highly interconnected geographically, which can lead to large-scale spatial disruptions in the event of failure. Possible adaptation measures include reducing energy demand (Section 4.2) and cooling water demand, increasing the degree of interconnection of the energy system, increasing back-up capacity (flexible generation or storage), spatial and technological diversification of energy sources and flexibility options (Yalew et al., 2020) (see above), and integrating impacts of climate change on energy demand and supply into energy strategies and business decisions. An example of mitigation co-benefits is the improvement of energy efficiency in buildings, which makes them less vulnerable to climate change impacts (Zachariadis and Hadjinicolaou, 2014) (see Section 3.3). Energy system design in terms of generation mix, interconnection grade, and availability of flexibility options has a greater impact than weather variability between different years or climate scenarios (Totschnig et al., 2017; Bloomfield et al., 2021).

Table 4.A.2 gives an overview of climate change impacts on electricity demand and supply components in Austria, as

identified in the current literature. The supply side is affected by temperature effects on thermal power plant efficiency and cooling requirements, and by changes in meteorological variables such as precipitation/evaporation, radiation, and wind speed on renewable electricity generation patterns (Kranzl et al., 2015). There is no clear trend regarding the impacts on the supply side (wind, solar PV, and hydropower generation) in Austria. Depending on the climate scenarios considered, either increasing or decreasing annual mean electricity generation is projected and has to be differentiated regionally (see Section 7.4.2 Energy). The impacts on hydropower are expected to be stronger than on wind and solar generation.

Additionally to Table 4.A.2, Figure 4.11 shows modeled relative changes of annual renewable electricity generation and annual heating and cooling demand for different global warming levels (GWL) compared to the reference period 1981–2010 based on Formayer et al. (2023) and Schöniger et al. (2023, 2024).

There is *low agreement* on the effects of climate change on the sign of change of overall hydropower generation in Austria (Stanton et al., 2016; Wagner et al., 2017), with some studies showing increasing (e.g., Simoes et al., 2021; Formayer et al., 2023) and others showing decreasing generation (e.g. Kranzl et al., 2010, 2015; Eitzinger et al., 2014; Schleyen et al., 2019). However, there is *high agreement*

that hydropower will show earlier runoff in spring, higher generation during winter, and lower generation during summer due to a change in the snowmelt period (Kranzl et al., 2010; Finger et al., 2012; Kling et al., 2012; Fuchs et al., 2013; Totschnig et al., 2017; Wagner et al., 2017; Blöschl et al., 2018; Formayer et al., 2023; Wechsler et al., 2023) (see Figure 4.12). This smoothed seasonality of hydropower is expected to decrease the need for seasonal storage (Kranzl et al., 2010; Blöschl et al., 2011). However, negative energy system impacts may arise from extreme events (droughts or flooding). For hydropower, an increase in interannual variability is observed, which poses a risk to the highly hydropower-based Austrian electricity system. However, the climate change impact on interannual hydropower variability is expected to be lower than the naturally high interannual variability of hydropower in Austria (until 2050) (Blöschl et al., 2018). (Pumped) storage hydropower plants are expected to be less affected by climate impacts due to their balancing capacity, which allows for some adaptation (Kranzl et al., 2010) (see Section 7.4.2). However, impacts of glacier melt dynamics are expected to limit the adaptive capacity of hydropower production with glacier catchments (Finger et al., 2012) and to affect the whole energy system in Austria (see Section 7.4.2).

On the demand side, climate change mainly affects the energy demand for heating and cooling (see Table 4.A.2).

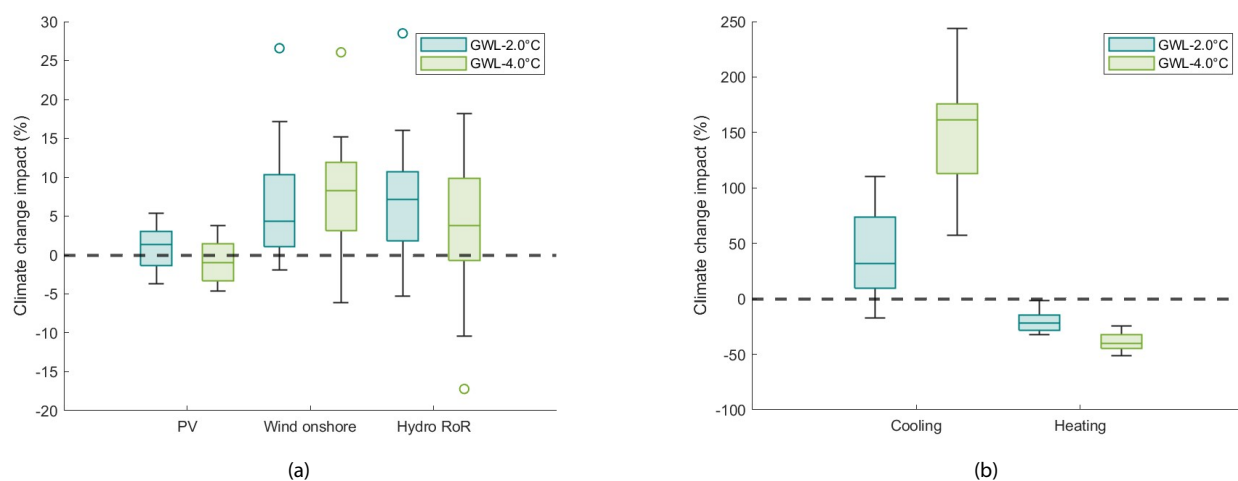


**Figure 4.11** Climate change impacts on the Austrian energy system for different global warming levels (GWL) compared to the mean of the reference period 1981–2010. (a) Relative changes of the annual electricity generation of PV, wind onshore, and hydro run-of-river and (b) on annual cooling and heating demand are shown. For each GWL, the box shows the 20 weather years in which that level is reached in the underlying climate scenario (2026–2045 for GWL 2.0°C and 2073–2092 for GWL 4.0°C). Findings: For wind and hydro, a slightly increasing annual generation is shown, for PV no trend is visible. There is a clear relative increase in cooling and decrease in heating demand. Despite the strong relative increase of cooling demand, there is an overall negative net effect on heating and cooling energy demand in Austria due to higher absolute heating than cooling demand. (Own illustration, data points are based on the RCP8.5 scenario of Formayer et al. (2023) and Schöniger et al. (2024)).

With increasing global warming levels, an increasing trend in cooling demand and a decreasing trend in heating demand are projected for Austria (see also Sections 3.2.3, 3.3.1). This sign of change is robust across studies and models (Bachner et al., 2013; Berger et al., 2014b; Kranzl et al., 2014a; Steininger et al., 2015; Damm et al., 2017; Bird et al., 2019; Ramsebner et al., 2021). This implies a more even seasonal profile of electric load by decreasing demand during the cold seasons and increasing the load during warm seasons. As heating demand is still expected to be significantly higher than cooling demand in absolute terms, the net effect of climate change on energy demand in Austria is found to be negative even under the strongest GWL considered (Bachner et al., 2013; Totschnig et al., 2017; Formayer et al., 2023). Kranzl et al. (2015) found an 18–20 % reduction in electricity demand for heating and cooling by 2050. Climate change impacts and adaptation on the demand side (e.g., peaking need for electric cooling during heat waves) can have significant effects on supply-side requirements (Totschnig et al., 2017; Rode et al., 2021; Vigié et al., 2021). Literature for Austria shows that critical situations for the electricity system are still mainly expected during winter, but heat waves are shown to pose an increasing risk to the Austrian and Central European electricity system (Schöniger et al., 2023; Gruber, 2024). If future energy system design and policies consider these climate impacts to build a resilient

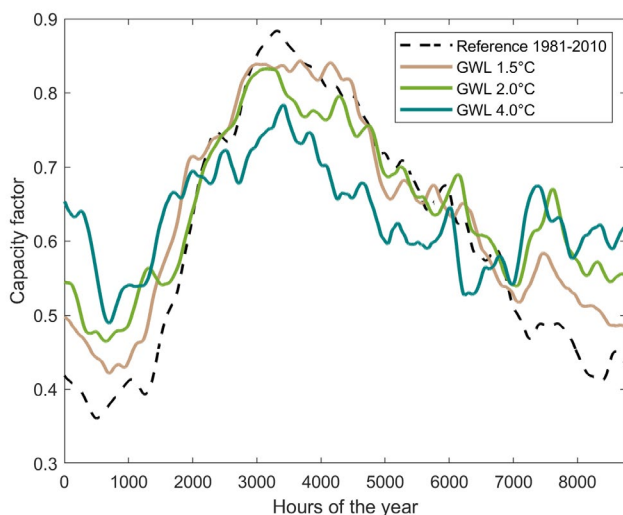


**Figure 4.12** Climate change impact on seasonal patterns of run-of-river hydropower generation in Austria for global warming levels (GWL) 1.5°C, 2.0°C, and 4.0°C compared to the reference period 1981–2010. (Own illustration; based on Formayer et al. (2023): SDM\_ICHEC-EC-EARTH\_rcp45/85\_r1i1p1\_KNMI-RACMO22E climate projections for GWL and ERA5-Land for reference period; GWL 1.5°C and 2.0°C contain data from the RCP4.5 and RCP8.5 scenario, GWL 4.0°C only from RCP8.5 scenario; 7-days rolling mean capacity factors are displayed).

energy system (van der Wiel et al., 2019), energy supply disruptions and their cascading effects can be avoided.

There is a research gap for quantitative climate change impacts on critical energy infrastructure in Austria. For other countries, peak capacity losses for thermal power plants in the range of 1.1–4.6 % at the end of the century have been calculated (Sathaye et al., 2013). The issue of increased capacity losses in transmission lines and substations due to higher temperature levels is found to account for up to an additional 8 % and 3.6 % of peak capacity (Sathaye et al., 2013), with a particular high risk in no-wind conditions at high temperatures. Grid-connected energy infrastructure can be impacted by hazards such as flows, floods, landslides, permafrost thawing, rockslides and other extreme meteorological events such as heavy precipitation, high temperatures, or strong winds (Schaeffer et al., 2012). Possible adaptation measures include incorporating future cooling demands into power infrastructure design parameters, or rerouting transmission in situations of local impacts where possible.

In terms of macroeconomic effects, the shift of the electricity load towards the summer is expected to result in gains in the overall energy system on the one hand, and costs due to increased cooling demand and electricity generation costs (e.g., increased peak load production, reduced hydropower during dry periods) on the other hand. Climate change impacts in the electricity sector are found to increase annual costs in the sector by about EUR<sub>2023</sub> 302.22–840.96 million in 2050 and, due to spillover effects, reduce GDP by EUR<sub>2023</sub> 216.81 million in the 2030s and by EUR<sub>2023</sub> 613.64 million in the 2050s (Kranzl et al., 2014b, 2015). For heating and cooling, a positive annual net effect of EUR<sub>2023</sub> 39.42 million (2016–2045) and EUR<sub>2023</sub> 65.7 million (2036–2065), respectively, was calculated (Kranzl et al., 2014b). Based on the same dynamics, Steininger et al. (2020) report average annual costs of EUR<sub>2023</sub> 347.42 million (2030) (2050: EUR<sub>2023</sub> 926.44–1,304.33 million – low border RCP4.5, high border RCP8.5). All costs are calculated without considering infrastructure failures or black-out risks due to extreme events and natural hazards. In general, there is a literature gap on costs linked to energy infrastructure damages and large-scale energy supply disruptions in Austria. In the electricity system, costs of such large-scale energy supply disruptions are estimated to be orders of magnitude higher than those associated with general electricity generation and can reach the future costs of an entire year's electricity consumption (Kranzl et al., 2014b). Reichl et al. (2013) estimate the costs of a power outage to the Austrian economy on a weekday morning in summer to

be about EUR<sub>2023</sub> 504.35–576.4 million (6 h duration) and EUR<sub>2023</sub> 1,080.75–1,585.1 million (24 h duration), with the energy-intensive manufacturing sector bearing the largest share of these disruption costs.

### 4.5.3. The necessary transformation: Achieving a decarbonized energy system

Even under stringent demand-side reductions, the supply side of the energy system and the related grids will have to be strongly transformed to reach climate neutrality: Infrastructure will have to be partly expanded and partly built back (Schmidt et al., 2025) (the scenario data used in this analysis is available at [aar2.ccca.ac.at/explorer](http://aar2.ccca.ac.at/explorer)). The technologies to harvest the low-hanging fruits of decarbonization, i.e., electrification of heating and mobility, and renewable electricity generation via solar PV and wind power, are readily available on global markets, but the expansion speed in Austria will have to increase considerably (Schmidt et al., 2025), although the maximum historical expansion of solar PV in 2023 is in line with climate neutrality goals (Statistik Austria, 2024a). However, to decarbonize industry, technologies and commodities are required, which are currently not available at scale, and where rapid upscaling will be challenging, such as for hydrogen production (Odenweller et al., 2022; IEA, 2023). For Austria, additional annual investment costs of a fully carbon-neutral economy are estimated to be in the range of EUR<sub>2023</sub> 6.2–10.8 billion, of which EUR<sub>2023</sub> 2.3–5 billion are for energy production, EUR<sub>2023</sub> 2.7–4 billion for transport, and EUR<sub>2023</sub> 0.7–0.9 billion for buildings (see Table 8.1). Relative costs depend, however, largely on uncertain assumptions about future fossil fuel prices, renewable energy (IEA, 2023) and capital costs (Bachner et al., 2019b).

The land resources required for the pathways to a carbon-neutral Austria do not technically limit the transition. This is particularly the case in scenarios where biomass use is not increased substantially above current levels: There is sufficient technical potential for wind power and solar PV (see Table 4.A.3) compared to biomass from agriculture or forestry, where complex trade-offs between energetic and other uses of natural resources exist (see Section 2.3.2). In particular, wind power has low direct land-use requirements (Turkovska et al., 2024), while solar PV land-use efficiency can be increased by using agri-photovoltaic schemes (Mikovits et al., 2024). However, biodiversity can be affected by energy system infrastructure: Birds, bats, and non-volant mammals are impacted by wind power, but adverse impacts can be mitigated to some extent, e.g., by the choice of tur-

bine locations or by turning off turbines in periods with high risks for bat collisions (McKenna et al., 2025). Depending on prior land-use and management of PV parks, solar PV installations can be beneficial or detrimental to plant and pollinator diversity (Blaydes et al., 2021; Nordberg et al., 2021). While there are in principle sufficient raw materials available to enable a global energy transition by 2050 (Wang et al., 2023), their mobilization is nevertheless challenging and can entail important trade-offs, such as conflicts with traditional or indigenous populations (Owen et al., 2023) or negative environmental impacts (Berthet et al., 2024). A circular economy can reduce the needs for mining substantially (see Cross-Chapter Box 5), and ecologically responsible mining and sourcing can reduce environmental impacts (Sonter et al., 2023). Overall, the net requirements for mining will decrease as a result of the energy transition, as the reduction in fossil fuel mining overcompensates for the additional mining of raw materials used in low-carbon technologies (Nijens et al., 2023). The risks, potentials, and uncertainties of carbon capture and storage technologies are discussed in more detail in Section 4.6.

In contrast, limited policy support is a crucial barrier in Austria: Implemented targets and corresponding policy support are still too low to achieve a fully carbon neutral Austria by 2040 (Umweltbundesamt, 2023b). Furthermore, even the federal targets for renewable energy expansion may not be met due to a mismatch with corresponding targets by federal states, e.g., for wind power (Baumann et al., 2021; BMK, 2023c). Even if policy support was sufficient on all governance levels, projects may fail due to a lack of acceptance by the local population (Scherhauser et al., 2017; Sposato and Hampl, 2018; Seidl et al., 2019). The latter barrier may be partly overcome through compensation payments or participatory planning methods (Kapeller and Biegelbauer, 2020; McKenna et al., 2025). Additionally, power grid infrastructure is also subject to public opposition (Friedl and Reichl, 2016), but will have to be significantly expanded in carbon-neutral scenarios for the Austrian energy system (BMK, 2023c). Regulatory innovations such as energy communities can support the establishment of decentralized and decarbonized energy systems in a participatory manner (Haas et al., 2022). However, renewable energy subsidy schemes can increase income inequality if policies are not designed to distribute the potential welfare gains and losses from renewable energy uptake in Austria evenly (interaction with SDG10). The speed of the transition is also limited by the necessary expertise of the workforce, which can suffer from detrimental boom and bust cycles and needs

corresponding policy solutions (Briggs et al., 2022). Of all the required supply-side technologies, solar PV is the most on track, both in terms of the realized expansion as well as in terms of the match between federal and federal province level goals (BMK, 2023c). However, as the generation profile of solar PV is unfavorable in Austrian conditions, overbuilding solar PV may imply the use of more integration technologies (Wehrle et al., 2021; Schmidt et al., 2025).

Table 4.A.3 and Table 4.A.4 show the potential of different renewable electricity potentials and cost in Austria.

#### 4.6. Decarbonization of hard-to-abate industries by carbon capture, geological storage, and utilization

Carbon Capture, Utilization and Storage (CCUS) refers to a chain of technologies to prevent CO<sub>2</sub> (carbon) emissions by capturing carbon dioxide (CO<sub>2</sub>) from suitable point sources, such as industrial facilities, and then permanently storing the captured CO<sub>2</sub> in the geological subsurface or using it as a feedstock for products (IPCC, 2005; Bui et al., 2018; Lehner, 2021; Ott, 2023). In combination with bioenergy (BECCS)

or direct air capture (DACCS) technologies, CCS also offers the potential for negative CO<sub>2</sub> emissions and thus the direct and permanent removal of CO<sub>2</sub> from the atmosphere (Bui et al., 2018; IPCC, 2023b); this is referred to as Carbon Dioxide Removal (CDR). A schematic overview is provided in Figure 4.13. CDR methods that do not involve CCUS technologies are not covered in this chapter. The reader is referred to the Cross-Chapter Box 6.

Analysis of sectoral climate policies shows that currently planned measures are not sufficient to reduce emissions to the extent necessary to achieve the climate goals of the Paris Agreement (Nascimento et al., 2022). In this context, CCUS is seen as an essential component for achieving climate goals (Bui et al., 2018; IPCC, 2023b). According to recent assessments for the EU, this would result in an average demand for carbon capture by CCS of 230–430 Mt/yr in 2030 and 930–1,200 Mt/yr in 2050, while the scale of CCU deployment could cover a wide range of 47–800 Mt/yr in 2050 (Butnar et al., 2020). Consequently, the European Commission has identified the deployment of CCU and CCS technologies during this decade as critical (COM/2020/562 final). CCUS can play a crucial role in decarbonizing the Austrian economy, especially with regard to hard-to-abate industrial

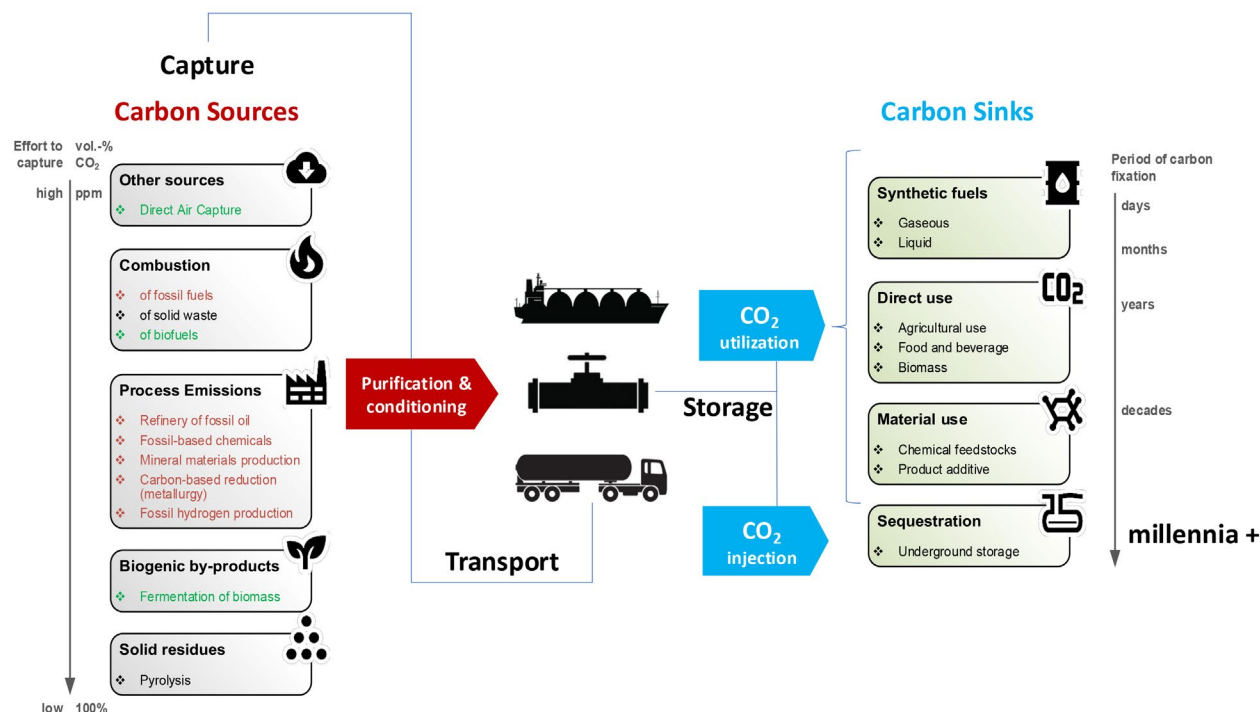


Figure 4.13 Potential carbon sources, sinks, and a qualitative indication of capture effort and fixation periods. Modified from CaTUS project proposal (ACRP, Klima + Energie Fonds, 2021) (Global CCS Institute, 2021; CaTUS, 2024).

emissions. In particular, CCUS can support CO<sub>2</sub>-intensive industries in Austria to meet CO<sub>2</sub> reduction targets while maintaining their competitiveness, which requires a clear definition of which emissions are generally avoidable and

which should be classified as hard-to-abate (BMF, 2024; Hochmeister et al., 2024a; Ott and Kulich, 2024). In addition, Austria's biomass potential likely plays a role in offsetting and achieving negative emissions.

### Cross-Chapter Box 6. Carbon dioxide removal

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**Main message:** Carbon Dioxide Removal (CDR) describes negative emission technologies that offset unavoidable current and historical emissions to the atmosphere. The assessment of the potential of each CDR option relies in part on the same energy and area resources, therefore the options should be considered as interdependent. The successful implementation of CDR options also depends on several external factors, such as technological developments, the regulatory framework, public perception, existing land use and energy demand under changing climate conditions.

**Definitions and principles:** CDR techniques encompass all anthropogenic activities that remove carbon dioxide (CO<sub>2</sub>) from the atmosphere and durably store it in geological, terrestrial and marine reservoirs or in products. CDR has two objectives: (i) to offset unavoidable anthropogenic CO<sub>2</sub> emissions to the atmosphere, and (ii) to create negative CO<sub>2</sub> emissions, i.e., offsetting historical anthropogenic emissions. Numerous existing and emerging CDR technologies are known, focusing on natural and technological means. They include existing and potential anthropogenic enhancement of biological or geochemical CO<sub>2</sub> sinks such as afforestation, reforestation, land restoration, and technical means such as bioenergy or direct air capture in combination with carbon capture and storage (BECCS and DACCS), biochar production (PyCCS) and chemical weathering in terrestrial or aquatic systems, but exclude natural CO<sub>2</sub> uptake not directly caused by human activities. For a positive CDR effect, the total quantity of atmospheric CO<sub>2</sub> physically removed and permanently stored must be higher than the total quantity of CO<sub>2</sub> emitted during the process.

**Potentials of CDR options for Austria:** The potential of the CDR options can only be assessed on a case-by-case basis. The many interdependencies require an estimate of the CDR potentials individually as presented in [CCBox 6 Figure 1](#), and the implementation in Austria would therefore require a careful consideration of the best combination of options and the mutual impairment of their potential. The CDR options, their potential scale of application, their costs and effectiveness, as well as their interference with other land uses and CO<sub>2</sub> storage options are described in detail in [Chapters 1, 2, 3 and 4](#). Considered aspects include technical readiness, land and other resource needs, geographical and geological constraints, primary energy demand, time scale of sequestration, environmental, social, and health impacts and potential risks, trade-offs and co-benefits. The technical and plausible CDR potential is presented in [CCBox 6 Figure 1](#) for the current potential (considering the current capacities and constraints until 2030) and the future potential (up to 2050). Additionally, a qualitative assessment has been made for the required area and energy demand, the public acceptance and any constraints regarding the legal framework for implementing the CDR option.

The potential for the long-term carbon dioxide removal of different land uses has been assessed for soil management, agroforestry and renaturation, as well as different forest management options (afforestation, adaptive or extensive forest management). Two CDR options consider a land use change, where technical measures, reducing food waste or special diets allow to gain some area for afforestation measures. Among the forest-related CDR options, different management strategies (e.g., change of tree species composition, shorter rotation) are considered. Depending on the CDR option ([Table 2.3, Sections 2.3.1 and 2.3.3](#)), the total mitigation effects are within a range of -1.2 MtCO<sub>2</sub>/ha and year and +8.0 MtCO<sub>2</sub>/ha and year compared to the reference of the year 2020.

| CDR Options                                                                                                                                                                                                                                                                                                                                                                                                   | Technical / plausible potential                                                                                                                                                     | Assumptions on plausibility<br>(need for area, energy, investments and costs, public acceptance, legal framework) |        |       |            |                   | Co-benefits / trade-offs                                                                                                                                                                     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------|-------|------------|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                                                                                                                                                                                                                                                               | CO <sub>2</sub> /yr until 2030/2050 + Max (CO <sub>2</sub> )                                                                                                                        | Area                                                                                                              | Energy | Costs | Acceptance | Legal adaptations |                                                                                                                                                                                              |
| <b>BECCS / DACCS</b><br>capture CO <sub>2</sub> for storage and utilization                                                                                                                                                                                                                                                                                                                                   | CCS:<br>3 to 25 Mt CO <sub>2</sub> /yr **<br>Total onshore storage capacity of several hundred Mt CO <sub>2</sub> in Austria **<br><br>CCU: 1 to 5 Mt CO <sub>2</sub> /yr **        | +                                                                                                                 | +++    | +++   | no         | required          | High demand for energy from biomass might raise conflicts with other uses of timber and pulp wood<br>(figures and references see Section 4.6)                                                |
| <b>Soil management</b><br>use plants timber for biochar in soils                                                                                                                                                                                                                                                                                                                                              | 0.9 to 3.7 t CO <sub>2</sub> /ha/yr<br><br>Based on global estimates<br>2030: 1 to 3.3 Gt CO <sub>2</sub> /yr<br>2050: 1.1 to 4.9 Gt CO <sub>2</sub> /yr                            | 0                                                                                                                 | +      | ++    | limited    | not required      | High competition on the market for timber and pulp wood as well as biomass for energy production<br>(figures and references see Section 2.3)                                                 |
| <b>Afforestation (LUC)</b><br>of agricultural land through a protein transition (lancet diet) and halving food waste                                                                                                                                                                                                                                                                                          | Compared to 2020:<br>3.3 to 8.0 Mt CO <sub>2</sub> /yr<br><br>Compared to Reference Scenario:<br>3.0 to 12.9 Mt CO <sub>2</sub> /yr                                                 | +                                                                                                                 | +      | +     | limited    | not required      | Loss of agricultural land and loss of biodiversity, lower income of livestock farmers, changes in landscape<br>(figures and references see Section 2.3)                                      |
| <b>Agroforestry (LUC)</b> increasing sinks through short rotation coppices, hedges and by technical mitigation measures on agricultural land                                                                                                                                                                                                                                                                  | Compared to reference scenario:<br>0.1 to 0.4 Mt CO <sub>2</sub> /yr                                                                                                                | ++                                                                                                                | ++     | ++    | limited    | not required      | Loss of agricultural land, partly increased biodiversity, changes in landscape<br>(figures and references see Section 2.3)                                                                   |
| <b>Renaturation</b><br>of wetlands under agricultural use                                                                                                                                                                                                                                                                                                                                                     | 1 to 100 kt CO <sub>2</sub> / yr (GWP100)<br>avg. -45 t CO <sub>2</sub> /ha/yr up to >-60 t CO <sub>2</sub> /ha/yr                                                                  | +                                                                                                                 | 0      | ++    | high       | not required      | Changes in biodiversity and landscape (drainage of peatlands/rewetting on extensively managed peatsites) reduction in feedstock and market crops<br>(figures and references see Section 2.3) |
| <b>Adaptive forest management</b><br>change of tree species composition                                                                                                                                                                                                                                                                                                                                       | Compared to 2020:<br>Sink is decreased by -0.1 to -1.2 Mt CO <sub>2</sub> /yr <sup>ν</sup><br><br>Compared to reference scenario:<br>4.1 to 4.9 Mt CO <sub>2</sub> /yr <sup>ν</sup> | 0                                                                                                                 | 0      | +     | limited    | not required      | Improved biodiversity, reduced vulnerability to climate change impacts, less availability of demanded coniferous timber assortments<br>(figures and references see Section 2.3)              |
| <b>Extensive forest management</b><br>reducing the overall use and harvest of wood                                                                                                                                                                                                                                                                                                                            | Compared to 2020:<br>1.4 to 4.4 Mt CO <sub>2</sub> /yr <sup>ν</sup><br><br>Compared to reference scenario:<br>9.3 to 11.1 Mt CO <sub>2</sub> /yr <sup>ν</sup>                       | 0                                                                                                                 | 0      | +     | limited    | not required      | Improved biodiversity, less availability of timber, less farmers' income and decreased rural employment<br>(figures and references see Section 2.3)                                          |
| * only if limited by geological<br>• reductions through industrial CCUS not considered<br><sup>ν</sup> average values (2010-2150)<br>0 no additional requirements for area, energy or investments<br>+ small additional requirements for area, energy or investments<br>++ medium additional requirements for area, energy or investments<br>+++ high additional requirements for area, energy or investments |                                                                                                                                                                                     |                                                                                                                   |        |       |            |                   |                                                                                                                                                                                              |

CCBox 6 Figure 1 Assessment of the potential of Carbon Dioxide Removal (CDR) options in Austria.

BECCS and DACCS refer to geological storage of CO<sub>2</sub> captured from the atmosphere and are thus derivatives of CCS (see Section 4.6). While classical CCS projects capture CO<sub>2</sub> from point sources, atmospheric CO<sub>2</sub> is less concentrated and captured by biomass (BE) or by direct air capture (DA). It should be noted that the required renewable biomass is only available on a decentralized basis, and long transport distances must be expected for centralized combustion and subsequent sequestration. Technically, CO<sub>2</sub> can only be removed from the atmosphere with a comparably high energy input, which is why DA has not yet reached the necessary technological maturity. BECCS, including geological storage, is in principle available as a technology for achieving negative emissions, but faces a time challenge in terms of political, legal and technical implementation (Section 4.6). The provision of biomass is also likely to be a limiting element in the BECCS chain (Section 2.3.2).

Several factors influence the potential of biochar application to agricultural soils, such as pyrolysis production, soil conditions, climate, field management, biomass availability, making it difficult to estimate its CDR potential. Therefore, the reported global potential ranges from 0.65 to 35 GtCO<sub>2</sub>eq/yr depend on the applied models and their assumptions (Tisserant and Cherubini, 2019). The IPCC (2023a) provides ranges of 0.1–4.9 GtCO<sub>2</sub>/yr (WG1) and 0.1–6.6 GtCO<sub>2</sub>/yr (WG3) in AR6 globally, Smith (2016) provides an estimate of 0.9–3.7 tCO<sub>2</sub>/ha/yr, which is used in CCBox 6 Figure 1.

In 2024, the European Council and the European Parliament reached a political agreement to establish an EU-level voluntary certification framework for permanent carbon removals, carbon farming and carbon storage in products to facilitate the emission reduction activities in the EU (Regulation (EU) 2024/3012). The timing of carbon uptake and storage is important, as there is a need to remove large quantities of carbon from the atmosphere within the next few decades. A large potential for a permanent carbon storage is seen in the construction sector with the use of organic construction materials during the use phase of the built environment; a carbon uptake at the beginning of the life-cycle is seen as less mature and efficient and there are challenges related to certification schemes in buildings and the recycling of timber products (Kuittinen et al., 2023). In any case, CDR techniques will have cost implications: In the construction industry, price increases of 20–30 % for steel and 20–80 % for cement can be expected (Material Economics, 2019).

Research on public perceptions of CDR options is limited, but reveals low levels of public awareness and knowledge (Smith et al., 2023). Generally, conventional CDR methods such as afforestation are favored over novel approaches such as DACCS, which often encounter uncertainty (Bellamy et al., 2016; Dumbrell et al., 2016; Jobin and Siegrist, 2020; Brutschin et al., 2024). With respect to land-based CDR methods, concerns about land use, biodiversity, and environmental impacts are more frequently raised. BECCS also raises concerns about land competition, food prices, biodiversity, and the sustainability of biomass. Research on public perception of CCS shows safety concerns about leakage and seismic risks of underground CO<sub>2</sub> storage (Cox et al., 2020). In addition, public scepticism appears to be higher in wealthier countries, as studies have shown lower confidence in the potential of science and technology to address climate change in these countries. This would call for more country-specific approaches to the deployment of potentially useful technologies (Brutschin et al., 2024). There is also a need for a clear, transparent and robust definition of what counts as hard-to-abate and a clear delineation of residual emissions in the net zero year. These should indicate how much and by whom emissions should be reduced by the various CDR options by 2040, as well as the corresponding storage, utilization, and removal capacities needed (Brad et al., 2024).

**Main challenges with CDR in Austria:** CDR options could be used in all sectors to offset unavoidable anthropogenic CO<sub>2</sub> emissions into the atmosphere, as well as to offset historical anthropogenic emissions to ensure climate change mitigation. Although they can serve to compensate for residual emissions that are hard-to-abate, CDR options are not a substitute for emission reductions to reach climate targets (*medium confidence*) (see Section 4.6). Correspondingly, an important political challenge is to send robust political signals that CDR cannot compensate for any delay in phasing out fossil fuels, especially given the limited and uncertain CDR potentials (Brad et al., 2024).

CDR options in Austria include land-based biological (i.e., afforestation, reforestation, ecosystem restoration, and soil management) and technical processes to capture and permanently store CO<sub>2</sub>, such as BECCS and DACCS. They differ in terms of their technical and plausible potentials, synergies and trade-offs, and technical readiness levels (*medium confidence*) (see Sections 2.3 and 4.6).

CDR options face several limitations; the availability of biomass for CDR may conflict with other land uses for energy production, construction purposes, pulp/paper industry, or conservation efforts; and long transport distances for the provision of renewable energy from biomass are to be expected. Geological storage capacities may also compete with other subsurface technologies, such as natural gas storage and future hydrogen storage operations (e.g., for steel production), and energetic uses, such as geothermal energy production and storage (Hochmeister et al., 2024a, 2024b; Ott and Kulich, 2024; BMK, 2024a; Kulich and Ott, 2025). Carbon capture and storage is currently prohibited on Austrian territory, but is currently under reconsideration by the Austrian CMS (see Section 4.6).

In the construction sector, there are several challenges related to the certification schemes in buildings and the recycling of timber products. Trade-offs exist also in storing carbon in buildings in comparison to other options (Maierhofer et al., 2024) and only a combination of various models and sectors together with the supply and demand as well as life cycle assessments of the whole supply chain of each CDR method can show that the total quantity of atmospheric CO<sub>2</sub> removed and permanently stored is greater than the total quantity of CO<sub>2</sub> emitted to the atmosphere (*medium confidence*) (see Sections 4.6 and 2.3).

The implementation of CDR requires future research to address the monitoring of CDR, such as imports of timber, reuse of material, and the definition of temporal aspects, such as the duration of CO<sub>2</sub> removal. It requires a robust common definition of permanent carbon storage, as the EU Commission's definition, for example, is incompatible with the terminology used in the UNFCCC and IPCC frameworks.

#### 4.6.1. Current status of CCUS technologies

**CO<sub>2</sub> capture and transport:** CCS requires CO<sub>2</sub> in a pure state and in large quantities from so-called point sources or CO<sub>2</sub>-intensive industries such as cement or steel production (Paltsev et al., 2021). Several technologies are available to capture CO<sub>2</sub> at the industrial site. These are largely mature (technology readiness level TRL 9) and are based, for example, on chemical absorption (e.g., amine scrubbing) or adsorption (Dziejarski et al., 2023). Existing industrial plants can be retrofitted for CO<sub>2</sub> capture, or special processes tailored to specific industrial processes can be used (Fröhlich et al., 2019). CO<sub>2</sub> capture is energy intensive, increasing energy demand in production processes, and water intensive, potentially putting pressure on water supply systems. Carbon capture largely determines the cost of CCUS operations (Kearns et al., 2021).

Because CCS places high demands on geological formations, the captured CO<sub>2</sub> must be transported over long distances to suitable storage sites, usually by pipeline or ship. The same applies to the use of CO<sub>2</sub>, which can be centralized at production sites. Transport distances from the capture site to the storage site range from a few kilometers to several hundred kilometers onshore or offshore (Ausfelder et al., 2020). Shorter transport distances are generally more economical and energy efficient but limit the potential for CCUS deployments due to the accessibility of suitable stor-

age sites. CO<sub>2</sub> transport by pipeline is in commercial use (NPC, 2019; Kearns et al., 2021) and is therefore at TRL 9. CO<sub>2</sub> transport by waterways has not yet been used for CCUS and is therefore at a lower TRL 4–7 (Ausfelder et al., 2020; Al Baroudi et al., 2021; Kearns et al., 2021). The combined cost of CO<sub>2</sub> transport and storage is generally assumed to be a uniform EUR<sub>2023</sub> 9.91 per tCO<sub>2</sub> (Smith et al., 2021), which is reasonable in some regions, but not in Europe. Europe has the highest transport and storage costs in the baseline scenario of around EUR<sub>2023</sub> 34.7 per tCO<sub>2</sub>, as offshore storage is preferred. However, even in Europe, onshore storage is expected to be more economic, in the range of EUR<sub>2023</sub> 15.87 per tCO<sub>2</sub>.

**Geological storage:** Suitable geological formations are found at depths greater than 800 m, where CO<sub>2</sub> is in a dense state that allows efficient use of pore space for storage (Angus et al., 1987; Benson et al., 2005). In this state, however, the CO<sub>2</sub> still has a lower density than the reservoir water and therefore experiences buoyancy; to prevent the injected CO<sub>2</sub> from migrating into higher layers containing drinking water or even into the atmosphere, a trap structure in combination with an impermeable caprock, e.g., an overlying claystone formation, is required (IPCC, 2005). Corresponding geological formations are known from oil and gas fields, which are suitable reservoirs for geological CO<sub>2</sub> storage, as are deep saline aquifers. In a suitable storage facility, CO<sub>2</sub> is permanently bound by physical and chemical processes (Xu et al.,

2003; De Silva et al., 2015; Krevor et al., 2015; Brandstätter et al., 2025), providing high storage security (Benson et al., 2005). Despite technical maturity, geological reservoirs are individually different and require site-specific development. Numerical reservoir modeling and uncertainty analysis are required to ensure safe storage. Monitoring options must be in place to detect CO<sub>2</sub> leakage during the injection phase and beyond (IPCC, 2005; Directive 2009/31/EC). Upon closure of a storage site, legal obligations for monitoring and corrective, preventive and remediation measures should be transferred to the competent authority (Directive 2009/31/EC). Geological CO<sub>2</sub> storage in hydrocarbon reservoirs and saline aquifers is commercially applied and therefore mature (Benson et al., 2005; Bui et al., 2018). However, storage options in unconventional geological reservoirs such as coal seams and volcanic (ultramafic) rocks are less developed (Benson et al., 2005; Kearns et al., 2021). There are currently about 30 ongoing CCS projects, 11 of which are capturing more than 1 Mt/yr of CO<sub>2</sub> for long-term storage (Global CCS Institute, 2021, 2023). Although these rates are still far from the actual problem of anthropogenic CO<sub>2</sub> emissions, CCS technology is successfully applied and available as a critical technology.

**Carbon utilization:** Various industries and their products depend on carbon as a feedstock. Carbon supply has been primarily based on petroleum, coal (coke), and natural gas (European Commission: Directorate-General for Energy, 2020). Thus, alternative carbon sources are required for a sustainable and renewable circular economy. One option is CCU, which is based on either renewable sources or holding CO<sub>2</sub> in closed loops (Hepburn et al., 2019). In CCU processes, CO<sub>2</sub> is used as a C1-building block to synthesize carbon-containing products. However, most of these products rerelease CO<sub>2</sub> during their utilization (e.g., e-fuels) or at the end of their lifetime (e.g., plastics). Therefore, CCU contributes to an atmospheric CO<sub>2</sub> reduction only when the CO<sub>2</sub> has been taken from the air, CO<sub>2</sub> is held in a closed loop, or products are generated that bind CO<sub>2</sub> for at least several hundred years (Hepburn et al., 2019).

CCU products of great relevance are sustainable aviation fuels that can either be produced from biomass feedstock in different process routes or synthesized from CO<sub>2</sub> with green hydrogen (Richter et al., 2018) (for biomass potentials see Section 2.3.2 on sufficiency oriented bioeconomy). Mineral carbonation, i.e., the production of carbonates from CO<sub>2</sub> and metal oxides, is a CCU option with a durable fixation of CO<sub>2</sub> (Olajire, 2013). Appropriate metal oxides can be found in primary rocks (e.g., serpentine) or also in secondary feed-

stocks (e.g., slags and ashes) (Wang et al., 2018). The carbonates can be utilized in the pulp and paper industry or as fillers in construction materials. Another promising CCU option is to retain the CO<sub>2</sub> in a closed loop (Rosenfeld et al., 2020). One potential application of such looping processes is in the steel industry until it transitions to carbon-neutral production.

#### 4.6.2. CCUS potential in and for Austria

In 2023, Austria's total GHG emissions amounted to 68.6 MtCO<sub>2</sub>eq (Umweltbundesamt, 2023a). The energy and industry sectors are responsible for more than 43 % of total emissions (CO<sub>2</sub>eq), with decentralized CO<sub>2</sub> sources such as agriculture and transportation accounting for 39 % (Umweltbundesamt, 2023a). In Austria, the steel and cement industries emit about 14.1 MtCO<sub>2</sub>/yr into the atmosphere. An overview of the largest industrial CO<sub>2</sub> sources and potential geological sinks in Austria is shown in Figure 4.14.

**Geological storage capacity:** An Austria-wide assessment of the CCUS potential is currently under development (CaCTUS, 2024). Significant potential storage regions are located in the sedimentary basins of the Upper Austrian Molasse Zone and the Vienna Basin as well as in the Styrian Basin (Hochmeister et al., 2024a, 2024b; Ott and Kulich, 2024; Kulich and Ott, 2025).

**Domestic hydrocarbon fields:** Hydrocarbon reservoirs are largely developed and well known, and therefore represent the fastest route to geological storage. The theoretical storage capacity of depleted hydrocarbon fields is estimated by Scharf and Clemens (2006) to be at 465 MtCO<sub>2</sub>. A recent Austria-wide study (CaCTUS, 2024; Hochmeister et al., 2024a, 2024b; Ott and Kulich, 2024; Kulich and Ott, 2025) takes a more conservative approach and shows that the largest hydrocarbon reservoirs represent a total effective storage potential of 250 MtCO<sub>2</sub>, taking into account fields with a storage capacity of more than 2 Mt. Excluding the highly perforated oil horizons, the largest gas and gas condensate fields still offer a total effective storage potential of >100 MtCO<sub>2</sub>. Assuming operating times of 10 to 30 years (European Commission, 2024), the storage capacities result in possible storage rates of 3–5 MtCO<sub>2</sub>/yr. Alternative uses of this underground space, such as hydrogen storage or geothermal energy recovery, are also taken into account.

**Domestic aquifers:** Saline aquifers have been hardly studied, with the exception of the Aderklaa conglomerate in the Vienna Basin; a theoretical storage capacity of 1,000 MtCO<sub>2</sub> has been calculated by Heinemann and Scharf (2004). Saline

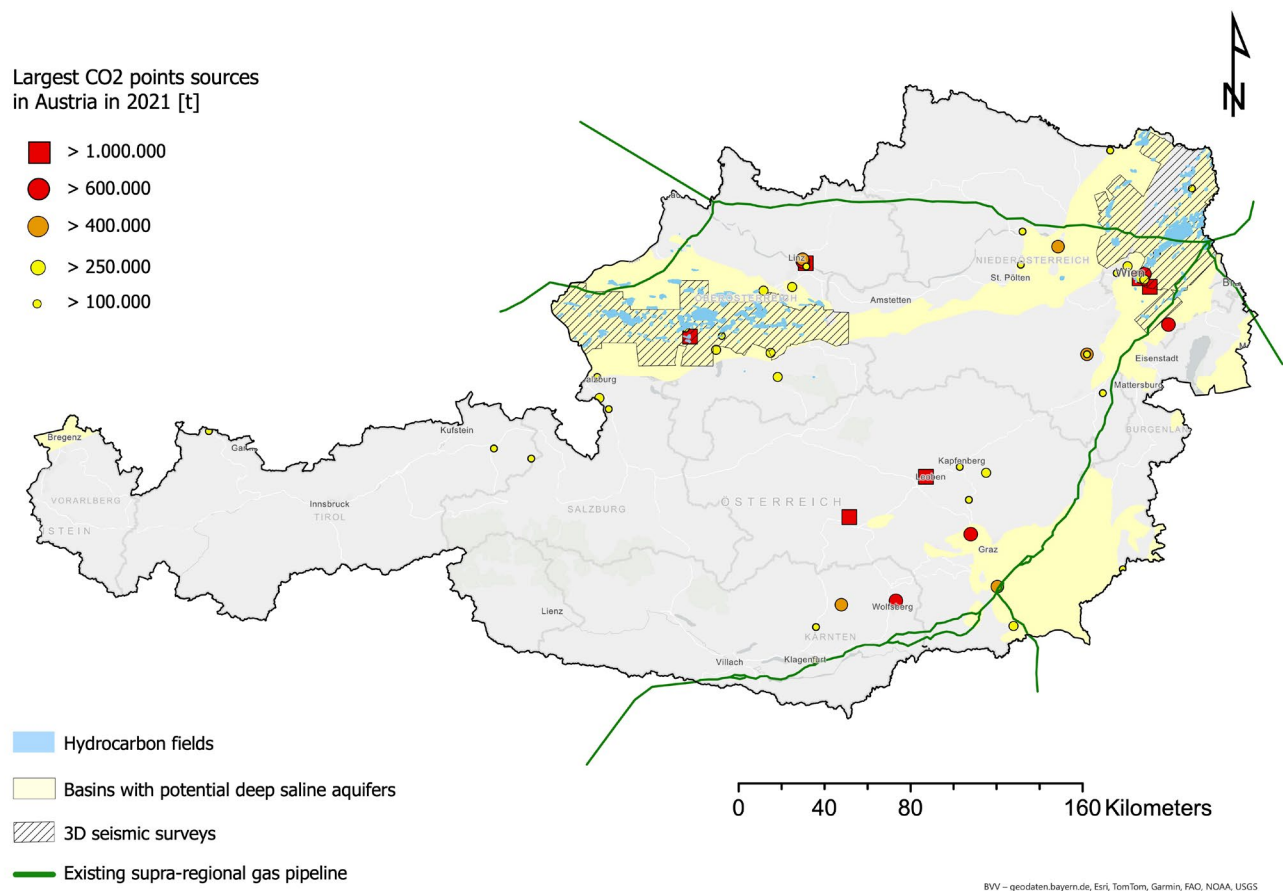


**Figure 4.14** Potential hard-to-abate carbon sources >0.1 MtCO<sub>2</sub> emissions in 2021 according to E-PRTR or ETS, and potential geological sinks. Montanuniversität Leoben (Hochmeister et al., 2024b, 2024a; Ott and Kulich, 2024; Kulich and Ott, 2025).

aquifers urgently need to be explored. In general, however, aquifers can be expected to have many times the storage capacity of hydrocarbon reservoirs.

**Storage capacity inside Austria:** Depending on the exact definition of ‘hard-to-abate CO<sub>2</sub> emissions’ (BMF, 2024), which range from 7 to 14 Mt/yr, and with the estimated storage capacity including all uncertainties, it can be stated that the storage capacity in Austria is sufficient for several decades.

**Storage outside Austria:** Securing and developing storage capacity outside Austria depends on factors that are difficult to estimate in terms of time and realism. These factors include the development of a suitable transport network, international agreements and the availability of storage capacity (see, e.g., Baltac et al., 2023). It can be assumed that there is sufficient storage capacity in the North Sea, estimated to be in the order of several 100 billion tons in total (Karvounis and Blunt, 2021), but it will take time to develop and will only be available to a limited extent in the medium term. For

example, the expansion of the Norwegian flagship project Northern Lights (Northern Lights, 2024) is estimated at only 5 Mt/yr by 2030. Austria is competing with other European countries. In any case, it can be assumed that large-scale storage outside Austria will be a later option (2040/2050). CO<sub>2</sub> storage in Austria therefore seems necessary, does not conflict with other European storage activities and would likely reduce Austrian emissions much faster.

**CCU potential in Austria:** No data are currently available specifically for Austria. In any case, CCU associated with fossil GHG emissions does not contribute to the removal of carbon from the atmosphere. CCU products produced from fossil CO<sub>2</sub> will eventually release GHG into the atmosphere at the end of their life cycle. However, carbon is needed for selected fuels and as a feedstock in the chemical industry. In the long term, CCU is an indispensable part of a future economic system. The availability and further development of CCU technologies and the necessary amounts of renewable energy for their operation must be ensured for the circular-

ity of the carbon economy in a defossilized economic system (Purr and Garvens, 2021). Consequently, the potential of CCU in general, and for Austria in particular, is limited to CO<sub>2</sub> captured directly from the atmosphere or biomass as a carbon source. In addition, closed carbon cycles and carbonates as long-term carbon fixation options contribute to the CO<sub>2</sub> utilization potential. Against this background, a first estimate of the CCU potential in Austria is between 1 and 5 MtCO<sub>2</sub>/yr, which has to be confirmed in the ongoing study (CaCTUS, 2024).

#### 4.6.3. Necessary transformations and R&D

The development of CCUS requires a national and European CO<sub>2</sub> transport network from CO<sub>2</sub> sources to CO<sub>2</sub> sinks, exploration and development of the geological subsurface as well as solutions for the storage and utilization of CO<sub>2</sub>. With the capacities explored and estimated to date in Austria, CCUS and geological storage in particular can make a significant contribution to national decarbonization. CCUS-specific R&D requires financial resources, an appropriate legal framework, public acceptance and a national CCUS roadmap for Austria (BMF, 2024; Hochmeister et al., 2024a; Ott and Kulich, 2024).

**Site-specific R&D on CCS:** Despite technological maturity, geological reservoirs require exploration and site-specific R&D for predictive modeling of CO<sub>2</sub> migration and reliable monitoring concepts for capacity and safety analysis. Therefore, geological CO<sub>2</sub> storage is not an off-the-shelf technology and should be considered early in the CCS implementation process.

**Phased implementation of CCS:** For geological storage, the timeframes to 2030 and 2040 are very short. This is because site development usually takes several years (Bui et al., 2018). Having storage capacity or export infrastructure in place by then will require rapid action and a strong commitment to implementation. The three domestic and international geological storage options discussed above are likely to have different development times and should therefore be phased over time. A phased approach allows for a timely entry into decarbonization through CCS and sustainable availability of storage volumes and rates in line with Austria's Carbon Management Strategy (CMS) and negative emissions ambitions. All options and their time constraints should be considered, e.g., Phase 1: Development of depleted hydrocarbon fields for a timely entry into decarbonization through CCS. Exploration of aquifers: Even in scenarios where aquifers are ultimately not developed due to the ex-

istence of alternatives, the precautionary principle requires the state be aware of possible future options and their storage capacity. Securing storage capacities outside Austria in accordance with the residual emissions to be expected in the future. Phase 2: Depending on the situation: Development of additional storage capacities in domestic aquifers or abroad.

**Public perception:** CCS projects do not usually fail for technical reasons, but because of a lack of social acceptance and the resulting political will (Witte, 2021). Early and targeted communication of the opportunities and risks of a technology offers the opportunity to bring negatively charged issues back to a factual level and should generally be given higher priority. In this way, the information level of society can be raised to a level at which meaningful opinion-forming can take place, which should then be seen as a prerequisite for creating acceptance (Cremer et al., 2008).

**CCU:** With regard to CCU, sufficient availability of renewable energy is a prerequisite for the climate-neutral operation of industrial processes. Cooperation with international CCU sites, which are expected to develop in areas with optimal conditions for renewable electricity generation, could be an opportunity for a circular carbon economy. In addition, direct air capture technologies and sustainable biomass feedstocks (e.g., cascaded biomass, microalgae) need to be further developed and optimized to achieve carbon neutrality (Purr and Garvens, 2021). The optimization of CCU processes in terms of energy efficiency, cost reduction through scaling and learning curves, and the development of novel catalytic, electrochemical, and photochemical CCU pathways pave the way for their beneficial implementation in a future defossilized economy (Klankermayer et al., 2016). Finally, a regulatory framework for CCU needs to be established, in particular for the crediting of CCU products in the EU Emissions Trading System (Böhringer and Lange, 2013; BMF, 2024).

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### 4.7. Provision by work

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#### 4.7.1. Work and climate change

Work, including unpaid care and paid employment, dominates daily life in Austria, and the structural dependence of persons and welfare systems on paid work currently tends to impede climate-neutral provisioning as well as climate-friendly living (Pettinger, 2017; Kreinin and Aigner, 2022; Aigner et al., 2023b; Bärnthaler and Gough, 2023;

Gerold et al., 2023; Hoffmann et al., 2023; Mason and Büchs, 2023) (*high confidence*). 90 % of the Austrian population (>10 years) is involved in care work (on average 3.5 h/d per household), while only 49 % of the Austrian population are involved in paid work (on average 8.25 h/d) (Statistik Austria, 2024b). The current unequal distribution of paid and unpaid work for the care of people (children, elderly, those in need of care) is strongly influenced by gender-specific divisions of labor (Kuhl et al., 2011; Bauhardt, 2013; Dengler and Lang, 2019, 2022; Knobloch, 2019; Cohen and MacGregor, 2020). Work time preferences follow social norms, with 17.5–30 % of Austrian workers defined as overemployed, i.e., who want to reduce paid working hours (Gerold and Nocker, 2018). Although unpaid care (incl. caring for oneself, household, community, society as well as nature) and paid work are indispensable for the functioning of provisioning systems and the formal economy (Biesecker et al., 2000; Biesecker and Hofmeister, 2006; Cleveland et al., 2017; Smetschka et al., 2023c), work has received little attention in climate science. While many individuals depend on income from paid employment, work is also a source of material livelihood, social integration, the creation of meaning and the development of self-identity (Feigl and Wukovitsch, 2018). In its current form, employment causes consumption, is biophysically intense and has ambivalent health impacts (Gerold et al., 2023). The climate effects of employment can be assessed by considering the goods and services as outputs from work, the tasks and activities workers perform at the workplace, the impact of employment conditions on the sustainability of workers' and their households' lifestyles, and the efficiency of the production process in relation to socially desired provisioning (Bohnenberger, 2022a).

High-productive, energy-intensive work is well-paid and structurally linked to low-productive, energy-light, unpaid or low-paid, very essential work (*limited evidence, medium agreement*). Large parts of paid work do not meet the climate-mitigation requirements (Hoffmann and Spash, 2021; Hofbauer et al., 2023), for instance, when emissions are allocated to work according to income or production (Aigner et al., 2023b; Hoffmann et al., 2023). 60 % of production-based emissions are related to exported goods and services, and thus increase the consumption-based emissions of other countries (Aigner et al., 2023b). Production-based emissions per job and per value-added unit are unevenly distributed across sectors, geography, institutional form (state, private, non-for-profit), firm size, income, working-hours, and occupation (Gabelberger et al., 2020; François et al., 2023b; Heyen, 2023; Oberholzer, 2023). Employment in

manufacturing, industry and transport (Hardt et al., 2020, 2021) is associated with high emissions. Employment in interpersonal care services causes lower emissions, but many of these activities are based on the upstream production of goods (Hardt et al., 2020; Aigner and Lichtenberger, 2021; Hardt et al., 2021; Hoffmann et al., 2023; Smetschka et al., 2023a). Due to their interpersonal nature, care and service sectors face barriers to fossil-fuel driven productivity, which leads to a devaluation of climate-friendly care that structurally links the two spheres (Baumol, 1967; Hardt et al., 2020; Aigner and Lichtenberger, 2021). Public provisioning, such as health and care, is a key part of the economy, and can lead to labor shortages and competition between the respective sectors. Social and economic marginalization and devaluation of unpaid care through the dominance of paid work takes place, which leads to time-competition between the two forms of work. Spending time on employment and market-based economic production reduces the time available for voluntary and alternative subsistence activities that satisfy needs with usually low-carbon emissions (Dengler and Strunk, 2018; Aulenbacher et al., 2021).

The work mode of living poses a structural barrier for climate-friendly mobility, food, housing as well as leisure practices, and fosters energy- and fossil-fuel-intensive practices (Hofbauer et al., 2023; Bohnenberger, 2022b; Gerold et al., 2023) (*medium confidence*). Both work acceleration (Rosa, 2005) and time pressure (Sullivan and Gershuny, 2018) affect climate-related decision making (Rinderspacher, 1985; Shove et al., 2009; Rosa et al., 2015; Schor, 2016; Großer et al., 2020; Chung, 2022). Employment and care are key motivations for the use of individual mobility in Austria and are therefore inherently related to emissions in the mobility sectors (see Smetschka et al., 2023b; Wiedenhofer et al., 2023). More than 50 % of travel distances of employees in Austria are work-related (44 % commuting and 9 % business related) (Tomschy et al., 2016). Although there have been changes in the work-induced consumption patterns, an overall reduction of work-induced emissions cannot be observed: In Germany, for example, increasing labor force participation increased household consumption footprints, offsetting technical efficiency improvements and declining paid work time per employee (Wiedenhofer et al., 2023). Similarly, mobility footprints (e.g., through teleworking) faced a (time) rebound effect as the number of trips declined but distance of commutes increased (Wiedenhofer et al., 2023). In addition to paid work, changes in unpaid care responsibilities also shift the modal split towards motor vehicles (Tomschy et al., 2016). A shift towards climate-friendly modes of living

requires a reconfiguration of working time to enable caring responsibilities (Hanbury et al., 2023). Some studies show that free time is mainly used for care activities (Gerold et al., 2017), but workers perceive additional recreational time from working time reduction as a key benefit (Hidasi et al., 2023; Antal et al., 2024).

46 % of Austrians believe that their current job does not contribute to the green transition (*limited evidence, high agreement*), which can be associated with contemporary societal conflicts entailing multiple actors and levels (European Commission: Directorate-General for Employment, Social Affairs and Inclusion, 2022). Workers at 'green' workplaces are more likely to engage in pro-environmental behaviors, while workers at workplaces that lack requirements for environmental knowledge in daily tasks, or where workers do not see their own impact or have no control over their own tasks, are less motivated to engage in such behaviors (Ciocirlan, 2017, 2023). Societal conflicts entail conflicts related to transitioning to climate-friendly work-life patterns, but also a lack of transitioning to green jobs (Fritz and Eversberg, 2024). This leads to anti-environmental actions, such as the defense of climate-damaging industries, but also to pro-environmental phenomena such as climate quitting (Brand and Wissen, 2021). Public infrastructure, industrial lobbying and state investments form a powerful consortium that establish the institutions, infrastructure, and rules upon which individuals form their preferences for need-satisfiers such as mode of commuting or job preservation in the automobile sector. Historically, this has increased car dependency (Mattioli et al., 2020). Today, a tendency towards acknowledging the climate implications in public investment decisions can be observed in housing or mobility, but not in the domain of work. Work-related institutions currently disregard both the impacts of climate crisis on work and the mitigation requirements for shaping work through labor law, social security systems, public services and industrial relations (Müller et al., 2019; Kopf, 2021; Bohnenberger, 2023) (*limited evidence, high agreement*).

#### 4.7.2. Work in a climate-friendly future perspective

A transition to a climate-friendly society will end the requirement for greenhouse gas emissions from paid employment or unpaid care (*limited evidence, high agreement*). This involves a complete shift away from climate-damaging products and services to climate-friendly outputs, incl. sectoral shifts and an end to employment-induced climate-harming

consumption. More work will be undertaken in person-related and resource-light sectors and activities, while energy- and resource-intensive sectors will be smaller, reducing the dependency of workers on climate-harming jobs. An overall trend of anxiety and political instability currently inhibits an efficient market or publicly planned distribution of workplaces to more essential work. This can be superseded by limiting the role of paid work for livelihoods and subsistence. Thereby, the reduction of working hours in paid work, can enable a better adaptation to climate impacts, e.g., when shifting working hours to less hot time periods, reducing work intensity through additional breaks, shifting work away from overheated locations, providing cooling systems, including greening of workplaces (Schulte et al., 2016; Masuda et al., 2021; Bauer et al., 2022; Boltz et al., 2023; Bühn and Voss, 2023).

Greening and sharing of paid employment and unpaid care will ensure quality of life, good work and climate-friendly living, work-life balance and sufficient provisioning of care (*medium confidence*). A reduction in the volume of paid work, especially energy- and resource-intensive work, is necessary to avoid exceeding ecological limits (Seidl and Zahrnt, 2019; Hoffmann and Spash, 2021). The achievement of social goals is contingent upon the decoupling of income and social security from employment and paid work (Petschow et al., 2018; Kubon-Gilke, 2019). A more equal distribution of paid work and unpaid care reduces time pressure and thereby enables the sharing of goods and climate-friendly lifestyles (Smetschka et al., 2019, 2024b). Compensatory forms of consumption (Röpke, 1999; Shove et al., 2009) which are triggered by dissatisfying forms of work will cease to exist.

Given the current business-as-usual, work will be severely impacted by the unfolding of the climate-crisis (Parsons et al., 2021) ([Chapters 1, 2, 3](#)), requiring sectoral shifts to the provisioning of basic goods such as health, care, food, and housing (*limited evidence, medium agreement*). To ensure the climate-resilience of work-systems, transformative adaptation measures ensure workers' security against the backdrop of an increasing number of heat waves and other extreme weather events (*medium confidence*). This shift will coincide with demographic trends that will drastically increase the demand for care (Famira-Mühlberger and Firgo, 2019). Impacts of climate change include the destruction of production sites through natural hazard events such as fires, avalanches, and floods (see [Chapters 1, 2, 3](#)), as well as declining labor productivity due to heat stress (Parsons et al., 2021). Perspectives from employees confirm this for

the Austrian health sector (Brugger et al., 2024a). For the past two decades, Parsons et al. (2022) estimate an annual labor loss of 20 hours per capita in Austria, a figure that is expected to rise substantially in the future (Parsons et al., 2022). Moreover, these impacts will disproportionately affect physically intensive workers and vulnerable groups (e.g., the elderly, people with disabilities), which in turn will lead to increasing care responsibilities, including new diseases (Chapters 1, 2, 3), and declining efficiency of current medication and general methods in the health sector (Bühn and Voss, 2023) (see Cross-Chapter Box 2).

### 4.7.3. Transformation towards climate-friendly work and green employment

To avoid climate-damaging production and to overcome labor supply constraints, climate-friendly regulation of labor markets can enable a shift from excess production to climate-friendly provisioning of essential services (Bärnthaler and Gough, 2023) (*medium confidence*). Production in energy- and emission-intensive sectors needs to be reduced, including hours worked in the respective sectors (Aigner et al., 2023b). Such a shift would also address future rising demand for provisioning of care (Famira-Mühlberger and Firgo, 2019). Climate-friendly public investments can (i) strengthen climate-friendly employment, (ii) satisfy societal needs, and (iii) ensure a socially acceptable transformation (Krisch et al., 2020; Schultheiß et al., 2021). Climate-neutrality plans at the European and national level require comprehensive changes, especially in the production sector (Gabelberger et al., 2020; Steininger et al., 2021; Meinhart et al., 2022). In the transformation phase to a climate-friendly system, the volume of labor is likely to remain constant due to the necessary reconstruction of the infrastructure (Aiginger, 2016). Overall, climate mitigation policies are expected to increase employment until 2030 (Alexandri et al., 2024). Shifting to renewable energy creates additional demand for labor in the short and long run, and value added in the respective sectors until 2030 (Goers et al., 2020), leading to more equal and less polarized European labor markets (Alexandri et al., 2024). The shift towards renewable energy faces a shortage of low-skilled labor although the transition will mainly increase medium- and high-skilled employment. Shifting the tax burden from human labor to energy and resource consumption could smooth this transition (Köppl and Schratzenstaller, 2019).

Workplace codetermination and greened industrial relations can avoid climate-damaging production and support

a shift to climate-friendly production processes and sustainable employment (Initiative Wege aus der Krise, 2019; Aigner et al., 2023b) (*medium confidence*). Employees and their representatives are aware of the need for transformation (e.g., Littig, 2017; Niedermoser, 2017; AK Wien, 2023, 2024; AK Wien and ÖGB, 2024), as are some companies (e.g., Global 2000 et al., 2017; BMK, 2022). Climate-friendly employment can be achieved through conversion of business models to more climate-friendly products and essential services (UNDP, 2015; Hoffmann and Spash, 2021; Hofbauer et al., 2023). Potential employment impacts have been explored, for example, for the phase-out of the internal combustion engine (Sala et al., 2020; Wissen et al., 2020). Unions and green collective bargaining can facilitate transitional assistance policies (SOC/747-EESC-2022-01-01, 2023; OECD, 2024). Guaranteeing material security and a fair distribution of transformation efforts is crucial (Specht-Prebenda, 2020; Wissen et al., 2020; ETUC, 2021; ÖGB, 2021). A just transition can be supported by stronger unionization in green sectors, strengthening unions as pro-environmental actors and improving working conditions in these sectors. A lack of compatibility of work activities and the business purpose with workers' values leads to moral stress and lower job satisfaction, which may explain the increasing climate quitting in climate-harming occupations (Net Positive Employee Barometer, 2023) and societal polarization about the green transition (Smetschka et al., 2024a). Climate-friendly provisioning systems (e.g., mobility, food) at the workplace may, however, positively contribute to climate protection at the workplace and beyond (*limited evidence, medium agreement*). This includes limiting business flights and limiting the serving of GHG-intensive foods such as meat or dairy products (*limited evidence, medium agreement*) and providing infrastructures for climate-friendly commuting, such as bicycle stations or incentives for low-carbon modes of transport for commuting (e.g., climate ticket, active mobility) (Heinfellner et al., 2024).

A redistribution of paid employment and unpaid care as well as relocating workplaces to people's living place through economic and labor market policies can enable climate-friendly work-life patterns (*medium confidence*). Shorter working hours are considered a suitable measure (Cieplinski et al., 2021; Vetter, 2023) to (i) facilitate a climate-friendly life outside of paid employment (Schor, 2005; Knight et al., 2013; Larsson et al., 2019), and to (ii) distribute the volume of employment more evenly (Antal, 2014; Gerold and Nocker, 2015; Seidl and Zahrnt, 2019; Figerl et al., 2021). The specific effects of reduced working hours on

individual behavior are ambiguous (Hanbury et al., 2019, 2023; Hofbauer et al., 2023). A shift in societal values toward a more balanced work-life relationship can reshape expectations about the meaning of work (Aichholzer et al., 2019) and the desire for shorter working hours (Csoka, 2018; *Arbeitszeiten im Fokus – Daten, Gestaltung, Bedarfe*, 2021). Making paid and unpaid care more attractive by raising wages, reducing working hours, and increasing visibility, can create incentives to shift time to low-energy and low-emission care activities (Aigner and Lichtenberger, 2021) and reduce gendered inequalities in care work (Pirklbauer and Wukovitsch, 2019; Gottschlich and Katz, 2023). Climate-friendly time policy (Reisch and Bietz, 2014) and care-oriented time policy (Heitkötter et al., 2009) focus on time as a lever for political design and a more equitable distribution of work between the sexes. Time policy can support climate-friendly lifestyles (Hartard et al., 2006; Rau, 2015; Schor, 2016) through reduced time pressure, deceleration, and reduced mental load that foster climate-friendly decisions in everyday life (Hofmeister and Mölders, 2021), green volunteering (Winker, 2021), substituting resource-intensive practices with time-intensive ones in many lifeworlds (Buhl et al., 2017), positive health co-benefits (APCC, 2019; Dengler et al., 2024), structural conditions such as reduced commuting through spatial, urban and transport planning (see [Section 3.3.2](#)), and temporal support for care work.

A more equal distribution of wealth and income, job-guarantees and public provisioning of basic goods (housing, food, mobility) can increase economic security and thus enable green labor market transformations as individual material consequences of switching jobs are reduced (Dukelow and Murphy, 2022; Lee and Koch, 2023) (*medium confidence*). The current coupling of income, social security, recognition, and participation in employment constrains the scope for climate policy (Hoffmann and Paulsen, 2020; Bohnenberger and Schultheis, 2021; Gerold et al., 2023). Therefore, measures to increase economic security during transitional phases, including an ecologically driven planned economic decline, include an unconditional basic income, greater self-sufficiency (Littig and Spitzer, 2011; Paech, 2012), or the provision of comprehensive services of general interest (Coote and Percy, 2020; Bohnenberger and Schultheis, 2021; Büchs, 2021; Gough, 2022; Bohnenberger, 2023; Rehm et al., 2023). An examination of public spending through the lens of gender and climate justice presents an opportunity to achieve emission reductions in the care sector (Schalatek, 2012). Time banks, for instance, show a potential to connect care work and employment, thereby

creating more socially and climate-friendly working time quotas (Schor, 2016; Bader et al., 2021).

Climate mainstreaming is required in all dimensions of labor and social policy, including labor law and unemployment insurance (*limited evidence, medium agreement*). Although employment is an important element of climate policy (Seidl and Zahrnt, 2019; Bohnenberger, 2022a; Kreinin and Aigner, 2022; Gerold et al., 2023), work has not been a focal point for climate-friendly interventions. There has been a focus on (re-)education and green skills particularly in engineering and managerial skills (Vona et al., 2015, 2018; Vona, 2018) and action plans are being developed mainly for the energy transition (for Austria, see BMK (2023a) and for the global level, IRENA and ILO (2021)). For details on (re-)education and green skills needs in Austria, see Dorr et al. (2023) and AMS (2024). Climate-related knowledge and skills also increase legitimacy (Pichler et al., 2021). Re-education in climate-harming occupations carries the risk of lock-ins in unsustainable jobs (Bohnenberger, 2022a). It is more promising to provide reskilling and upskilling support for jobs in care, education, and resource-light sectors, where labor shortages exist. In addition, in many instances, special education and, consequently, an adaptation of the curricula is needed (Dorr et al., 2023; AMS, 2024). Brugger et al. (2024b) might provide one best-case example for the health sector. A complete shift to climate-friendly work systems requires a comprehensive transformation of work, as emphasized by literature on Just Transition (ILO, 2015; TUDCN, 2019); Sustainable Work (UNDP, 2015; Barth et al., 2016; Littig et al., 2018) and Post-Work (Frayne, 2016; Hoffmann and Paulsen, 2020). Greening work requires a structural change of welfare systems towards a sustainable welfare state (Bohnenberger and Schultheis, 2021; Bohnenberger, 2023; Hirvilammi et al., 2023), which is currently being considered within Austria's social security outlook (BMSGPK, 2024). This implies integrating climate mainstreaming across all sectors and institutions of social security (Bohnenberger, 2021), including unemployment insurance and employment policy, where initial approaches have already been developed for the Austrian labor market service (Neier et al., 2022, 2024; Smetschka et al., 2024a). Work not only structures daily lives and production processes, but is also subject to a wide range of laws and political conflicts (Smetschka et al., 2024a). Achieving a transformation of work through targeted policies thus requires critical reflection and consideration of related actors and institutions, including social partners, unions, employer associations, social insurance and social movements (e.g., women's rights movements) (Smetschka et al., 2024a).

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