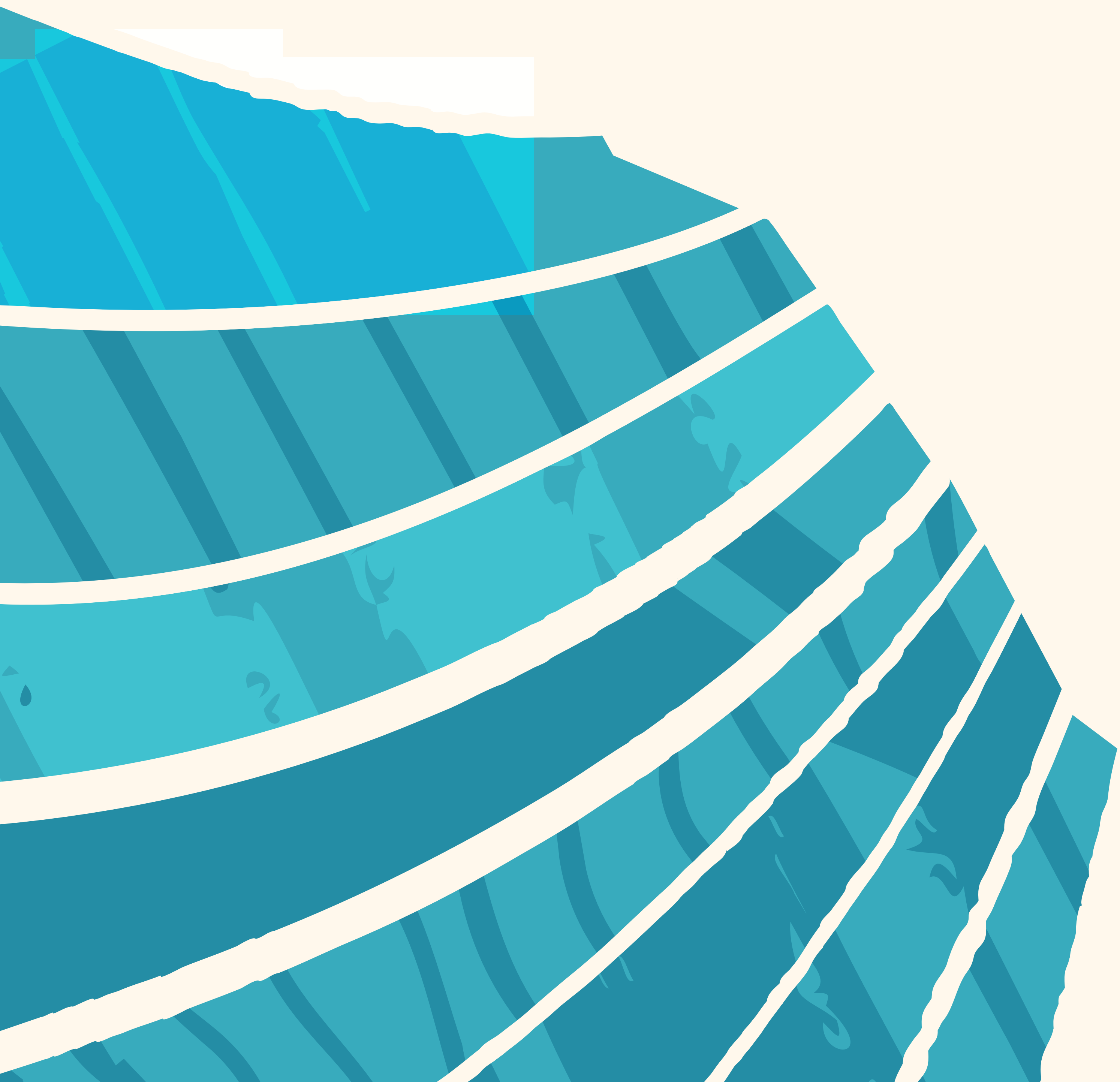
Second Austrian Assessment Report on Climate Change | AAR2
Austrian Panel on Climate Change | APCC | 2025

## Chapter 3

# Built environments and mobility



# Second Austrian Assessment Report on Climate Change | AAR2

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## Built environments and mobility

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## EXECUTIVE SUMMARY

**Buildings and transportation provide essential services, while direct energy use accounts for 36 % and 34 % of Austria's total end-use energy consumption in 2023, contributing 9 % and 29 % of total national greenhouse gas (GHG) emissions, respectively (*high confidence*).** Including indirect GHG emissions from district heating and electricity used in buildings and mobility (e.g., heat pumps, electric vehicles) in their respective sectors would increase these shares, accounting for 3.4 % (buildings) and 0.3 % (transport) of the total national emissions in 2022 (*high confidence*). {3.3.1, 3.4.1}

**Sustainable cities, villages, and settlements feature short distances for work, leisure, schools, and daily necessities as well as appropriate infrastructure for diverse modes of active mobility. Settlement areas have significant potential for GHG emissions savings, with urban households emitting about one-half to one-third of suburban ones due to smaller physical footprints, shorter distances traveled, and lower car dependency (*high confidence*).** 'Urban' and 'rural' here align along a continuum, with continued **suburbanization representing the most direct climate policy challenge.** This points to the need to avoid green-field development in favor of maintaining and fostering compact settlements (*high confidence*). {3.2, 3.4.2}

**Compact urban development and densification can be achieved by improved utilization of existing planning instruments and the development of strong multi-level governance and coordination (*high confidence*). Challenges include urban heat island (UHI) effects and preferences for single-family homes and car ownership (*high confidence*).** Addressing these deeply ingrained lifestyles – rooted in prevailing social norms and perceived convenience – is a crucial challenge for advancing decarbonization in the housing and transport sector (*high confidence*). {3.2, 3.4.2}

**Adapting Austria's built environment to climate change entails prioritizing resilient water management, greening initiatives for local ambient air cooling and water retention, protection of infrastructure from landslides and flooding as well as robust information, communication and early warning systems (*high confidence*).** This necessitates integrating climate considerations into spatial planning as well as building design guidelines and standards, including adaptable building codes and infrastructure regulations (*high confidence*). Localized limits to adaptation may arise under extreme warming scenarios (*low confidence*). {3.2.3, 3.3.3, 3.4.4}

**Absolute building GHG emissions decreased by about 43 % between 1990 and 2022, despite increases in the number and size of housing units (*high confidence*).** This decoupling was due to rapid deployment of renewable energy sources and district heating, better insulated buildings and less need for heating due to higher ambient temperatures (*high confidence*). {3.3.1}

**Main pathways for further reduction of building-sector GHG emissions include replacement of oil and gas burners by renewable energy driven systems, implementing air-heat recovery in mechanical ventilation systems, building retrofitting by further improving insulation levels, adopting circular design principles and the use of low-emission construction materials – while considering embedded environmental impacts across their entire lifecycle (*high confidence*).** Main uncertain countervailing factors stem from potential population growth – according to official Austrian projections – and a potential shortage of installers qualified to deploy transition technologies based on renewables. Climate change is projected to decrease heating and moderately increase cooling demand in buildings – reducing net energy consumption and increasing the need for combined heating and cooling systems (adaptation) (*high confidence*). {3.3.1, 3.3.2}

**Electrification of buildings and road transport – with heat pumps and electric vehicles pivotal – will lead to a dominant role for electricity as the main source of energy in both sectors (*high confidence*).** Supporting policies, regulations, and infrastructure investments are expected to accelerate this transition (*high confidence*). {3.3.1, 3.4.2, 3.4.3}

**Road transport accounts for 99 % of GHG emissions in the Austrian transport sector (excluding international flights), with freight transport contributing 35 % in 2023 (*high confidence*).** After peaking in 2005, GHG emissions in transport saw a steady rise from 2012 onward. Substantial reductions occurred only in recent years, beginning in 2020, largely driven by external factors such as the COVID-19 pandemic and Russia's invasion of Ukraine. Nevertheless, in 2023, transport-related emissions remained 42 % above the 1990 level (*high confidence*). {3.4.1, 3.4.3}

**An expected increasing demand for freight transport, combined with limited potential for rail modal shifts, and a still limited availability of competitive low-carbon trucking alternatives render it difficult to achieve full transport sector decarbonization by 2040 (*medium evidence, high agreement*).** {3.4.1, 3.4.3}

**A combination of 'pull' and 'push' measures provides the most effective strategy for decarbonizing transport and housing. Push measures, including higher fuel taxes or bans on fossil-fuel-based heating systems, are essential for creating disincentives for carbon-intensive choices. Pull measures – such as affordable public transport, improved cycling infrastructure, and incentives for building renovations or switching from fossil-fuel heating to renewable alternatives – further encourage behavioral change by improving the attractiveness of low-carbon choices. Pull measures can also help in improving the public acceptability of push measures, in particular by mitigating potential negative distributional impacts of push measures (*medium confidence*).** Aligned with the ASI (Avoid/Shift/Improve) framework, these measures can reduce demand for emission-intensive activities and construction (avoid), promote sustainable alternatives like public transport and heat pumps (shift), and improve efficiency through technological advances, such as electric vehicles, deep building retrofits, circular design and the utilization of low-emission materials – while considering embedded lifecycle impacts (improve) (*medium confidence*). {3.3.1, 3.3.2, 3.3.3, 3.4.2, 3.4.3, Cross-Chapter Box 4}

**Reduced dependence on motorized transport has multiple co-benefits and positive spillover effects: Lower energy and resource requirements for vehicle production and recycling, improved traffic safety, less noise and local pollution, improved public space quality due to parking and road space freed up for alternative uses (e.g., green space), and improved health through the use of active mobility (*high confidence*).** {3.4.1, 3.4.2, 3.4.3}

**GHG emissions from constructing, maintaining and renovating buildings and infrastructure present a major challenge (*high confidence*). Key levers to drive reductions are revised building codes, infrastructure regulations (e.g., minimum parking requirements) as well as tendering and procurement policies that take embedded emissions and circular design approaches into account (*medium confidence*).** {3.3.1, 3.3.2, 3.3.3, 3.4.4}

## 3.1. Chapter introduction

Climate change affects the built environment and transport, both via long-term trends (e.g., rising temperatures) and via extreme weather events like floods, droughts, and storms. Spatial planning, transport and building infrastructure are thus relevant for adapting to climate change and also play a crucial role in cutting greenhouse gas (GHG) emissions (Creutzig et al., 2015; Haberl et al., 2023). This requires a reconsideration of traditional village and urban configurations on the one hand, and building codes and mobility cultures on the other hand.

While assessing the sectors fundamental to the built environment and mobility in the context of climate change and sustainability, Figure 3.1 outlines the various, often interconnected disciplines considered. Hence, this chapter starts with a macro view of the impact of cities and settlements on the climate, and vice versa, as well as the potential to use spatial planning to reduce GHG emissions (Section 3.2). After detailing key developments and projections (Section 3.2.1), the chapter focuses on reducing land consumption in times of population and economic growth (Section 3.2.2), an important lever to lessen overall climate impacts and exposures, and impacts and risks of climate change within urban environments (Section 3.2.3). Section 3.3 focuses on buildings and their past, present, and future climate impacts and exposures from the perspectives of building technology and renewables (3.3.1), construction material (3.3.2) and legislation (3.3.3). Section 3.4 does the same for the passenger (3.4.2) and freight transport sector (3.4.3), as well as the related road and rail infrastructure (3.4.4). Notably for infrastructure, adaptation to climate change plays a crucial role. The spatial structure shapes behavioral choices, in particular with respect to buildings and mobility. Accordingly, urban and regional spatial planning, buildings and transport systems are closely related to demand-side climate change mitigation. Therefore, it is critical to understand household-level GHG emissions-footprints as linked to broader land-use, building, and mobility choices.

Chapter 3 is closely linked to the other chapters of the report. It builds on the estimates of Chapter 1 regarding changes in the frequency of extreme weather events in order to assess potential adaptations to climate change in spatial planning, buildings, and transport (infrastructure). The emphasis on spatial planning in Chapter 3 has implications for land available for other uses (agriculture, forests, etc.), which are the focus of Chapter 2. Chapter 3 and Chapter 4 are particularly related via the energy sector, as electrification is a

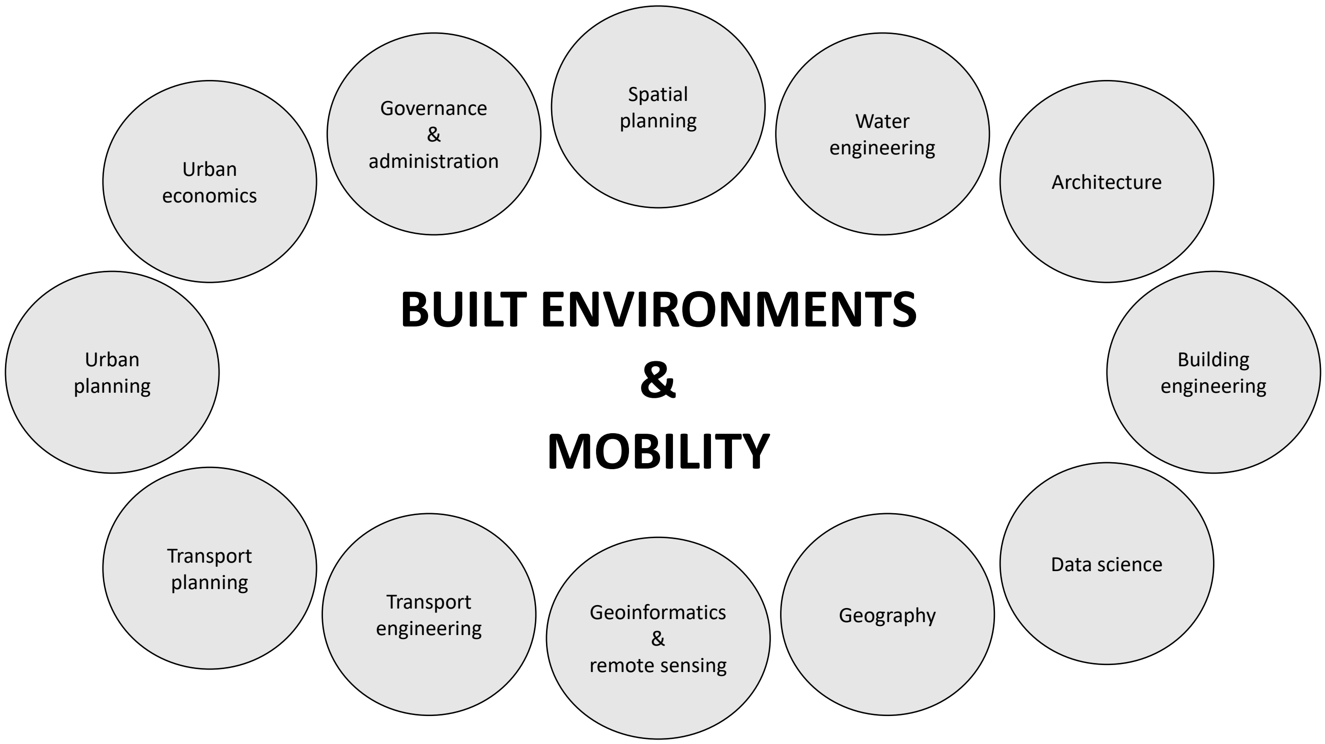



Figure 3.1 Disciplines involved in the study of climate change and solutions, specifically for climate change mitigation and adaptation, as considered in this chapter. Each discipline adds its own perspective and limits to the analysis. Given the complexity and open system nature of urban issues, it is necessary to consider and move between different perspectives.

main strategy for the decarbonization of the building and transport sectors. Further links exist to other topics of Chapter 4, including the volume of freight transport correlating closely with economic activities, tourism and work being a main source of travel demand, or teleworking as a form of work that does not require daily commuting. Links to Chapter 5 arise from demand patterns and lifestyle choices that impact the desirability and acceptance of different forms of housing and mobility behavior, and of different types of spatial surroundings; the distributional impacts of buildings, mobility, and spatial planning policies link these two chapters. Following the understanding of the recent IPCC report (Creutzig et al., 2022; IPCC, 2022b), demand-side mitigation includes both socio-behavioral shifts (the lifestyle domain of Chapter 5 of this report) and physical infrastructures as major modifiers enabling or prohibiting certain lifestyles (the domain of this chapter). Due to the involvement of different governmental levels (EU, national, provincial, municipal, local) in spatial planning, buildings, and transport, Chapter 6 provides an important governance/political context to Chapter 3. Chapter 7, meanwhile, intersects with Chapter 3 along multiple dimensions, including spatial and infrastructure planning, mobility, and buildings, as they are related to mountain regions. With its overarching focus on transformation pathways, Chapter 8 encompasses sectoral scenarios in particular for buildings and transportation.

## 3.2. Cities, settlements, and spatial planning

This section evaluates how urban areas and spatial planning influence climate change mitigation and adaptation. Section 3.2.1 discusses trends and projections in urban development, while Section 3.2.2 explores land-use strategies for reducing greenhouse gas (GHG) emissions. Section 3.2.3 focuses on climate risks to cities and settlements, addressing the resilience of infrastructure and adaptive capacity. Additionally, Chapter Box 3.1 highlights the 'Zukunft Linz' climate adaptation plan as a case study in urban resilience.

### 3.2.1. Cities and settlements

Cities and urban settlements are both impacted by and likewise directly contribute to climate change, via a host of interwoven demographic, economic, land use and infrastructural changes (Rosenzweig et al., 2010; Weichselbaumer et al., 2022). Worldwide, roughly 75 % of global GHG emissions come from urban and suburban settlements, attributable primarily to residential buildings, followed by commercial/industrial buildings, transport, and waste/sewage (e.g., Satterthwaite, 2008; Hickman and Banister, 2015).

Meanwhile, both Europe and Austria are experiencing continued urbanization: In Europe approximately 75 % live in urban settlements with more than 10,000 inhabitants today (UN DESA, 2019), a figure that is expected to rise to 83.7 % by 2050. Austria represents a lower rate of urbanization, at 59.2 % of its 8.7 million inhabitants (in 2019), expected to rise to 71 % in 2050, according to UN DESA (2019). Recent statistics show that the total population of Austria has increased to 9.2 million in 2024 (Statistik Austria, 2024b).

Further analysis points to the importance of a nuanced view of urbanization, e.g., drawing clear distinctions between the dense urban core with multi-family housing and efficient, multimodal transport infrastructure, and the continuing suburbanization at the urban periphery of larger cities and between cities and small(er) settlements, often with single-family housing and limited mobility choices (Steinegger, 2023). This increasingly pressures local administrations to ensure adequate, affordable, and climate-resilient housing while simultaneously expanding infrastructure to support more climate-friendly mobility (see Section 3.2.3). Divergent regional population growth rates call for detailed plans and planning instruments for both mitigation and adaptation, while also necessitating cross-regional coordination and management. The long-term nature of spatial planning creates particular urgency, given Austria's climate neutrality goal for 2040.

Climate change affects cities and urban settlements most directly via intensity and frequency of extreme weather events, including heavy rain fall, droughts, and heat (see also Section 1.2). Heat events are becoming more frequent in Austria (see Figure 3.2 for increase in hot days, i.e., with a daily maximum temperature over 30°C). This is of particular significance for the built environment, exacerbated by urban heat island (UHI) effects (Oke and Fuggle, 1972). Meanwhile, cold stress in winter is reduced by increasing temperature, as, e.g., illustrated in Figure 3.3, showing historic trends in hot and ice days in Vienna (see Section 3.3.1 and Section 4.5.2 for the impacts on space heating and cooling). These phenomena are exacerbated by continued surface sealing and loss of open and green space, which impairs natural cooling and water retention functions. There is wide regional variation in exposure, susceptibility, and coping capacities both across and within cities, especially those with

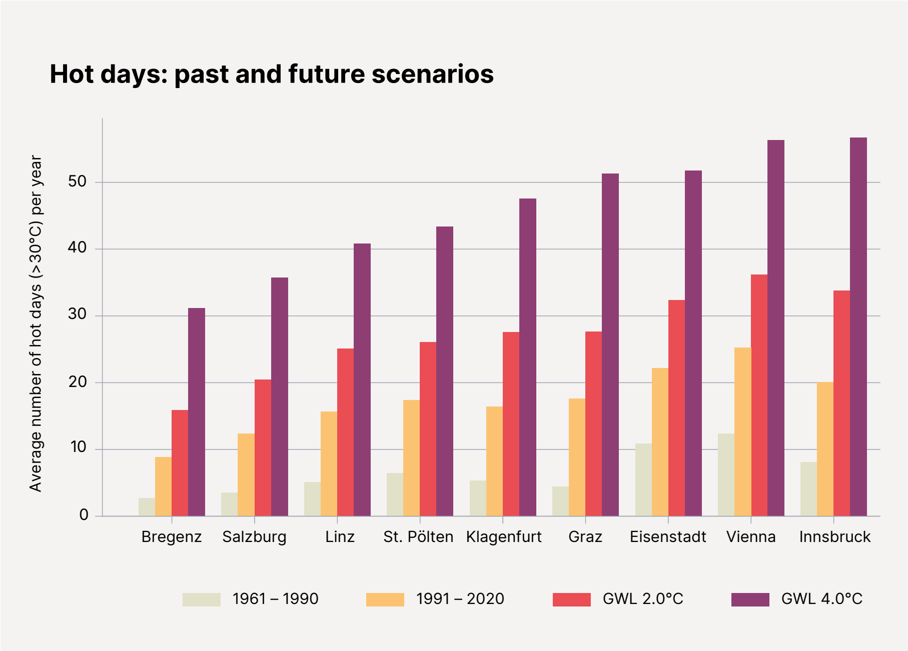



**Figure 3.2** Hot days yearly average in the nine provincial capitals measured in the past decades and forecasted for two different climate scenarios (with and without global climate protection measures, i.e., GWL 2.0°C and GWL 4.0°C, resp.) (GeoSphere Austria, 2022).

high socio-spatial differentiation, e.g., access to public transport and green spaces (Krellenberg et al., 2017). In Vienna, for example, socio-spatial inequalities have increased in the context of rising labor inequality and an uneven restructuring of the urban housing market (Kadi et al., 2022). There is some evidence of 'green gentrification', referring to the fact that the renaturation of urban spaces can lead to rising housing prices and socio-demographic upgrading, and thereby to the (in)direct displacement of underprivileged groups, who already suffer most from environmental injustices, in the private rental segment (Friesenecker et al., 2023).

Overall, detailed geospatial information on urban vulnerability in Austria is limited, with some exceptions, e.g., Linz (see Chapter Box 3.1) and Vienna (e.g., Weatherpark GmbH, 2021, with a grid resolution of 10 m). The 'Urban Heat Island Strategy City of Vienna' (Magistrat der Stadt Wien, 2015) demonstrates various actions and their implementation that reduce heat in the summer months, including strategic and technical measures, to improve micro- and neighborhood climates. The 'Heat Action Plan' (Stadt Wien, 2022) identifies 'vulnerable' people and groups, such as elderly and socially isolated people, people in need of care, people with chronic care-dependency, and people with chronic or mental illnesses, pregnant women, young children, or people living and working in particularly difficult conditions. The change adaptation in 'Graz Action Plan' (Stadt Graz, 2018) defines action fields but does not address vulnerable areas or place-based adaptation measures.

Making Austrian cities and the broader built environment 'climate-fit' involves both climate adaptation and mitigation efforts which are highly interwoven and need both be considered in integrated urban planning and development processes. Strong linkages exist to both, the transport sector (Section 3.4) and the building sector (Section 3.3), in terms of retrofitting existing structures and buildings but also to make efficient use of public space in terms of de-sealing, multifunctional uses and greening, which likewise enhance the quality of life in a broader sense. In addition, new development projects should be planned and designed from the ground up to be climate-fit by implementing integrated sustainable development approaches, thus contributing to the necessary sustainable urban transformations. Overall, compact cities with reduced mobility needs through short-

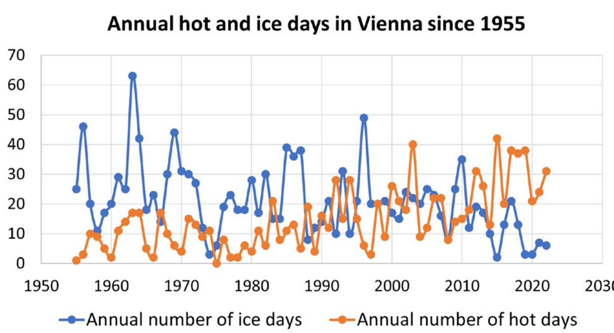
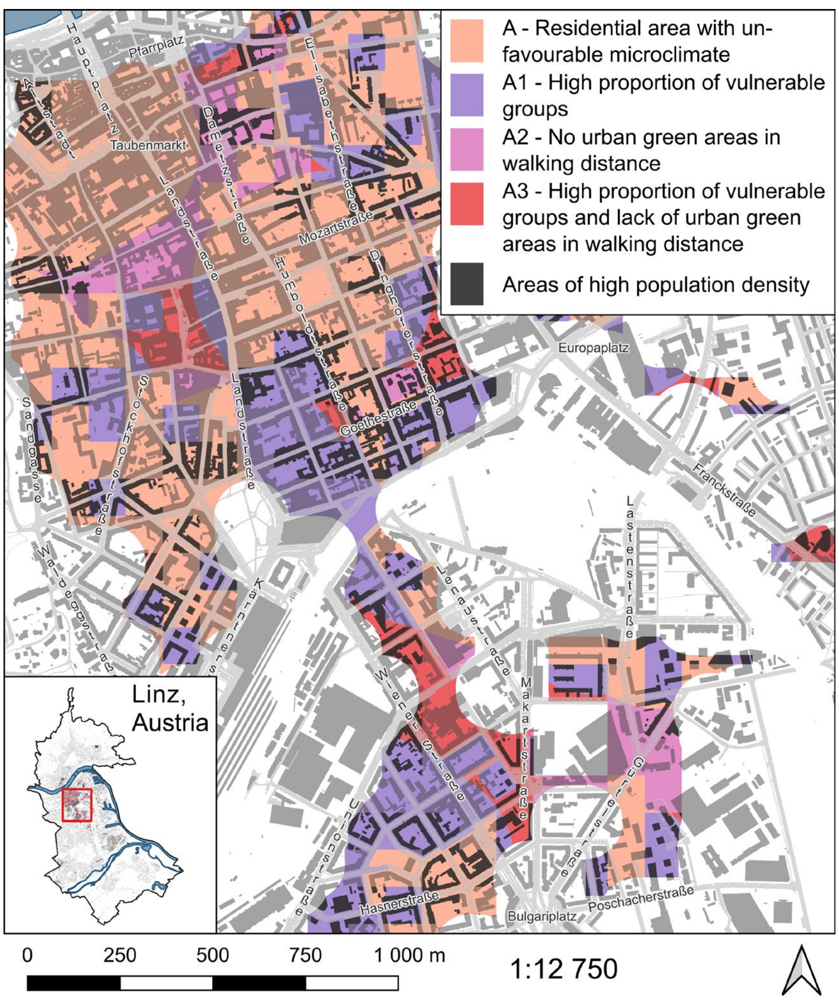



**Figure 3.3** Frequency of hot days (maximum daily temperature exceeding 30°C) and ice days (maximum daily temperature below 0°C) recorded in Vienna (Stadt Wien, 2024).

er distances (e.g., the '15-minute city' concept) and more inclusive planning and design of public space (e.g., the 'superblock' approach) to support multiple uses of open space, will allow mitigation and adaptation measures to be considered together, supporting the fundamental transformations needed in urban development and spatial planning (WBGU – Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, 2011, 2016).

## Chapter Box 3.1. Climate change adaptation plan 'Zukunft Linz' ('Future Linz')

'Zukunft Linz' ('Future Linz') forms the basis for climate change adaptation in Linz (Magistrat Linz, 2023), based on detailed, spatially disaggregated risk assessments linked to exposure and vulnerability, taking into account adaptive capacity (Box 3.1 Figure 1). The map shows regions of high priority for heat-related adaptation measures. Additionally, exposure maps exist for hail, fluvial floods, and storms, allowing for the prioritization of adaptation efforts and risk monitoring (BML, 2023). The expertise is housed within Linz's urban climatology and environmental management (UCEM) division, with an urban climatologist and two additional climate change adaptation staff members who help prioritize and coordinate city-wide adaptation efforts across city departments. This includes, e.g., planning for heat events negatively affecting public health and thermal comfort. For example, Linz's medium- to long-term projects include a greening initiative focused on tree planting to address UHI effects, a stream renaturation program to restore natural habitats and prevent flooding, and a heat emergency plan based on spatially disaggregated risk events (Box 3.1 Figure 1).




**Box 3.1 Figure 1** Excerpt of the heat risk map of Linz focused on the districts 'Innere Stadt' and 'Bulgariplatzviertel', showing spatially resolved vulnerabilities and adaptive capacities (Horak and Peßenteiner, 2023). Vulnerability considers residents' age, pre-existing medical conditions, and socio-economic status. Adaptive capacity is based on publicly accessible urban green areas >7,500 m² and tree cover within walking distance of at most 250 m.

### 3.2.2. Land-use and spatial planning

#### Strategic context in Austria

Land-use planning takes account of and aims to influence spatial development trends. In 2021, the office of the Austrian Conference on Spatial Planning (ÖROK) published the 'ÖREK 2030', the Austrian Spatial Development Concept for Austria (ÖROK, 2021), elaborated with input by stakeholders from all governmental levels including the state, the federal provinces, districts and municipalities. The strategy is the most important federal document providing a joint vision for future development foci. The ÖREK 2030 outlines the key themes of need for urban and regional transformation for the next 10 years in four pillars (ÖROK, 2021):

- A parsimonious and sparing use of spatial resources;
- The strengthening of the social and spatial cohesion;
- The sustainable and climate sensitive development of economic spaces and systems;
- The development of vertical and horizontal governance.

Land-use planning remains a key tool for enhancing Austria's resilience and adaptive capacity while guiding contemporary development trends, such as multilocality, connectivity, mobility, land use, economic activities, digitalization, and housing. It plays a crucial role in both preventing additional emissions and enabling effective adaptation and mitigation measures (ÖROK, 2021).

The governance of and legal systems in Austria imply that these overall goals can only be achieved through efficient vertical and horizontal governmental coordination (see Section 6.4). There are three main levels: The federal government is only legally responsible for the development of sectoral plans and, through the ÖROK, for the development of the spatial development strategy. Due to the Austrian Constitution, which grants the right to develop their own laws in any policy area that is not regulated at the federal level, the nine federal provinces have the right to develop spatial development laws ('Raumordnungsgesetze') in the absence of a federal spatial planning regulation (BGBl. Nr. 1/1930, 2024, art. 15). As a result, each of the nine federal provinces has its own legal framework. In general, the federal level remains with competences to outline strategy documents as well as sectoral plans. Further, the federal provinces have the obligation to provide the frameworks and legal specifications for local land-use regulation (Gruber et al., 2018). In line with the subsidiarity principle, the right for legal instruments linked to land-use regulation lies with the municipal level. The municipalities in Austria have the responsibility to develop strategic development concepts, zoning plans, and/or building regulation plans (BGBl. Nr. 1/1930, 2024, art. 118). In some federal provinces, development plans and strategies may also be developed at the regional level.

This multi-level governance framework implies that the federal government only can act through strategic guidelines to address many of Austria's developmental changes. To address certain developmental challenges, such as land take, the ÖROK can devise implementation plans – for instance the Land Protection Strategy for Austria ('Bodenstrategie für Österreich') (ÖROK, 2023b). Recently, the limitations of the multi-level governance system have become evident: Although the federal provinces – who hold the legal authority – have adopted the Land Protection Strategy, the final version omits the commitment to limit land take to a maximum of 2.5 hectares per day, as originally outlined in the 2020–2024 government program. This case illustrates the complexity of tackling critical challenges in spatial planning within a multi-level governance context. Effective land use monitoring and planning are essential for identifying areas that are exposed and vulnerable to, or likely to be impacted by, climate change-related extreme events, such as severe droughts or intense rainfalls causing floods (see also Cross-Chapter Box 1). Land use planning plays an important role in managing spatial development in a sustainable way.

#### Key development trends and risk factors

Overall, climate change is associated with more extreme weather events (IPCC, 2021a), an increase in the number of hot days, and a shift in seasonal extremes (Fuchs et al., 2015, 2022) (see Section 3.2.1). Impacts differ between urban and rural areas, and between lowland and mountainous areas, which is particularly relevant for Austria (see Section 1.2.2). For example, an increase in extreme rainfall events after long periods of drought can have potentially devastating impacts on agricultural practices in mountainous areas (see Sections 2.2.1, 7.4.2 and Table 2.2) and an increased occurrence of avalanches puts more settlements at risk (Permanent Secretariat of the Alpine Convention, 2017).

The projected increase of annual mean temperatures also suggests that several European regions, especially Austria, will be particularly affected (IPCC, 2022a). The increased amplitude of phenomena associated with extreme hydro-meteorological or compound events, as well as their increased number, can have devastating impacts on existing economic systems, social justice, human health, existing infrastructure, and the built environment in general (see also Cross-Chapter Box 1 and the Cross-Chapter Box 2). In addition to these meteorological developments, soil sealing exacerbates the negative impacts of heat waves, particularly in urban areas, by increasing the UHI effect (see Section 3.2.3).

Demographic development trends, such as ageing regions, do not necessarily coincide with land consumption patterns. The ÖROK estimates a population growth of 3.2 % to 9.22 million inhabitants in 2030 compared to 2021 (ÖROK, 2021). This growth is not equally distributed. On the contrary, some Austrian regions, especially urban areas, continue to grow while others continue to shrink: The ÖREK 2030 estimates that the population of the Vienna Region will grow by more than 15 % by 2040, while some regions, such as the Lavanttal, will shrink by around 10 % (ÖROK, 2021).

It is striking that land consumption continues even in areas with declining population (Dallhammer et al., 2022). While some regions are experiencing shrinkage, Austria's overall population continues to grow, creating demand for additional housing units in urban areas. In rural areas, this new demand is being met primarily with single-family and two-family homes, mostly detached or semi-detached. In urbanized areas, apartment buildings are the norm. These housing demands, as well as industrial developments, result in new soil sealing.

At the same time, demographic development trends will lead to a higher percentage of older people in many regions of Austria. The ÖROK regional forecast up to January 2050 suggests a continuous trend towards an ageing population, especially in rural areas (ÖROK, 2023c). Figure 3.4 illustrates these ageing trends occurring in mountainous areas and rural Austria.

## Reducing land consumption in times of population and economic growth

The European Commission called for target of No-Net-Land-Take by 2050, which was concretized in 2021 with the Soil Protection Strategy for 2030 (European Commission,

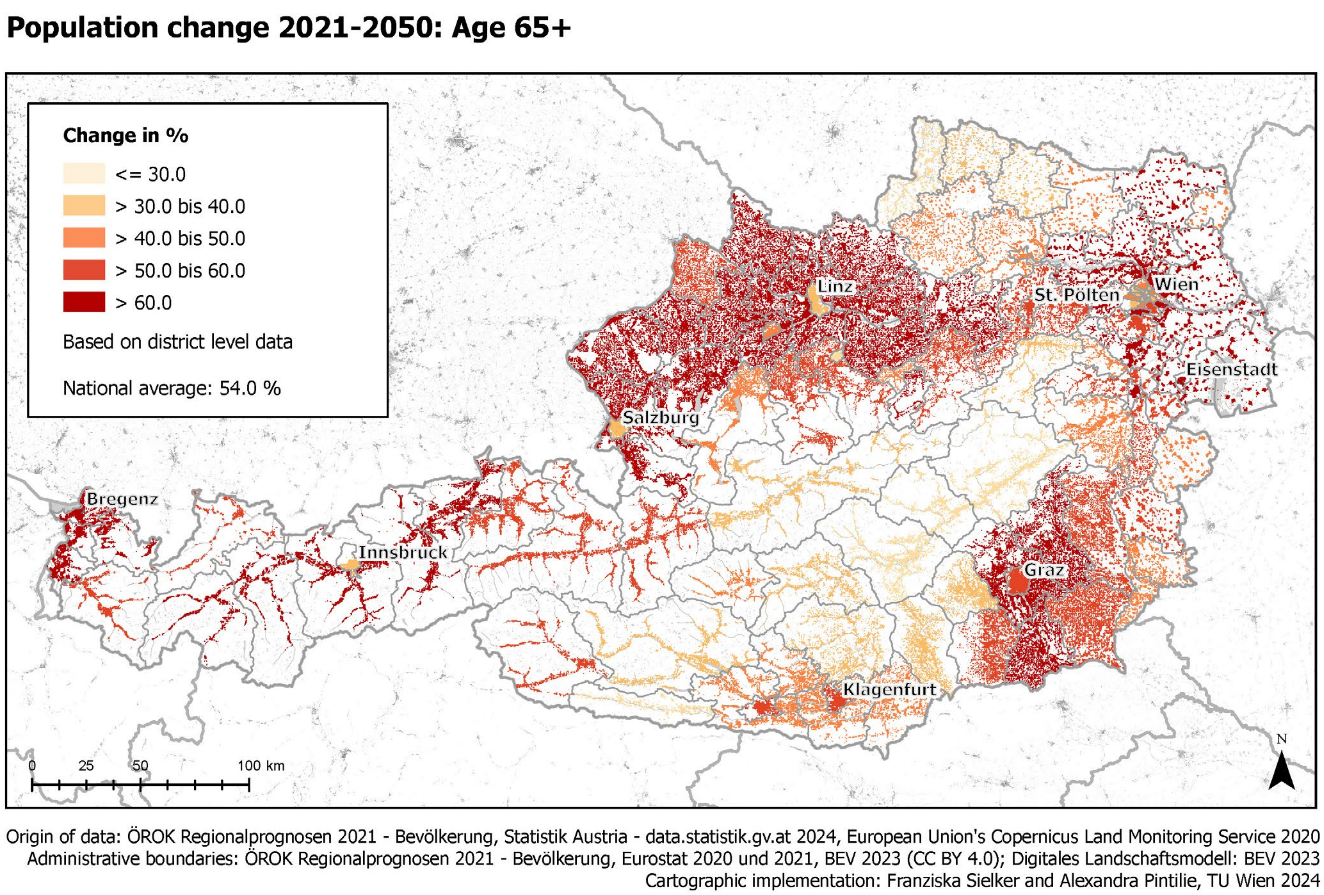



**Figure 3.4** Projected regional population changes in Austria from 2021 to 2050, focusing on individuals aged 65 and older, based on the regional forecast from ÖROK (Sielker and Pintilie, 2024, based on ÖROK, 2021).

2022c). By 2023, Member States were required to set their objectives for reducing land take. In 2022, the ÖROK introduced a new methodology to measure land take and soil sealing in Austria (ÖROK, 2023d).

In parallel, both on the EU level and in Austria, a process is underway to provide conceptual clarity on the difference between land take and soil sealing. The term 'land take' in the sense of 'land consumption' includes built-up areas as well as urban green areas and land used for agricultural, forestry, or other economic activities. The term 'soil sealing' or 'imperviousness' refers to the situation in which the nature of the soil changes in a way that it becomes an impermeable medium (Marquard et al., 2020; Decoville and Feltgen, 2023). Land take, including buildings for housing, infrastructure, recreational activities as well as cultivation areas, involves the long-term loss of biologically productive soil.

Figure 3.5 visualizes the degree of soil sealing and potential permanent settlement areas. Especially in Austria, which has a high proportion of alpine areas, the concept of permanent settlement area is of great importance. It refers to the inhabited and (economically) usable area available for settlement development, agricultural production, and infrastructure. It consists of a settlement area and a potentially inhabitable area, the latter including agricultural and green areas. The uninhabitable area (non-settlement area) is made up of forest areas, alpine grassland, wasteland, and water bodies. The CORINE Land Cover data as well as population and employment data (see ÖROK, 2015; Statistik Austria, 2023a) form the basis for the delineation of permanent settlement areas. This data was overlayed with information regarding the imperviousness degree. Soil sealing, as mentioned above, refers to areas that are continuously covered with a layer that is completely impermeable to water and air. The data from the Copernicus Land Monitoring Service represent the degree of sealing, in percent and aggregated to a 100 x 100 m grid (European Environment Agency, 2020). This method was chosen to add to the existing ÖROK Atlas (ÖROK, 2023d), which maps the proportion of soil sealing in administrative units. By making use of the granularity of the most recent Copernicus data, Figure 3.5 overlaps soil

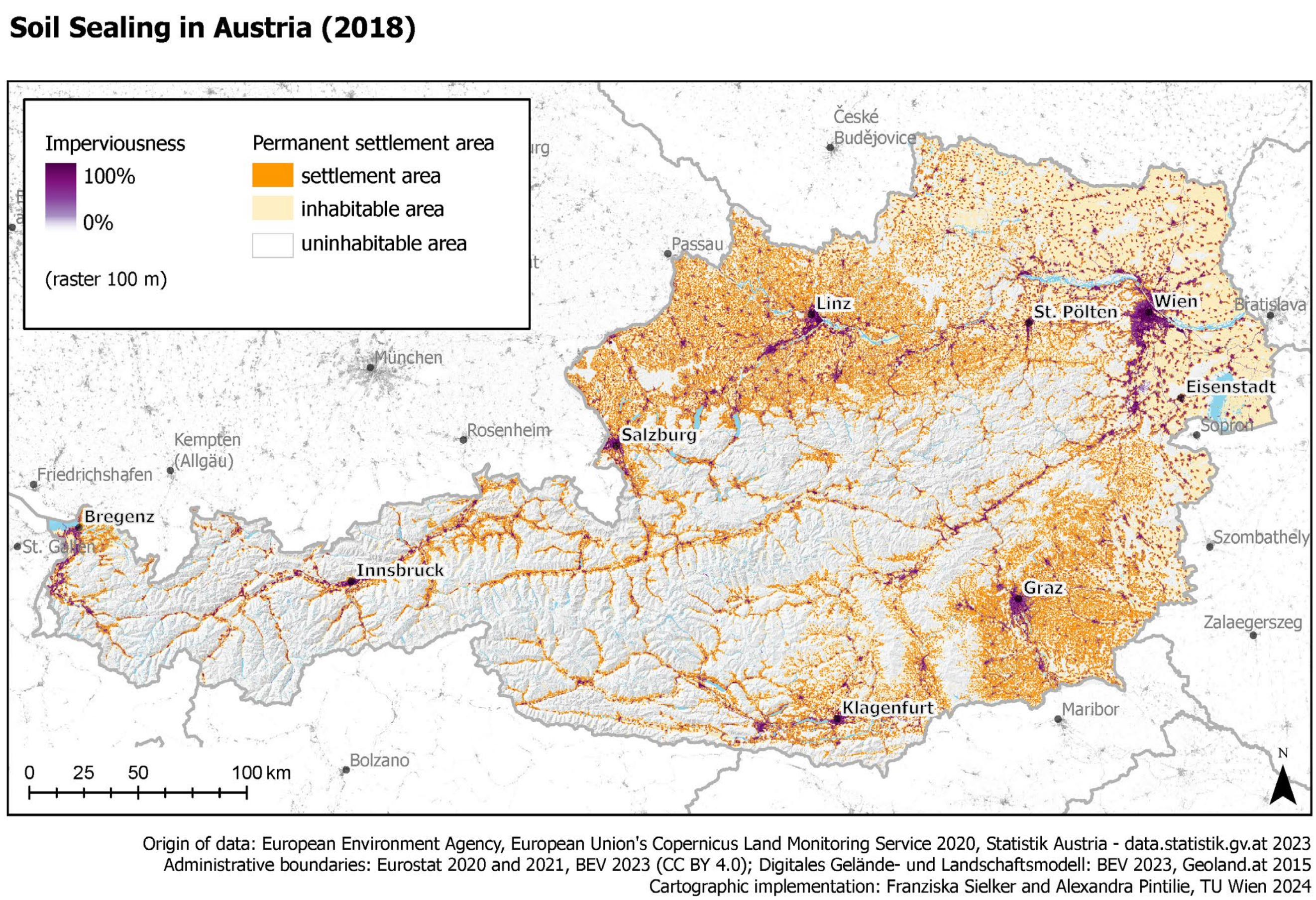



**Figure 3.5** Soil sealing in Austria, as observed in the year 2018, showing the extent of land covered by impervious surfaces (Sielker and Pintilie, 2024, based on European Environment Agency, 2020).

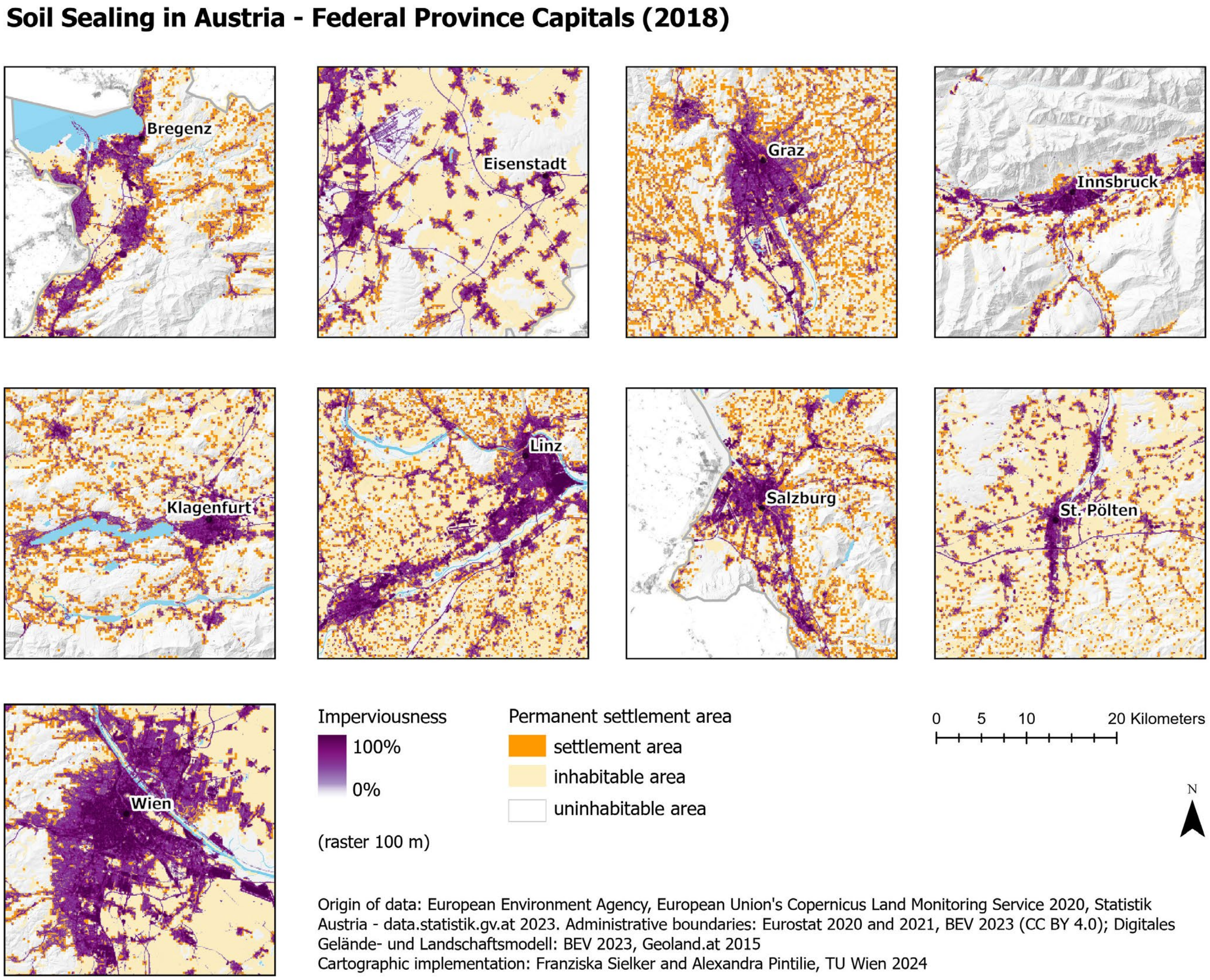



**Figure 3.6** Soil sealing in the capitals of Austria's federal provinces in the year 2018 (Sielker and Pintilie, 2024, based on European Environment Agency, 2020).

imperviousness with the potentially inhabitable land, allowing for a spatially detailed visualization. To get a sense of this granularity, Figure 3.6 provides zoom views for the capitals of the federal provinces.

Austria's continued excessive land consumption is in stark contrast to the objective of climate resilience, as open spaces continue to be sealed. Using its own methodology, which is also based on data on building land zoning, the ÖROK presented relevant figures in its report on land take and soil sealing in Austria. Accordingly, in 2022, an area of approximately 5,648 km² has been changed in a way that the land is no longer available for agricultural and/or forestry production or as natural habitat. This is described as land take in contrast to soil sealing. Land take marks roughly 17.3 % of the permanent settlement areas in Austria. More than half of this area (52 % or 2,964 km²) was already sealed in 2022 (ÖROK, 2022). If the land consumption within Austria continues at this pace, conflicts around land use will increase in the inhabitable settlement areas, as is shown in Figure 3.5 and Figure 3.6.

A key takeaway from Figure 3.5 is that in the potentially inhabitable areas of Austria, a diversity of uses has to be realized. In many cases, these are mutually exclusive land use demands, as for example agriculture and housing. Considering the diversity of land use demands in the context of population development, the pressure on urbanized areas in particular will continue to increase. Decisions on new land take, and in particular soil sealing, need to take into account the potential negative impacts in other areas. In the long-term, land take in general and sealed soil in particular has serious implications for natural ecosystems. Biodiversity loss and habitat fragmentation are some of the consequences.

Similarly, as mentioned above, the systems of governance and planning in Austria tend towards a strong executive power with substantial planning-relevant competences at the district level, followed by the provincial level and a relatively weak state level with its main competences in sectoral plans. With regard to soil sealing, local development strategies and zoning are key to prevention. However, there is no overall Austrian strategy that sets targets for local authorities. In addition to land use plans, there are a number of instruments that can support the goal of no-net-land-take. These include, for example, climate checks for potential building land, environmental impact assessments for new construction projects, funding schemes for area recycling and unsealing, and using the opportunity to define settlement boundaries for local development (see also ÖROK, 2023a).

A key challenge for the future is therefore to make better use of existing instruments and to develop incentives to reduce new designations of building land. In order for local authorities to achieve overarching goals such as improving resilience and adaptive capacity, greater multi-level governance coordination may be useful. Multi-level governance discourses, including additional training and education, as well as raising awareness of the role of each local authority in contributing to these overarching goals, will be key.

## Spatial energy and infrastructure planning

Achieving climate neutrality in the built environment is closely linked to the transformation of energy infrastructure (Camarasa et al., 2022; European Commission: Directorate-General for Energy et al., 2022; Billerbeck et al., 2024; Fallahnejad et al., 2024). This applies to the grids used to transport energy (electricity, district heating and eventually gases) and distribute it to end-users. It also applies to renewable energy generation, some of which is on-site, directly connected to buildings, such as building mounted photovoltaics (PV), or in the form of renewable energy generation sites, such as wind farms or ground-mounted PV. Both components have a strong spatial component and are linked to the planning of settlements in urban and rural contexts. While the second component is more closely related to renewable energy generation (Sections 4.5.2, 4.5.3) and biomass (Sections 2.1.1, 2.2.1, 2.3.2), this section will focus on the first component, i.e., the spatial component of energy grid infrastructure in relation to settlement structure, energy densities and related planning activities.

A key question in the decarbonization of the built environment is which part of the building stock should be connected to which energy infrastructure in order to provide a full supply of renewable energy (also taking into account the potential of measures to reduce energy demand). While more or less all buildings in Austria with a relevant energy demand are connected to the electricity grid, this is not the case for district heating and gas grids. High infrastructure costs for supplying only a low number of connected end-users should be avoided. In this context, spatial planning is important to ensure high connection rates and thus a high economic utilization of infrastructure investments. For district heating grids, the challenge is to identify and implement district heating areas in line with decarbonization plans, connecting climate neutral, renewable heat supply resources with heat demand (Billerbeck et al., 2024; Fallahnejad et al., 2024). For the gas grid infrastructure, spatial energy planning will become even more important, considering that the simple substitution of fossil gas by renewable gases may not be fully possible or very expensive, thus requiring a gradual decommissioning of the gas grid (see, e.g., Zwickl-Bernhard and Auer, 2022).

Recognizing these needs, the revised energy efficiency directive (Directive (EU) 2023/1791) of the European Union foresees the enforcement of local heating and cooling plans at least in municipalities with a population greater than 45,000. These plans should include a strategy for enforcing renewable heating and cooling, waste heat, and district heating and cooling. This should be based on a thorough analysis of heating and cooling systems in the local building stock as well as an analysis of energy efficiency measures. Clearly, these provisions will also need to be implemented in Austria with the corresponding effects.

In some European countries, municipal and spatial energy planning have a long tradition, particularly in Denmark (see, e.g., Chittum and Østergaard, 2014; Büchele, 2019). In addition, there is a considerable tradition of developing tools for spatial energy planning and municipal strategic energy planning, as described, for example, in Mirakyan and De Guio (2013), Stöglehner et al. (2016), Büchele et al. (2019), and Mandel et al. (2023). In addition, several tools have been developed in recent years to support municipalities in particular in the task of municipal heat planning, such as the 'Hotmaps' tool (Hotmaps Project, 2023) or 'Thermos' (Thermos, 2021). However, one of the main bottlenecks for effective spatial energy planning is a solid database, first of all on the buildings, their energy performance and related energy consumption, the resulting energy density and their existing technologies, in particular heating systems. Activities to improve data availability in this respect in Austria in recent years can be summarized along two lines. The first is mainly based on open access data and applies different algorithms to merge these datasets in order to derive the required data on a high spatial resolution, e.g., at the hectare level. Examples include the 'Energiemosaik', the project 'Enerspired cities' (Schardinger et al., 2021) and the 'Austrian Heatmap'[1]. The second line of activities aims to provide a higher resolution, i.e., at the building level, and also builds on non-open data sources, such as the building registry 'AGWR' (Statistik Austria, 2024a), including information from building energy performance certificates or datasets from chimney sweeps and plumbers. Here, mainly the project 'Spatial Energy Planning'[2], within the framework of the 'green energy lab' program, developed new methods and approaches for the three regions of Salzburg, Styria and Vienna.

Several municipalities, local and regional authorities have implemented approaches and partly regulatory policy instruments of spatial energy planning. For example, the city of Vienna established the concept of 'climate protection areas' in 2018, and since then, the energy planning department 'MA 20' has been gradually implementing this concept by defining different areas where the use of fossil fuels is restricted by law (see also Erker et al., 2021).

In part, the concept of spatial energy planning also needs to be redefined and placed in the context of full climate neutrality targets, i.e., restricting the use of fossil fuels in some areas makes sense in a policy regime where fossil fuels in general are not restricted. However, since an overall policy regime is needed in which fossil fuels are completely phased out, spatial energy planning needs to support this goal by defining the areas where this phase-out must take place first. Moreover, in such a policy regime, spatial energy planning is also needed to define areas where shared energy infrastructure facilitating the phase-out of fossil fuels should be preferred to individual (even renewable) solutions. This applies, e.g., to renewable district heating and cooling or public transportation infrastructure. Overall, there is a consensus in the scientific community that gases (be it fossil or renewable) should be used for high-temperature, high-exergy applications and not for low-temperature applications such as space and water heating (see, e.g., European Commission: Directorate-General for Energy et al., 2022; Rosenow, 2022).

[1] austrian-heatmap.gv.at (BMK, 2022a), building also on the methods developed by Müller et al. (2019)

[2] waermeplanung.at (SEP, 2021)

For spatial energy planning, this implies that gas grids in residential areas should be decommissioned (see also Rodgarkia-Dara et al., 2023). The supply of gases to industrial processes is closely linked to other dimensions of spatial energy planning.

While spatial energy planning has historically relied heavily on one-time data collection efforts, there is now a strong trend toward more innovative data approaches that rely on cross-regional, dynamic, automated, digitalized, continuously updated, and flexible data collection approaches to support planning and policy processes at different spatial scales. There is a strong consensus in the literature on the relevance of spatial energy planning and related energy infrastructure planning in achieving climate neutrality (see, e.g., Büchele, 2019; Büchele et al., 2019; Horak et al., 2022; Dumke et al., 2024; Fallahnejad et al., 2024).

### 3.2.3. Climate impacts and risks

#### Urban heat islands

Urban settlements are particularly vulnerable to heat island effects, which affect human health (Tong et al., 2021) (see also Cross-Chapter Box 2). The spatial variation of urban temperature is highly specific to urban form (Zekar et al., 2023), with a direct link between surface sealing and surface temperatures, especially at night, as the built environment (asphalt, buildings) stores heat during the day and releases it at night, resulting in tropical nights (not below 20°C) (Rippstein et al., 2023, fig. 3.7). This poses particular health risks, despite behavioral and physiological adaptations over time (Hagen and Weihs, 2023).

Ameliorating extreme heat in urban environments is critical to reducing heat-related mortality (Martilli et al., 2020). Similar to studies on land surface temperature, studies on air temperature stress the impact of vegetation cover and tree canopy presence, which results in a cooling effect and reduces the ambient temperature (Zumwald et al., 2021). Integrated mitigation and adaptation strategies, such as improved building insulation, are key to ameliorating urban heat island effects (see Section 3.2.3 Integrated mitigation and adaptation strategies).

Older and higher-income neighborhoods are typically associated with more vegetation cover and thus less pronounced urban heat island effects. Heat mitigation may need to focus particularly on lower-income communities, where historical underinvestment has resulted in less green space and more surface sealing (Section 3.2.1).

## Urban water impacts

Austria's urban water infrastructure is highly developed, with 95 % of the Austrian population connected to central drainage systems and 93 % to central water supplies. Both combined sewer systems – where wastewater and stormwater flow through a single pipe – and separate sewer systems – where wastewater and stormwater are carried in distinct pipes – are used. While combined sewer systems are efficient during normal conditions, they can cause overflows during heavy rainfall, leading to untreated or partially treated stormwater and wastewater discharges into nearby waterbodies, called combined sewer overflow (CSO) emissions. Using separate sewer systems reduces the risk of CSO but requires additional infrastructure. Over the last 20 years, decentralized stormwater treatment has been increasingly adopted to mitigate the challenges of urban runoff. As Austria's urban water management sector has a net estimated annual energy consumption of 282 GWh and GHG emissions of 278,000 $tCO_2eq$ (Zach, 2022) (*limited evidence, medium agreement*), energy recovery from wastewater is considered a critical strategy to make the sector carbon neutral or even a carbon dioxide ($CO_2$) sink.

Relevant climate change impacts on urban water infrastructure are changing precipitation and temperature patterns, including increased occurrences of dry periods, excessive heat, extreme precipitation events, and tropical nights (Arnbjerg-Nielsen et al., 2013; Kourtis and Tsihrintzis, 2021). Detailed information on climate projections for Austrian settlements is provided in Chapter 1 (Section 1.2.2; Figures 1.4, 1.5, 1.7 and 1.8) and Section 2.2.2. While there are seasonal and regional variations, there is *medium to high confidence* that rainfall intensities for typical design events (return period 5-10 years) and extreme events (return >100 years) will grow (see Cross-Chapter Box 1). Rainfall intensities for short-duration events are expected to increase by 10 % per degree of temperature rise. Additionally, as mentioned in Section 3.2.2, soil sealing in urban areas is on the rise, resulting in more paved spaces.

Intensified precipitation and soil sealing together boost surface runoff and hence challenge urban drainage systems. For combined sewer systems, this results in increased runoff to wastewater treatment plants and increased CSO emissions, clearly increasing impacts for already slightly shorter event return periods (*medium evidence, high agreement*). As of 2024, the EU proposal for a revised 'Urban Wastewater Treatment Directive' (European Commission, 2022a) limits combined sewer overflow emissions to be below 2 % of annual wastewater runoff. Currently, several Austrian cities are expected to exceed this limit (Muschalla, 2023), and as climate change impacts are expected to worsen, this will lead to adaptation and investment requirements (*limited evidence, high agreement*).

For both combined and separate systems, an increase in rainfall intensities of extreme events also elevates the risk of pluvial floods. To enhance resilience to these climate impacts, necessary adaptation measures include either (1) expanding existing drainage infrastructure or (2) implementing strategies such as de-sealing surfaces, decentralized stormwater management to reduce runoff into drainage systems, and integrating blue-green infrastructure (e.g., vegetation and stormwater ponds) (Kleidorfer et al., 2018). The second approach seems economically and ecologically superior, however, detailed investment demand is unclear and needs to be assessed. De-coupling and de-sealing of surfaces would improve the water and energy balance by increasing infiltration, evapotranspiration and storage of water (Oral et al., 2020; Probst et al., 2022; Ferreira et al., 2024) (*high confidence*). Moreover, such adaptation strategies offer the opportunity to transform existing systems by integrating sustainable, ecological solutions and providing aesthetic, social, and economic benefits. However, compared to existing central systems, this can complexify planning and maintenance procedures (Fletcher et al., 2015).

A transition pathway towards sustainable drainage concepts requires mandatory decentralized stormwater management for new and reconstructed buildings and the implementation of adaptation measures into spatial planning, prohibiting sealing of surfaces and providing the necessary data sources for decision making (e.g., risk maps for pluvial flooding) (Mikovits et al., 2017). Decentralized stormwater management systems often require construction on private property, making it crucial to develop strategies and incentives to facilitate the disconnection of existing stormwater inflows from the drainage system. While many cities and settlements already require that new buildings refrain from connecting stormwater to existing drainage systems, there are generally no incentives to encourage retrofitting in older developments. Introducing split fees – where stormwater and wastewater discharges to the drainage system are billed separately – could serve as a potential financial motivator. Alternatively, providing financial support or subsidies to encourage disconnection of currently connected areas from the drainage system is another viable approach.

In addition to runoff reduction, stormwater harvesting and reuse are becoming increasingly important as precipitation patterns change and water resources are reduced due to longer dry periods between rainfall events and increased water demand for irrigation of nature-based-solutions (vegetation) for urban cooling (Funke and Kleidorfer, 2024) (see Section 3.2.3 Urban heat islands). Therefore, investments in long-term storage systems can not only reduce the demand for drinking water, but also reduce peak flows and provide water to urban vegetation to increase cooling during heat waves.

Overall, urban areas need to prepare for extreme events by establishing risk maps, early warning systems and emergency plans, and by collecting and providing the necessary data to develop such plans. Consequently, water management is part of integrated climate change mitigation and adaptation planning (Ürge-Vorsatz et al., 2018) (see below).

#### Integrated mitigation and adaptation strategies

Urban development and spatial planning can support both mitigation and adaptation. While sometimes in conflict, some strategies, such as better insulated buildings, can address both simultaneously (see, e.g., Section 3.2.3 Urban heat islands).

Compact cities are widely understood as a main strategy for designing low-carbon cities (see also Cross-Chapter Box 4 and Cross-Chapter Box 5) (Stöglehner et al., 2016; Stöglehner and Abart-Heriszt, 2022; Statistik Austria, 2024d). Short distances translate to less distance driven by car and/or higher modal shares of active modes of transportation. High density also means that public transit fulfills the economics of density preconditions to become more financially viable (Creutzig, 2014).

Urban infrastructures can reduce energy use and resulting GHG emissions, for example by reducing thermal loss in denser buildings (Borck and Brueckner, 2018). Avoiding urban sprawl, associated with several externalities (Dieleman and Wegener, 2004), can, in turn, be guided macro-economically by increasing fuel prices and marginal costs of motorized transport to obtain a spatially optimal equilibrium (Creutzig, 2014). Compact cities can lead to urban heat islands and sealed surfaces can prevent water storage and effective water management strategies (see Section 3.2.3 Urban heat islands, Urban water impacts).

Two key strategies can help moderate this trade-off. First, at the macro-scale, new urban developments could follow a star-shaped design, with public transit lines radiating out from the city center while preserving green space in between transit axes (Pierer and Creutzig, 2019). Second, particularly in already built environments, a key strategy is to focus on urban space readaptation. This includes changing inefficient use of street space, such as by unsealing and repurposing parking spaces, or thinking in terms of multi-purpose uses. This would discourage private automobility (the main driver of urban transport GHG emissions; see Section 3.4.2) and support the management of both water extremes and heat waves. Other options include vertical greening of buildings, green roofs, increasing tree cover along city streets, and improved long-term water storage.

Public health is another motivation for compact '15-minute cities' (Caprotti et al., 2024). Highly accessible walkable and cyclable urban design is not only a major mitigation option, it also provides more inclusive city services related to well-being (Lwasa et al., 2023). Solutions include planning cities around walkable sub-centers where multiple destinations such as shopping, work, leisure activities, and others, can be reached without driving (Newman and Kenworthy, 2006; Oswald et al., 2020).

## 3.3. Buildings

This section assesses the building sector's contribution to climate change mitigation and adaptation, emphasizing technology, materials, policy, and legislation. Section 3.3.1 examines energy demand, renewable technologies, and emission reduction pathways in buildings. Section 3.3.2 addresses the decarbonization of construction materials, while Section 3.3.3 reviews legal frameworks, barriers, and opportunities for reducing emissions in the building sector. Chapter Box 3.2 further explores energy storage in buildings, highlighting key technological needs and solutions.

### 3.3.1. Statistics and scenarios of technologies and renewables in buildings

#### Current status

This section outlines the current baseline for the Austrian building sector, based on recent statistics, including data on building numbers and types, energy demand, energy carriers, and greenhouse gas (GHG) emissions. The sector is dominated by single- and two-apartment residential buildings, while nonresidential structures make up 11.6 % of the total building stock (Table 3.1). This section provides an overview of the key assumptions and outcomes of scenarios and measures aimed at reducing energy demand and GHG

**Table 3.1** Number of buildings in Austria in 2021 (Statistik Austria, 2024d).

| Building type →<br>↓ Ownership | Residential building with 1 apartment | Residential building with 2 apartments | Residential building with 3 or more apartments | Other buildings |
|---|---|---|---|---|
| Private persons | 1,477,870 | 287,101 | 160,002 | 175,819 |
| Corporations under public law | 11,006 | 1,868 | 28,086 | 42,541 |
| Non-profit building associations | 27,785 | 1,575 | 60,242 | 2,268 |
| Other legal persons | 14,853 | 2,208 | 25,400 | 56,153 |
| Total by type | 1,531,514 | 292,752 | 273,730 | 276,781 |
| Total overall | 2,374,777 | | | |

emissions (refer to Section 3.3.3 for a legislative perspective on the topic).

Austria's housing stock totals 4.91 million apartments (Statistik Austria, 2021). Of these, 4.02 million are classified as primary residences, while the remaining 0.89 million consist of second homes, holiday properties, or vacant units for various reasons. This distribution is key to understanding residential trends and housing market dynamics in Austria.

Almost all subsidies for housing decarbonization in Austria are contingent upon the registration of a primary residence. In the multi-apartment sector, the legal framework plays a crucial role in shaping the conditions for decarbonization efforts. Housing law regulations vary significantly across different types of properties, including owner-occupied apartments, privately rented apartments, housing association rentals, and municipal rentals.

Of the 1.78 million main-residence apartments in detached houses with one or two units, 1.45 million are owner-occupied. In multi-apartment buildings, about a third of the 2.23 million apartments are privately rented, a quarter are housing association rentals, and a fifth are owner-occupied. The remaining apartments are municipal or have another legal status (Statistik Austria, 2023c).

The end-use energy demand presented in Table 3.2 indicates that, according to the statistics of 2022, fossil fuels account for 29 % of the total demand, primarily from gas and oil. Biomass accounts for about 19 %, while district heating has grown significantly to 15.5 %, with a relative increase of 175 % from 1990 to 2022. Electricity demand, which comprises 29.5 % of the total, includes space heating, domestic hot water (such as direct electric heating, heat pump compressors, hot water preparation, and heating system controls, including ventilation and heat recovery), as well as air conditioning, household electricity, and other uses. The 12 % reduction in end-use energy demand from 2021 to 2022 is largely attributed to the milder weather conditions in 2022 compared to 2021. From 2022 to 2023, this demand decreased by a further 6 %, resulting in a 36 % share of total end-use energy consumption, partly due to the increasing replacement of fossil fuel boilers with heat pumps (BMK, 2024a).

**Table 3.2** End-use energy demand in the Austrian building sector, expressed in terajoules [TJ] (Umweltbundesamt, 2024b).

| Type →<br>↓ Year | Oil | Coal | Gas | Biomass | Electricity* | District heating* | Ambient heat, etc.** | Total*** |
|---|---|---|---|---|---|---|---|---|
| 1990 | 93,451 | 27,578 | 46,093 | 60,457 | 73,412 | 21,798 | 2,239 | 326,143 |
| 2005 | 92,796 | 4,682 | 88,876 | 61,791 | 103,487 | 43,050 | 7,042 | 402,803 |
| 2021 | 51,143 | 478 | 83,024 | 90,944 | 118,456 | 68,098 | 24,914 | 437,062 |
| 2022 | 44,025 | 358 | 67,438 | 72,722 | 113,321 | 59,730 | 27,074 | 384,673 |
| 2021–2022 | -14 % | -25 % | -19 % | -20 % | -4,3 % | -12 % | +8.7 % | -12 % |
| 1990–2022 | -53 % | -99 % | +46 % | +20 % | +54 % | +174 % | +1,109 % | +18 % |
| Share 2022 | 11.4 % | 0.1 % | 17.5 % | 18.9 % | 29.5 % | 15.5 % | 7.0 % | 100 % |

* *GHG emissions from electricity generation and district heating are attributed to the energy and industry sector.*
** *Geothermal, ambient heat (for heat pumps) and solar thermal.*
*** *Including other fuels (combustible waste, peat).*

**Table 3.3** The GHG emissions from the operation of the Austrian building sector, broken down into private households and commercial buildings, measured in million tons $CO_2eq$ [$MtCO_2eq$] (Umweltbundesamt, 2024b).

| Year →<br>↓ Main contributor | 1990 | 2021 | 2022 | Rel. change 2021–2022 | Rel. change 1990–2022 | Share of national GHG emissions 2022 |
|---|---|---|---|---|---|---|
| Private households | 10.605 | 7.326 | 6.154 | -16 % | -42 % | 8.4 % |
| *thereof stationary* | *10.414* | *7.219* | *6.047* | *-16 %* | *-42 %* | *8.3 %* |
| *thereof mobile* | *0.191* | *0.108* | *0.107* | *-0.9 %* | *-44 %* | *0.1 %* |
| Public and private services | 2.313 | 1.537 | 1.224 | -20 % | -47 % | 1.7 % |
| Building sector | 12.918 | 8.863 | 7.378 | -17 % | -43 % | 10 % |

Table 3.3 shows GHG emissions and their relative reductions in Austria's building sector between 1990 and 2022. GHG emissions from district heating and electricity generation are allocated to the energy and industry sector. However, when accounting for the GHG emissions linked to the electricity demand of buildings – 26.6 % of total electricity demand for private households, 16.3 % for public and private services as well as 82.5 % for district heating (Umweltbundesamt, 2024b) – the building sector's share of total emissions in 2022 increases from 10 to 13.5 % (*high confidence*). The share of direct emissions decreased by 20 % to 5.886 $MtCO_2eq$ from 2022 to 2023, driven by the increased adoption of heat pumps, which shifts fossil fuel demand to electricity need, accounted for in the energy sector. As heat pumps are far more efficient than fossil fuel boilers, this transition reduces the overall emissions. However, the figures for 2023 cannot be determined as the corresponding data is not available yet.

## Greenhouse gas reduction and climate change mitigation scenarios

Relevant climate change impacts for buildings are changes in maximum, minimum and monthly ambient temperature, which reduces space heating demand in winter but increases space cooling demand in summer. All available mitigation scenarios take into account: The projected number of buildings (considering increases due to population growth), the projected thermal state of buildings (new, renovated, divided by building type and age), the thermal renovation rate and thermal quality (the space heating demand after renovation), the proposed share of renewable energy carriers for new and exchanged old heating, ventilation and air-conditioning (HVAC) systems, and the HVAC exchange rate. Using these values, the scenarios calculate a combination of enhanced energy efficiency and a transition to renewable energy sources. Regarding future population development, quantitative international migration scenarios that take into account different climate change scenarios (RCPs) are not available at the moment. Therefore, the predictions of Statistik Austria (2024c), which are based on the current situation, are used for Austria. A more detailed discussion can be found in Section 6.8.2.

While the scenarios outlined in the literature vary in scope, they share a high degree of similarity in their assumptions and outcomes. Some studies focus exclusively on technical aspects and address annual energy balances for buildings without considering seasonal storage or broader geographic areas (Pfeifer et al., 2016; Dobler et al., 2018). Others adopt a more comprehensive approach, encompassing all sectors (Ebenbichler et al., 2018; Umweltbundesamt, 2019; Kranzl et al., 2020; Steininger et al., 2021). Additionally, some studies incorporate pricing mechanisms and macroeconomic factors, extending their analyses to cover Austria in its entirety as well as the dynamics of European energy markets. Brandes et al. (2021) and Luderer et al. (2021) perform scenario calculations for Germany with hourly resolution, incorporating energy storage solutions into their analyses. Ebenbichler et al. (2024) developed a Tyrol-focused scenario on an hourly basis, incorporating short- and long-term storage solutions while considering 2050 projections for Austria, Germany, Italy, France, and the broader European context (see also Chapter Box 3.2 for more information on energy storage in buildings). The official Austrian scenarios WEM (With Existing Measures), WAM (With Advanced Measures) and Transition (reaching nearly fossil free energy system by 2040), are presented in a report by the Environment Agency Austria (Umweltbundesamt, 2023a). In the WAM scenario, fossil fuels are not used directly for space heating or cooling; however, fossil fuels are still included in electricity production. At the time of writing, the input data for the NetZero2040 scenarios (such as renovation rate, thermal quality, exchange rate to renewables) have not yet been published (NetZero2040, 2024).

Projections for Austrian settlements in the scenarios show population growth and a similar renovation rate as today, but with deeper renovations resulting in lower energy demand per square meter of renovated space. Overall, the final energy demand for heating is expected to decrease by 10 to 50 % by 2040/2050, despite population growth and increasing heated area, due to an assumed constant capita per floor area. This reduction is largely driven by thermal renovation and partly driven by climate change. The demand for cooling energy is anticipated to rise significantly, depending on the climate scenario, but remains low in absolute terms (see Figure 3.7 and Figure 4.12). Building design must account for rising temperatures to minimize cooling demand (Frischknecht et al., 2020). HVAC systems will shift from fossil fuels to renewable sources, primarily heat pumps, but also district heating (fossil-free), biomass and, to a lesser extent, direct electric heating. In all back-casting scenarios, building operations can be achieved without fossil fuels. However, achieving this sooner requires a higher renovation rate and faster replacement of HVAC systems. Yet, all forecasting scenarios still include some fossil fuel use by 2050, while all of the backcasting scenarios, by definition, phase out fossil fuels.

Biomass use for heating is constrained by its sustainable potential, primarily sourced from residues in the saw, paper, and pulp industries, with some contributions from wood. The biomass must be allocated across different applications, including combined heat and power (CHP) plants, direct heat use in district heating systems, and decentralized biomass stoves. Additionally, wood is used as a building material, acting as a temporary $CO_2$ sink. However, the growing demand for biomass in the industry, particularly as a raw material for chemical products, limits its availability for energy use. As a result, the share of biomass in the overall energy system will remain small compared to electricity generated from renewable sources. Some biomass may also come from sawmill waste or imported biomass (see Sections 2.1.1, 2.3.2).

Required adaptation measures for buildings will be the renovation to much lower space heating energy demand values than current building codes require. Additionally, the adaptation to higher ambient temperatures decreases the winter space heating demand (at times when energy costs are high due to reduced renewable energy production) and increases the need for space cooling energy (at times when sufficient renewable energy from PV and hydropower is available) (see Sections 4.5.2, 4.5.3). As a result, further tightening building code requirements remains a topic of debate.

Figure 3.7 shows that across all climate scenarios analyzed (from +1.3°C for RCP 2.6 in 2050 to +4.3°C for RCP 8.5 in 2080 – i.e., the projected future local mean temperature increases, in this case in Innsbruck, compared to today's mean), the reduction in heating demand exceeds the increase in cooling demand for single-family houses (OIB, 2019, 2023; Streicher et al., 2024b). Cooling demand only becomes evident when temperatures rise more than 2°C. Similar findings are, e.g., reported by Schöniger et al. (2023), Suna et al. (2024), and Sonnleithner et al. (2023). Ziemele et

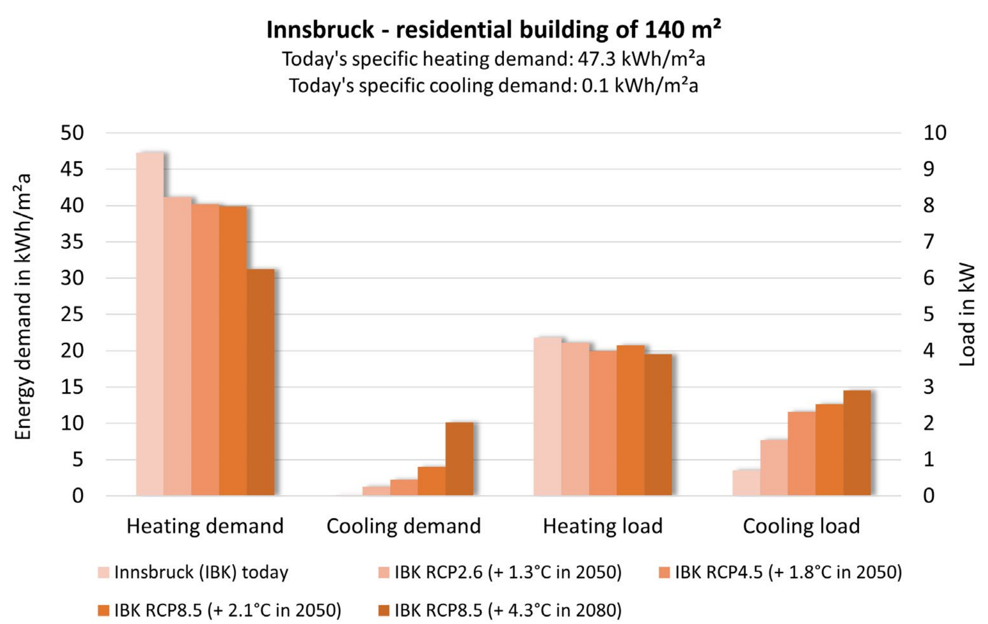



**Figure 3.7** Space heating and cooling energy demand (left y-axis) and corresponding heating and cooling loads (right y-axis) for a single-family house in Innsbruck, comparing current conditions (based on 2000–2019 weather data, with radiation data from 1996–2015) with future projections for 2050 (under three distinct climate scenarios) and 2080 (under one scenario) in Innsbruck (Streicher et al., 2024b).

al. (2023) found comparable results for Riga, while Wilbanks et al. (2008) reviewed studies in the U.S., and Elnagar et al. (2023) performed an analysis for cases in Belgium, factoring in renovation rates.

In summary, the literature consistently shows a decrease in winter heating demand during periods of limited renewable energy production, coupled with an increase in summer cooling demand during periods of high renewable energy availability. Therefore, climate change does not pose an increased risk to the energy system in terms of heating and cooling demand. However, the design of flexible HVAC systems that can provide both heating and cooling – such as heat pumps integrated into ceiling- or air-based systems – is a cost-effective adaptation strategy to address climate variability (*high confidence*).

## Improve, Shift and Avoid measures in the building sector

The thermal renovation rates and renovation depth, i.e., space heating demand after renovation (improve) and replacement of heating system rates (shift), are estimated to be between 1.3 and 3 % per year for renovation and 3 and 5 % per year for replacement of HVAC equipment in all scenarios mentioned in the previous section. The lower end of this range reflects historical trends, where most renovations or replacements occur only when components fail, reach the end of their lifecycle, or change ownership. The classification of improve and avoid is done according to the Cross-Chapter Box 4.

Based on these assumptions, the costs for high level renovation or replacement are calculated as the difference between the standard renovation/replacement costs and those for achieving high energy efficiency and renewable energy standards (i.e., additional costs). Using the historic renovation/replacement rate, a reduction of the final energy demand of buildings (including household electricity, domestic hot water, space heating and cooling) is calculated to be approximately 14 % (WEM/WAM) to 30 % (Ebenbichler et al., 2018) by 2050, for different renovation depth assumptions, i.e., the space heating energy consumption assumed in the renovation scenarios after the thermal renovation of a building is varied between current maximum allowable space heating demand values of OIB 6 (thematic guideline number 6 by the 'Österreichisches Institut für Bautechnik') (OIB, 2019) down to half of these values.

In all backcasting scenarios (Tyrol 2050, Transition Scenario, Ebenbichler et al., 2018) 100 % renewable energy supply is achieved. However, in some forward scenarios (WEM/WAM), the electricity demand for buildings is not fully decarbonized (see the previous Section). In some scenarios, the renovation/replacement rate is increased to achieve reduced energy consumption sooner, e.g., by 2040. In such cases, still functioning building components with residual value must be replaced, which increases the costs. With a thermal renovation rate of 3 % and a high renovation depth, the total final energy demand of buildings could be reduced by about 26 % by 2050 (Steininger et al., 2024) (*high confidence*).

Additionally, the production of essential renovation materials (insulation, windows, shading) and renewable-based HVAC systems (in all cited scenarios primarily heat pumps, but also district heating and biomass) will need to slightly increase. This has to be accompanied by the training and education of a larger workforce, including planners, plumbers, and craftsmen. Streicher et al. (2024a) estimate that the Tyrol 2050 scenario (Ebenbichler et al., 2018) would require an additional 580 and 660 installers and 44 and 36 planners for heat pumps and photovoltaic systems, respectively. These numbers can be multiplied by a factor of 12 to approximate the total Austrian demand (in relation to the population of Tyrol). Furthermore, legislation banning new oil and gas boilers has already been enacted (BGBl. I Nr. 6/2020; BGBl. I Nr. 8/2024). At present, a substantial subsidy for phasing out oil and gas is stimulating market growth (KPC, 2022; BMK, 2024c), and as economies of scale take effect and more products become available, both investment and installation costs are expected to decrease.

Steininger et al. (2024) recommend a combination of push and pull measures to drive policy action (for legislation, see Section 3.3.3). These include stricter building codes, prohibitions on new fossil-based HVAC systems, and incentives to accelerate the transition to fossil-free HVAC solutions. Subsidies should target technologies that are not yet widely available or lack sufficient expertise in production, planning, and installation. Current building codes (OIB, 2019) optimize investment and operating costs, resulting in designs close to passive house standards. However, buildings with higher energy demand (and cost) are allowed if the efficiency of the HVAC system is 30 % higher than a reference system or a rooftop PV is integrated (dual way), even if the efficiency of the building itself is not directly linked to the HVAC system or the renewable energy produced by the building. The WEM and WAM scenarios, as well as the Tyrol 2050 scenario (Ebenbichler et al., 2018), slightly reduce the allowable OIB 6 useful energy demand for space heating; Ebenbichler et al. (2018) even halve the current OIB 6 values. Listed buildings are not included in OIB 6 as they represent a small proportion of the total building stock. Subsidies for these measures should be phased out once market demand is met or prices fall to sustainable levels. Public acceptance can be improved ensuring sufficient skilled labor and affordable costs to normalize these technologies (similar to the adoption of triple-pane windows in Austria, Germany and Switzerland) (*robust evidence, medium agreement*).

The current standards for snow loads (Austrian Standards, 2022; last adaptation in 2022, ÖNORM B1991-1-3:2022-05) or the publicly available data on flood zones, landslides, etc. in a report from the Austrian Government (BML, 2023) show that the requirements are continuously adapted and used to improve related building standards. Existing buildings may need to be adapted to the changing requirements (*medium evidence, high agreement*).

Avoid (sufficiency) measures in the building sector include, e.g., reducing the square meters of living space per person, reducing heating/increasing cooling set-temperatures, and reducing the number of technical appliances (Zimmermann, 2018). The current average net-living-area in Austria is about 47 $m^2$/person. This has increased from about 32 $m^2$/person in the year 1990 (Statistik Austria, 2004, 2022c). The room temperature for the calculation of energy certificates has even been increased from 20 to 22°C in recent years to better reflect reality (e.g., Austrian Standards, 2019). One avoiding strategy is the taxation of long-term vacant apartments, a measure currently implemented in the federal provinces of Tyrol, Styria, and Salzburg, and planned for adoption throughout Austria (Koller et al., 2023; Parlamentsdirektion, 2024b) (*robust evidence, medium agreement*).

## Chapter Box 3.2. Energy storage in buildings – technologies and needs

**Introduction:** The growing reliance on variable renewable energy sources has heightened the need for energy storage and demand adjustments. Buildings, due to their size and thermal inertia, represent significant opportunities for flexibility. This chapter box explores (1) current energy storage technologies and demand response in buildings, (2) load-shifting and storage potential in Austria's building stock, and (3) barriers, drivers, and policy requirements. Related e-mobility considerations are addressed in Chapter Box 3.3.

**State-of-the-art energy storage and demand response in buildings:** Thermal energy storage, the most common method in buildings, is used for domestic hot water and space heating. Storage types include (Borri et al., 2021):

- Sensible heat storage: Uses water tanks or the thermal mass of buildings (e.g., concrete floors). Effective for day-to-night storage up to a maximum of 2-3 days, it is widely used for its simplicity and cost-effectiveness, allowing for short term demand shifting in systems with heat pumps or electric boilers (Miara et al., 2014; Bechtel et al., 2020; Fitzpatrick et al., 2020). However, it involves increased heating demands due to thermal losses in water storage systems or slight overheating in winter (and undercooling in summer) within buildings (Pasqui et al., 2023). Despite this, local renewables and off-peak electricity can offset costs and GHG emissions (Mascherbauer et al., 2022b; Schöniger et al., 2024).
- Latent heat storage: Relies on phase-change materials (PCMs) to maintain specific temperatures but faces challenges in efficiency and implementation. Streicher et al. (2008) could find no advantages of phase change materials as energy storage in buildings compared to water or thermal masses.
- Chemical and sorption-based storage: Offers high-capacity, long-term storage with minimal losses, but remains costly and complex (Ding and Riffat, 2013; Bao and Ma, 2022). As a result, this type is virtually absent from the market.

Battery systems, increasingly paired with photovoltaic (PV) installations, align energy generation with household demand. However, their high costs and limited seasonal storage capacity primarily confine their usage to short-term applications, such as daily or weekly energy balancing (Ochs et al., 2021; Li et al., 2023). Advanced hydrogen systems with fuel cells, while flexible, are even less cost-effective.

**Flexibility and energy storage in Austrian buildings:** Buildings equipped with heat pumps and thermal storage systems can stabilize electricity and district heating grids on a daily basis (Schöniger and Morawetz, 2022; Suna et al., 2022). Studies such as by Heidenthaler et al. (2023) and Wolisz et al. (2016) highlight thermal activation and preheating/ cooling as key mechanisms for demand shifting, even over several days. Research by Tosatto et al. (2023) and Magni and Ochs (2021) projects significant load-shifting potential in Austrian regions, while Turner et al. (2015) confirms precooling benefits in lightweight structures. Overall, thermal mass insulated from indoor air proves critical for demand flexibility (Reynders et al., 2013; Masy et al., 2015; Le Dréau and Heiselberg, 2016; Luo et al., 2020).

Nationally, dynamic pricing shows potential to optimize electrified heating systems, but incentives remain insufficient for consumers (Mascherbauer et al., 2022a; Schöniger et al., 2024). Thermal inertia studies estimate 50 % of peak heating loads can be shifted to off-peak periods in post-1980 buildings (Weiß et al., 2019). By 2040, demand-response-optimized heat pump operation could achieve cost reductions of 50-75 % (Amann et al., 2023b).

**Barriers, drivers and policy needs:** Variable electricity tariffs, such as real-time pricing, could incentivize demand-side flexibility (Fitzpatrick et al., 2020). Studies suggest regulations are needed to balance retailer profits and consumer welfare (Guo and Weeks, 2022). While savings from smart systems currently only marginally outweigh their costs, future high renewable energy integration could increase their value.

For flexibility adoption to grow, policies must standardize and subsidize smart systems. By 2050, widespread heat pump use and supportive policies could significantly impact electricity grids and renewable energy integration. Challenges and opportunities in decarbonizing energy are further discussed in Sections 4.5.2 and 4.5.3.

### 3.3.2. Construction products

Population growth, increasing per capita net floor area, sustainability concerns and changing lifestyles are contributing to a significant increase in both new construction and building renovations (IPCC, 2021b). As a result, the production of construction products used for new buildings and renovations represents 11 % of total global energy- and process-related GHG emissions, with steel and cement production contributing more than half of these emissions (Röck et al., 2020). Consequently, there is growing interest in utilizing materials with low embodied environmental impacts. In addition, the reuse and recycling of materials is becoming increasingly important to reduce the demand for new resources. In Austria, 2.4 million buildings – both residential and non-residential (see Table 3.1) – are responsible for a significant portion of GHG emissions. While most of these emissions come from the operational phase of buildings, an increasing share is associated with the production of construction materials, which is typically attributed to the industrial sector or associated with electricity use and therefore falls under the emissions of the energy sector. In order to meet its climate goals, Austria aims to significantly reduce these building emissions by 2040 (see Section 3.3.1), which can only be achieved if both operational and embodied emissions reduced simultaneously.

More than half of the emissions of new buildings can be related to the embodied emissions of materials when considering the entire lifecycle (IEA, 2019; Frischknecht et al., 2020; Röck et al., 2020). In a study by Truger et al. (2022) for Austria, total GHG emissions associated with the building stock increase by a factor of 3 to 4 when the system boundaries are extended to include the entire lifecycle of buildings (including the embodied emissions of buildings), ranging from 7 $MtCO_2eq$/year (Table 3.3) of direct operational emissions (i.e., 10 % of national emissions) to 22-31 $MtCO_2eq$/year for Austria. In this sense, the most promising decarbonization measures for materials listed in the decarbonization roadmap currently developed by the EU (Le Den et al., 2023) are related to the embodied impacts of the products and materials used in buildings. They can be grouped into the Avoid-Shift-Improve (ASI) framework as follows (see also Cross-Chapter Box 4):

- **Avoid:** Focus on minimizing resource use by repurposing existing products and optimizing material efficiency. Examples include reusing building components, integrating void formers into concrete slabs, and optimizing structural designs to reduce material demand.
- **Shift:** Transition to alternative materials that are circular, low-carbon, or bio-based, thereby reducing environmental impact and supporting sustainable practices.

- **Improve:** Enhance the efficiency and sustainability of current production methods. This involves increasing the share of renewable energy used in manufacturing processes and integrating technologies like carbon capture to reduce emissions.

The recently released UN report 'Building Materials and the Climate: Constructing a New Future' (United Nations Environment Programme and Yale Center for Ecosystems + Architecture, 2023) provides a comprehensive overview of measures to decarbonize construction materials. These efforts are further bolstered by evolving EU legislation, particularly within the framework of the EU Green Deal, which aims to reduce GHG emissions across member states (COM/2019/640 final). Key directives under this framework include initiatives promoting circular economy procurement and the ongoing revision of the Construction Product Regulation (CPR) (European Commission, 2020a). These focus on enhancing environmental sustainability and establishing robust markets for the reuse and recycling of construction materials. In addition to the regulations on the European level, i.e., the Energy Performance of Buildings Directive (Directive (EU) 2023/1791) and the CPR, Austria is preparing its own directives (OIB, 2023), which align with and build on EU measures, as detailed in Section 3.3.3. In addition, more emphasis needs to be placed on equipping building stakeholders with the knowledge and skills needed to effectively implement these decarbonization measures.

Scenarios for the decarbonization of building products that align with the Austrian context include:

- Minimizing the use of new building products by leveraging existing structures. Refurbishing the existing building stock not only reduces the need for new materials but is also essential to reducing carbon emissions from older buildings. This approach is highlighted in the updated Energy Performance of Buildings Directive (EPBD, European Commission, 2024b).
- Utilizing construction products with low embodied emissions (Frischknecht et al., 2019; Röck et al., 2020).
- Improving embodied emissions in material production. Advances in production processes and improved energy mixes can lower emissions (Potrč Obrecht et al., 2021). Alaux et al. (2024) demonstrated how future material production trends may influence the sector's overall carbon footprint.
- Adopting circular economy principles, which can significantly reduce embodied emissions (Ghisellini et al., 2018; Malabi Eberhardt et al., 2020; Mirzaie et al., 2020) – see also Cross-Chapter Box 5. However, data on the potential reuse of materials from existing stocks is sparse. In Vienna, researchers are investigating the local potential (Lederer et al., 2020; Lederer and Blasenbauer, 2024), while the project 'Kraisbau', funded by the Austrian Research Promotion Agency (FFG), aims to provide further estimates (Kraisbau, 2022). In this context, more emphasis should be placed on building design to tailor new buildings for circular (re)use (Kanters, 2020; Akhimien et al., 2021).
- Reducing material use through efficient construction techniques: For example, comparing prefabricated wood-frame houses with traditional solid construction methods, such as those using resource-intensive materials like reinforced concrete or masonry, and incorporating void formers to reduce the volume of concrete or other materials required, demonstrates how resource efficiency and reduced embodied carbon can be achieved in construction (Mañes-Navarrete et al., 2024).
- Incorporating carbon storage in materials: The EU's provisional agreement on a certification framework for carbon removal promotes the temporary storage of carbon in durable materials, such as wood-based construction products, that are intended to remain in the building for at least 35 years. However, when a comprehensive, system-wide boundary is applied to the analysis, it becomes clear that the promotion of wood-use in buildings is only advantageous over reduced harvesting under certain conditions (*high confidence*). Maierhofer et al. (2024) for Austria find that key criteria such as a high carbon intensity of the energy system and the efficient and sustainable use of wood building materials are critical for realizing these benefits. Similar conclusions are reached by Fehrenbach et al. (2022) and Soimakallio et al. (2022), which are in line with assessments using discounting principles (Peng et al., 2023) (see also Section 2.3.2).

Alaux et al. (2024) quantified the potential reductions in GHG emissions for various materials, taking into account decarbonization strategies such as better energy mixes, circular practices, and production advances. While a 10 % reduction seems possible for most materials, wood could even reach 35 % by 2050, but only if the extended scope is not considered, as shown by Maierhofer et al. (2024). Achieving climate goals will ultimately require decarbonizing the entire construction lifecycle, including materials (European Commission, 2020b; Toth et al., 2022) (*robust evidence, medium agreement*).

### 3.3.3. Legal reforms – barriers and perspectives

Austria is known for its high building standards, which excel in thermal quality, durability, ecological considerations, affordability, and social aspects of housing. There is a strong political commitment to meet international GHG reduction targets, aiming for net zero emissions by 2040 – ten years ahead of the 2050 global benchmark. This ambition is reflected at the federal level in the government program of the ÖVP-Green coalition (2020–2025) (BKA, 2020) and in several federal provinces, such as Vienna. Despite this commitment, experts are skeptical about the feasibility of achieving these goals with the measures currently in place (Habert et al., 2020; Steininger et al., 2024) (*medium confidence*).

#### Impact of EU legislation

Austria, a member of the EU since 1995, implements EU legislation in areas of EU competence, such as energy policy. Although housing is not directly under EU competence, related regulations have a significant impact on the sector, particularly with regard to climate targets. Key EU legislation includes the Energy Performance of Buildings Directive (first introduced in 2002, last revised in 2024) (European Commission, 2024b), as well as supporting measures such as the Energy Efficiency Directive (Directive (EU) 2023/1791), the revised Renewable Energy Directive (Directive (EU) 2023/2413), and the Alternative Fuels Infrastructure Regulation (European Commission, 2024a). The following key EU legislative frameworks are shaping Austria's energy and buildings policy:

- The European Climate Law 2021 (Regulation (EU) 2021/1119) mandates climate neutrality by 2050, a 55 % reduction in GHG emissions by 2030 compared to 1990 levels ('Fit for 55'), and outlines implementation mechanisms. Several of the twelve proposed measures target the construction, housing, and real estate sectors.
- The Energy Performance of Buildings Directive (EPBD) (draft revision, 2021): As part of the Fit for 55 package, this directive proposes a mandatory zero-emission standard for all new buildings starting in 2030 (COM/2021/802 final). It also aims to tackle inefficiency in existing buildings by progressively phasing out the 15 % of properties with the highest energy consumption through rental and sale bans. To boost renovation rates, the directive includes financial support measures to cushion the impact on low-income households, facilitating compliance while ensuring social equity.
- Inclusion of buildings in the EU Emissions Trading System as of 2026: This expansion, combined with the already existing $CO_2$ pricing mechanism, will increase the cost of heating with fossil fuels like oil and gas.
- The tightening of the Renewable Energy Directive (Directive (EU) 2018/2001) puts further pressure on national legislation to phase out oil and gas, not only with subsidies but also using regulatory measures.
- The Energy Efficiency Directive (Directive (EU) 2018/2002) sets a renovation target of 3 % for public buildings.
- The Effort-Sharing Regulation (Regulation (EU) 2018/842) tightens emission reduction targets, imposing stricter national obligations.
- The new Environmental, Social, and Governance (ESG) criteria (COM/2023/314 final) and the EU Taxonomy Regulation (Regulation (EU) 2020/852) are likely to be a game-changer for commercial real estate, as they will make it much more difficult to finance properties with poor thermal efficiency, leading to a reduction in the value of such buildings.

In response to the energy market disruptions caused by Russia's invasion of Ukraine, the European Commission introduced the REPowerEU Plan (European Commission, 2022b). This strategy focuses on diversifying energy sources, accelerating clean energy adoption, and promoting energy savings. Integrated into the EU Recovery and Resilience Facility (RRF), the plan enforces even stricter regulations under the already demanding frameworks. These developments underscore the increasing regulatory pressure on Austria's housing and energy sectors, with significant implications for achieving climate resilience (*high confidence*).

#### Existing legal regulations and measures

Austria has long pursued legal reforms in its building sector to advance climate protection, heavily influenced by EU legislation. Among the key elements of the regulatory framework is the Condominium Act ('Wohnungseigentumsgesetz') (BGBl. I Nr. 70/2002), which introduced reforms such as revised quorum rules to facilitate decision-making within condominium owners' associations. These changes make it easier to implement building decarbonization measures. In addition, mandatory minimum contributions to reserve funds ensure that more financial resources are available, allowing investments to be made without relying solely on external financing.

The Limited-Profit Housing Act ('Wohnungsgemeinnützigkeitsgesetz') (BGBl. Nr. 139/1979), provides the most supportive framework for decarbonization. Limited-Profit Housing Associations (LPHAs, 'Gemeinnützige Bauvereinigungen') benefit from strong financing mechanisms such as the 'maintenance and improvement contribution', which can be as high as $EUR_{2023}$ 2.33 per square meter per month. LPHAs can also use energy savings contracting and enforce rent increases after retrofits, making them particularly effective for large-scale energy efficiency projects.

On the other hand, the Tenancy Act ('Mietrechtsgesetz') (BGBl. Nr. 520/1981), has proved resistant to reform due to enduring ideological divisions among political parties. This is particularly problematic in the segment of older rent-protected buildings built before 1945, where energy efficiency has no impact on allowable rents. As a result, it remains difficult to recover retrofit costs through rent adjustments.

Construction law, administered by Austria's federal provinces, has significantly improved energy performance standards primarily in response to EU directives such as the EPBD (European Commission, 2024b). In order to harmonize regional building laws, the OIB has issued thematic guidelines, including guidelines on energy saving and thermal insulation ('Richtlinie 6', OIB, 2019). A new thematic guideline ('Richtlinie 7') on the sustainable use of natural resources is about to be adopted and implemented (OIB, 2023). Other relevant regulations include the Building Energy Performance Certificate Act ('Energieausweis-Vorlage-Gesetz') (BGBl. I Nr. 27/2012) and the Heating and Cooling Costs Billing Act ('Heiz- und Kältekostenabrechnungsgesetz') (BGBl. Nr. 827/1992).

In terms of financial incentives, both the federal and provincial governments offer extensive subsidies for building renovation and heating system replacement. The federal provinces provide around $EUR_{2023}$ 500 million anually (Amann, 2019; Amann et al., 2023a). Federal initiatives include the Refurbishment Initiative ('Sanierungsoffensive'), the Out of Oil and Gas Bonus ('Raus aus Öl und Gas Bonus'), and Clean Heating for All Initiative ('Sauber Heizen für Alle'), which can cover up to 100 % of the costs of replacing heating systems for households at risk of poverty. Subsidies totaling $EUR_{2023}$ 2.66 billion will be available between 2024 and 2027 (Amann et al., 2023a). In early 2024, the federal government has announced additional support from the Housing Package ('Wohnbaupaket') (Parlamentsdirektion, 2024a).

Provincial housing subsidies are based on regional laws and decrees, and federal subsidies are administered under the Law on Domestic Environmental Subsidies ('Umweltförderungsgesetz') (BGBl. I Nr. 152/2023). Recent tax incentives, although less prominent, include measures to benefit homeowners through income tax reductions and businesses through corporate tax adjustments (*medium evidence, high agreement*).

## Pending legal reforms

One of the most significant policy instruments in the Austrian political system is the Fiscal Equalization Act, which regulates the distribution of funds between the federal state, provinces, and municipalities, usually for a five-year period (see also Section 6.4.1). The latest agreement, reached at the end of 2023, introduced several changes. While housing subsidies have always played an important role in previous financial equalization agreements, almost all authorities have now been transferred to the federal provinces. As a result, the current financial equalization scheme contains few regulations on housing. Notably, a 'future fund' has been established, allocating approximately $EUR_{2023}$ 300 million per year for housing-related measures. These funds are available if certain renovation and land consumption targets are met, with an equivalent amount earmarked for increasing the share of renewable energy.

The Renewable Heat Act (BGBl. I Nr. 8/2024) prohibits the installation of oil and gas boilers in new buildings. However, it does not (yet) regulate the replacement of existing fossil fuel boilers. In addition to the Renewable Heat Act, housing law reforms are essential. A particular challenge is the Tenancy Act (or MRG, as introduced above), which has so far been largely resistant to reform. Essential reforms include the mandatory cooperation of tenants in the decarbonization of heating systems and the establishment of a fair distribution of the associated costs between landlords and tenants. The Condominium Act (WEG) also needs further reform to be aligned with decarbonization goals.

Land acquisition regulations ('Grundverkehrsrecht') could be used to reduce building-land hoarding (see Section 3.2). Housing subsidies, both for new construction and renovation, could be more explicitly linked to climate protection goals. The federal provinces have the primary responsibility for ensuring that no one is left behind on the path to climate neutrality. To stimulate climate-friendly investments in an economically sustainable way, policymakers could implement tiered incentive structures that prioritize long-term energy efficiency and carbon neutrality, as those outlined in the 'COVID-19 investment premium', while ensuring broad accessibility and minimizing deadweight effects (Weyerstraß, 2021).

### Preconditions for achieving building decarbonization by 2040

In addition to a massive reduction in the energy demand of the buildings and a switch to renewable energy sources (see Section 3.3.1), district heating systems need to be decarbonized. Simulations show that if the renovation rate is increased from the current 1.5 to 2.8 % by 2030, the entire thermally inefficient building stock could be completely renovated by 2040 (Amann et al., 2021). At the same time, nearly 700,000 oil-heated apartments will need to be converted by 2035, followed by more than one million gas-heated apartments by 2040 (in terms of registered main residences). Success in this area will depend on a significant increase in the number of buildings heated by district heating, biomass, or heat pumps (Amann, 2023; Streicher et al., 2024a).

While decarbonizing the building sector by 2040 is technically feasible, it depends on creating the right framework conditions. Key challenges include a shortage of skilled workers and the need for increased innovation. In addition, Austria's federal system, characterized by strong provincial autonomy and inadequate cooperation mechanisms, poses a significant obstacle. The current financial equalization framework is insufficient to address the scale of necessary reforms at both the federal and provincial levels. Therefore, new models of cooperation and coordination will be essential (Amann, 2023) (see also Section 6.4.1).

## 3.4. Transport and infrastructure

This section explores the role of transport and infrastructure in reducing emissions and adapting to climate change. Section 3.4.1 introduces the transport sector's emission trends and provides an overview of this subchapter. Section 3.4.2 focuses on decarbonization in the passenger transport sector, while Section 3.4.3 focuses on decarbonization in the freight transport sector. Section 3.4.4 discusses the GHG emissions embodied in road and rail infrastructure, as well as climate risks for transport infrastructure and related adaptation needs. Chapter Box 3.3 discusses the flexibility potential of electro-mobility in Austria.

### 3.4.1. Introduction

The transport sector is Austria's second largest emitter of GHGs after industry. In 2023, direct GHG emissions associated with the movement of people and goods within Austria, together with fuel sold domestically, totaled 19.8 million $tCO_2eq$, excluding international air traffic (Umweltbundesamt, 2024c). This corresponds to 29 % of Austria's total GHG emissions in 2023 (Umweltbundesamt, 2024c). Notably, transport remains the only sector where GHG emissions have not decreased since the base year 1990 (see Figure 3.8). After a continuous increase in emissions from 2012 onwards, significant reductions were observed only during and after the COVID-19 pandemic, as shown in Figure 3.8. These reductions were primarily driven by external factors: In 2020, GHG emissions fell by 13.5 % in a single year due to the pandemic and related lockdown restrictions that reduced transportation activity (Umweltbundesamt, 2024c). The low emission levels in 2022, similar to those in 2020, were largely influenced by Russia's invasion of Ukraine and the resulting European energy crisis, which drove up energy costs. The further decrease in emissions in 2023 was mainly attributed to lower economic output, which also reduced fuel exports from Austria (Heinfellner et al., 2024b).

In 2022 (the latest year available for Europe-wide comparison), renewable energy sources accounted for 10 % of energy consumption in the Austrian transport sector (European Commission: Eurostat, 2024). While this was slightly above the EU average, it remained significantly below the EU's 2030 target of 29 % (*medium evidence, high agreement*).

In 2023, roughly 34 % of total transport GHG emissions were generated by roadside freight transport, 65 % by roadside passenger transport and the remaining share by rail, shipping and domestic aviation. This highlights that transport emissions are overwhelmingly dominated by road transport. Within this category, diesel-powered passenger cars accounted for the largest share (42 %), followed by heavy-duty vehicles (26 %) and gasoline-powered passenger cars (23 %) (Heinfellner et al., 2024b).

International aviation is excluded from national emission inventories due to the lack of reporting requirements. While national domestic traffic accounted for only 0.2 % of total transport sector GHG emissions in 2023, the inclusion of international flights (originating or landing in Austria) would significantly increase this figure (Heinfellner et al., 2024b). Aviation emissions peaked in 2019 and, despite the dip during COVID-19, showed a strong upward trend af-

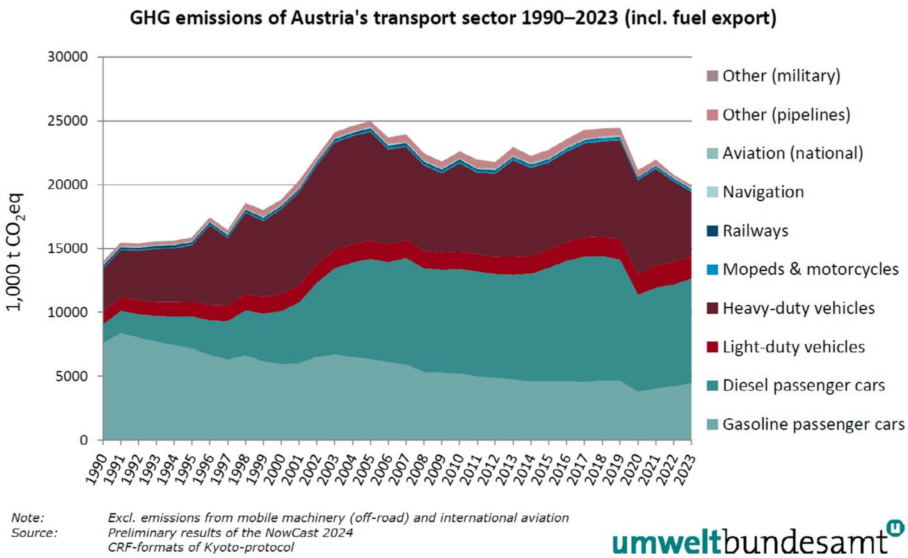



**Figure 3.8** Greenhouse gas emissions from Austria's transport sector from 1990 to 2023 (Heinfellner et al., 2024b).

ter the pandemic. By 2023, aviation emissions had already exceeded the level of 2018 (VCÖ, 2024a). Aviation affects global warming not only through GHG emissions, but also through nitrogen oxide ($NO_x$) emissions and the release of pollutants into sensitive atmospheric layers, leading to cloud formation effects. These combined factors amplify the aviation's impact on global warming, making its effect substantially greater than those of the GHG emissions alone (Lee et al., 2021) (*medium confidence*).

The intensity of direct emissions from different modes of transport is illustrated in Figure 3.9, which shows the GHG emissions per passenger kilometer for the main modes of transport using the latest available data from June 2024. There is a striking disparity between rail and road transport. This is largely due to the fact that 81 % of passenger trains run on a catenary system powered entirely by renewable electricity sources, with 95 % of the energy coming from hydropower and the remaining 5 % from other renewables (ÖBB-Holding AG, 2022). For aviation, Figure 3.9 includes the significant warming effects of GHGs other than $CO_2$ that are released into sensitive layers of the atmosphere (as explained above).

It is important to note that GHG emissions are not limited to the use of vehicles, but are also emitted during the entire lifecycle of an individual vehicle, including construction, disposal and recycling ('cradle-to-grave' emissions). For battery electric vehicles (BEVs), these indirect emissions include in particular those from energy production (De Blas et al., 2020; Owen et al., 2023) (*high confidence*). In Austria's official GHG reporting, such indirect emissions are not allocated to the transport sector, but to the industry or energy sector (if their source is in Austria). However, for most purchased vehicles, the construction phase takes place outside Austria. In addition, the construction, maintenance,

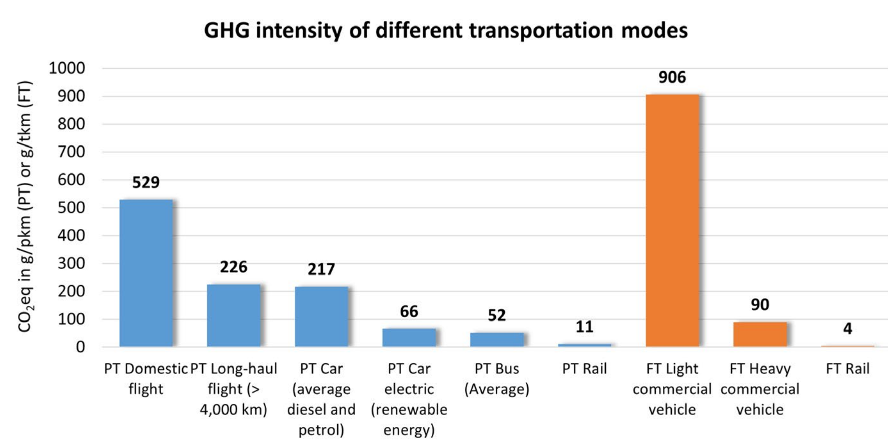



**Figure 3.9** Greenhouse gas intensity of different transportation modes in Austria as of June 2024: Passenger transportation (PT, in $gCO_2$eq per passenger-kilometer) and freight transportation (FT, in $gCO_2$eq per ton-kilometer) (Umweltbundesamt, 2024a).

and disposal of road and rail infrastructure contribute significantly to GHG emissions (see Section 3.4.4). For road infrastructure, emissions vary by road type, usage patterns, and surface material (e.g., asphalt versus concrete), adding an estimated 0.4–6.4 % to transport-related emissions (Gruber and Hofko, 2023). Rail infrastructure emits 60 % more than rail operations in Austria – this relatively large offset is due to the low operational emissions of Austrian rail systems, which are largely powered by renewable energy. From a stock-flow perspective, which assesses material stocks of existing infrastructure and the flows required for maintenance, walking and public transport are the most efficient in providing services in terms of resource use and emissions. Road transport, on the other hand, ranks lowest in this respect (Virág et al., 2022b) (*medium confidence*).

**Risks:** In the transport sector, climate change risks primarily relate to infrastructure disruptions and damage caused by extreme weather events. These lead to significant repair costs and can cause delays and uncertainty for both passenger and freight transport (*medium evidence, high agreement*) (Section 3.4.4).

**Impacts and adaptation mechanisms:** The main expected impacts of climate change on the transport sector are damage to infrastructure caused by extreme weather events. These can be mitigated through adaptation measures, such as protecting rail and road infrastructure from landslides or treefall, and using more heat-resistant surface materials (*medium evidence, high agreement*). Climate change is also expected to directly affect transport mode choices: Higher summer temperatures may reduce the attractiveness of active modes such as walking and cycling, while milder temperatures and lack of snow in winters may increase their attractiveness, leading to ambiguous and likely location-specific effects (*medium confidence*). In addition, destination preferences could shift; for example, lower altitude winter tourism areas in the Alps are likely to become less attractive (Li et al., 2024) (see also Sections 4.3.3, 7.4.2) (*medium evidence, high agreement*).

**Mitigation options:** There are numerous mitigation options for both freight and passenger transport that fit into the Avoid-Shift-Improve (ASI) framework (see also the Cross-Chapter Box 4):

- Avoid: Reduce GHG emissions by decreasing the number of trips.
- Shift: Reduce GHG emissions by shifting to transport modes with lower GHG intensity.
- Improve: Reduce GHG emissions by adopting less GHG-intensive technologies, especially in the (remaining) road-based traffic.

There is a broad consensus that no single policy is sufficient, but that comprehensive policy packages are needed to achieve the necessary reductions in GHG emissions associated with the transport of goods and people, as shown in two recent research projects (QUALITY, aPPRAISE) for the case of Austria (Thaller et al., 2021; Dugan et al., 2022; Hössinger et al., 2023) as well as in the recently published 'Maßnahmenbericht Mobilitätswende' (Heinfellner et al., 2024a) (*high confidence*). In particular, push policies such as pricing mechanisms and speed limits are essential. Similarly, pull policies (e.g., improvements in public transport) and technological advances alone will not be sufficient, especially as the availability of renewable energy remains a limiting factor – likely beyond 2040 (*robust evidence, medium agreement*). Rising electricity costs also pose a substantial risk to transport electrification by slowing the transition process (*medium confidence*).

Specific recommendations for Austria have been outlined in the Austrian 2030 Mobility Master Plan (MMP) (BMK, 2021b), on the basis of which strategies for different sub-areas of mobility have been developed and published. The MMP, the report 'Pathways to Zero Carbon Transport Sector' (Angelini et al., 2022) and the scenarios calculated by the Austrian Environmental Agency (Umweltbundesamt, 2023a) all show that a substantial modal shift away from road transport is necessary to meet Austria's climate goals – continued growth in road-based travel (passenger-kilometers) and freight transport (ton-kilometers)[3] is considered unsustainable (*medium confidence*). Regarding infrastructure, besides limiting the construction of new infrastructure, mitigation options focused on emissions associated with the construction, maintenance and, in some cases, recycling of infrastructure are fairly limited (*medium confidence*). Some progress has been made in developing materials and technologies to reduce the embodied emissions (see also Section 4.2). Incentives to consider GHG reductions in the tendering process can be seen as a low-hanging fruit and key enabler (also for innovation) in this context (*medium evidence, high agreement*).

[3] Ton-kilometers or [tkm], measures the transportation of one ton of goods over one kilometer, a common metric unit in freight logistics.

Most mitigation options in the transport sector have significant co-benefits (see Section 8.3.1), including reduced pollution, improved public health, improved quality and availability of public spaces (as cars take up about 10 times more space than other mobility modes), and mitigation of urban heat islands (UHIs) (Sovacool et al., 2021; Maier et al., 2023) (see also Section 3.2.3 Integrated mitigation and adaptation strategies) (*high confidence*). Reducing reliance on private car ownership could not only substantially reduce material demand, including for electric vehicle batteries (see Haas et al., 2025) (see Section 4.2), but also reduce household mobility expenditures (Schönfelder et al., 2016) (*high confidence*). In addition, higher taxation on vehicle ownership or use (e.g., through road pricing) could generate broader co-benefits by allowing the redistribution of tax revenues for investment in, for example, public transport. Such measures may become essential as electrification reduces public revenues from fuel taxes, which together with associated VAT revenues currently account for about 5 % of Austria's national public tax revenues (BMDV, 2022) (*high confidence*). Finally, Chapter Box 3.3 describes the potential of electric vehicles (EVs) to address the issue of uneven renewable energy distribution and the resulting need to balance residual loads.

Many of the most effective mitigation options, which are typically fiscal and regulatory in nature, face significant implementation challenges. These difficulties stem from the involvement of multiple governance levels (see Section 6.4.1), vested material interests from industries such as automotive (Gössling et al., 2016; Pichler et al., 2021) and construction industries (see Sections 6.2, 6.4), and deeply entrenched societal norms and perceptions regarding private vehicle use and ownership (Mattioli et al., 2020) (see Sections 6.2, 5.3.1, 5.3.2), which in turn reduce public acceptance of stringent policies (*high confidence*).

Transport is a recurring theme throughout this report and is addressed from a number of perspectives. Chapter 4 examines GHG emissions embedded in infrastructure, energy demand from electrification, and emissions associated with the tourism sector. Chapter 5 looks at inequalities in emissions between socio-economic groups (5.2.2), public acceptance of policies (5.6.3), and the influence of lifestyles and norms (5.3), issues that are also related to mobility. Sections 6.2 and 6.4 discuss how the automotive industry hinders the implementation of effective policies, while Section 6.5.1 outlines the Austrian legal framework for transport. Chapter 7 deals with mobility and tourism in the Alpine region. Chapter 8 presents mitigation scenarios involving the transport sector (Section 8.4), its contribution to achieving the Sustainable Development Goals (SDGs) (Section 8.3.2), and the costs and potentials (Section 8.3.1) for decarbonizing the transport sector.

## 3.4.2. Person mobility

### Status quo and trends

**Transport performance:** In 1990, approximately 76.7 billion passenger kilometers were traveled in Austria. By 2019, the last year before the COVID-19 pandemic, this figure had increased by 41 % to about 107.9 billion passenger kilometers (European Environment Agency, 2022), while the Austrian population grew by only about 16 % over the same period (Statistik Austria, 2022a). Mobility surveys conducted in 1983, 1995, and 2013/2014 show that the average daily travel distance of Austrians has steadily increased from 22 to 29 to 34 kilometers, respectively. Remarkably, the average daily travel time has remained almost unchanged at around 70 minutes (European Environment Agency, 2021b). This increase in passenger kilometers per capita, especially by car, correlates with several trends: The emergence of decentralized settlement structures (see Section 3.2.1), the functional segregation of livelihood functions, the expansion of 'social network geographies', and the continuous expansion of transport infrastructure (see Section 3.4.4). In addition, tourism contributes significantly to travel demand in Austria, as described in Sections 4.3 and 7.4.2.

**Modal split:** In 2022, motorized individual transport – including passenger cars and motorized two-wheelers – accounted for approximately 68 % of total domestic passenger transport performance (Heinfellner et al., 2024b). In 2018, the modal split at the trip-level was distributed as follows: 16 % for walking, 7 % for cycling, 61 % for car, and 16 % for public transport (BMK, 2021b). However, when evaluated by distance traveled, only 3 % of the total distance was covered by active modes (walking and cycling), reflecting their shorter average trip lengths, 27 % by public transport, and 70 % by car (European Commission: Directorate-General for Mobility and Transport, 2023). Despite the dominance of car travel, Austria stands out within the EU for its comparatively high use of public transport (Odyssee-Mure, 2022a).

The modal split is strongly influenced by the spatial characteristics of residential areas. For instance, car usage accounts for only 26 % of trips made by residents of Vienna (Wiener Linien, 2023). However, for commuters crossing Vienna's city limits from the surrounding regions on weekdays, the car modal share increases significantly to 77 % (Magistrat Wien, 2023). Despite the fact that many trips cover relatively short distances, car use remains prevalent: 40 % of all car trips are less than 5 km (BMK, 2016, Fig. 4.5–14). During and after the COVID-19 pandemic, the private car emerged as the 'winner' of the crisis, while active mobility gained attention as a promising alternative, especially at the expense of public transport (Hauger et al., 2022). Early data from post-pandemic years suggest that active mobility has maintained a higher modal share compared to pre-pandemic years (Bronnenmayer, 2024). The popularity of e-bikes has surged in recent years, with approximately one in two bicycles sold being an e-bike, resulting in a total stock of approximately 1.1 million e-bikes in Austria (BMK, 2023b). On the other hand, newer mobility forms such as e-scooters and car-sharing or car-pooling currently hold a small modal share (primarily in urban areas). Overall, these modes mainly tend to replace trips that would have been made by cycling, walking or public transport, especially in the absence of measures discouraging private car ownership and use (Mock, 2023). Research from Vienna and Zurich indicates that private ownership of e-bikes or e-scooters is more likely to substitute car trips than shared micromobility options (Laa and Leth, 2020; Bieliński et al., 2021; Shibayama et al., 2021; Reck et al., 2022; Mock, 2023) (*medium confidence*).

**Emissions from car travel:** Motorized individual transport accounts for nearly 65 % of Austria's total transport emissions, making it the primary source of GHGs in the sector. Domestic GHG emissions from passenger cars and motorized two-wheelers increased from 8.9 million $tCO_2eq$ in 1990 to 11.5 million $tCO_2eq$ in 2023. Taking into account price-related fuel exports (fuel purchased in Austria but consumed abroad), these emissions increase further, from 1.0 million $tCO_2eq$ in 1990 to 2.2 million $tCO_2eq$ in 2023 (Heinfellner et al., 2024b). However, the volume of price-related fuel exports dropped significantly in 2022 due to high energy costs in Austria. The growing share of EVs in the Austrian fleet is expected to significantly reduce transport-related emissions in the medium term, driven by EU regulations that aim to phase out combustion engine vehicles by 2035 (with some exceptions) (Regulation (EU) 2023/851). By the end of 2023, purely electric vehicles accounted for 20 % of newly registered passenger cars (Statistik Austria, 2024e) and 3.0 % of the total passenger car fleet in Austria (Statistik Austria, 2023b). It is noteworthy that about 80 % of these electric vehicles are company cars. In an EU-wide comparison, Austria ranked fifth in EV adoption in 2022 (EAFO, 2023).

**Car ownership:** The motorization rate in Austria has increased significantly in recent decades, rising from 391 passenger cars per 1,000 inhabitants in 1990 to 566 per 1,000 inhabitants at the end of 2022 (Statistik Austria, 2023b), a figure close to the EU average (European Commission: Eurostat, 2023). Austria's car fleet is relatively young, with an average age of 8.7 years in 2021, one of the lowest in the EU, despite a gradual increase over time, which is likely to reflect improvements in vehicle durability (ÖAMTC, 2003; ACEA, 2023b). Car ownership patterns vary significantly by settlement type. A substantial proportion of households own more than one car, especially in smaller towns and villages. In municipalities with less than 10,000 inhabitants, 38 % of households owned more than one car in 2019/20, whereas in Vienna this figure was only 7 % in the same period. Notably, car-free households are more common in Vienna, with 47 % of households reporting no car ownership in 2019/20, compared to 41 % a decade earlier. By contrast, only 12 % of households in smaller municipalities reported being car-free (Statistik Austria, 2011, 2022b).

Austria has not yet experienced a significant decline in the acquisitions of driving licenses among young adults, a trend observed in several other countries. In fact, the number of licenses issued to individuals aged 15 to 24 increased slightly from 119,789 in 2019 to 121,667 in 2022 (Statistik Austria, 2023: 'Kfz-Lenkberechtigungen'). This suggests that outside of urban areas – especially Vienna – the 'peak car' phenomenon has arguably not yet been reached in Austria. At the same time, there has been a notable shift in vehicle preferences, with the market share of SUVs increasing dramatically in recent years. The share of SUVs rose from 8.2 % in 2005 to 21.0 % in 2015, and by the first half of 2023, SUVs accounted for 44.5 % of all new car registrations (VCÖ, 2023b). This trend has substantial environmental implications, as SUVs generally have a higher carbon footprint in both production and use than smaller, lighter vehicles.

**Socioeconomic aspects:** On average, households allocate about 12 % of their net income to mobility expenditures, a share that is consistent across income groups but reflects higher absolute spending in wealthier households (Schönfelder et al., 2016; Aschauer et al., 2019). Higher mobility spending is often associated with greater GHG emissions, largely due to the ownership of more and larger vehicles. Air travel consumption is also unevenly distributed, with highly educated, young, and urban individuals in Austria taking a disproportionate share of flights (Falk and Hagsten, 2021) (*medium evidence, high agreement*) (see also Section 5.2.2).

## Chapter Box 3.3. Flexibility potential of electro-mobility in Austria

**Introduction:** The expected demand for electricity from electro-mobility has important implications for the design of the electricity market, which is undergoing a transformative shift due to the expansion of renewable energy sources (see also Section 4.5). This shift transforms the market paradigm from one where flexible generation meets inflexible demand to one where flexible demand meets inflexible generation, requiring multiple flexibility options (Gea-Bermúdez et al., 2021; Plaum et al., 2022) (see also Chapter Box 3.2). Flexibility is critical not only for balancing generation and demand (Gade et al., 2022; Saffari et al., 2023), but also for addressing the uneven distribution of renewable energy and subsequent managing of residual loads (Allard et al., 2020). Greater demand-side flexibility can reduce reliance on fossil-fuel power plants, thereby reducing GHG emissions and minimizing curtailment of renewable energy. This, in turn, can encourage further investment in renewable energy sources (Loschan et al., 2023, 2024). In particular, electric vehicles (EVs) have a high flexibility potential (i.e., the difference between the load and the available capacity during the time span of the vehicle's connection to the power grid), even surpassing heat pumps (Karimi-Arpanahi et al., 2022; Kröger et al., 2023) (*medium confidence*).

**Impact of electro-mobility on electricity demand:** In a scenario where 50 % of passenger cars in Austria are battery-electric vehicles (BEVs) (2.5 million cars) with a specific energy demand of 16.60 kWh/100 km (Desai et al., 2023) and an annual mileage of 13,900 km (VCÖ, 2023a), the total annual charging demand would be 5.8 TWh. Fleet forecasts by Angelini et al. (2022), for light- and heavy-duty vehicles indicate an additional charging demand of 0.6 TWh by 2030. This would increase Austria's annual electricity demand, currently totaling 60.7 TWh (E-control, 2023), by 10 % (*medium evidence, high agreement*).

**Flexibility potential of electro-mobility:** EV demand-side flexibility can be used at the local level for peak shaving (Ioakimidis et al., 2018; Li et al., 2020; Van Kriekinge et al., 2021; Zheng et al., 2021) and valley filling (Zhang et al., 2014a, 2014b; Jian et al., 2017; Ioakimidis et al., 2018), leading to reduced renewable energy curtailment (Haddadian et al., 2015, 2016; Schuller et al., 2015). The chosen charging strategy affects the flexibility potential: For slow charging with lower charging power, vehicles are connected to the charging station for a longer period of time, while fast charging with higher power levels is mainly used when the connection to the charging station is limited to 1–2 hours. The flexibility potential is especially high during night hours (Flammini et al., 2019; Loschan et al., 2023), when the majority of slow charging processes take place (Speth and Plötz, 2024) (*medium evidence, high agreement*). It should, however, be noted that the full flexibility potential offered by EVs is constrained by the requirement to meet transportation needs and by the temporal and spatial availability of the charging infrastructure and the vehicle (Mills and MacGill, 2018).

**Bidirectional technology potential:** In addition to the potential of demand-side flexibility, Vehicle-To-Grid (V2G) technology ('bidirectional charging') allows the vehicle battery to be used to supply electricity to the system, further expanding the range of potential interactions between BEVs and the electricity sector (Misconel et al., 2022). For example, EVs can be used to transport electricity by charging at one location, driving to a destination, and discharging there to act as an electricity supplier, thereby reducing grid use (Khodayar et al., 2012; Verzijlbergh et al., 2014; Nikoobakht et al., 2019). This flexibility can further reduce the need for the expansion of transmission capacity and redispatch measures (Loschan et al., 2023), improve the balance between generation and demand (Bibak and Tekiner-Mogulkoc, 2022), and reduce peak demand (Tan and Wang, 2017). In this way, EVs can provide ancillary services and reserves (Thingvad et al., 2019; Osório et al., 2021; Figgener et al., 2022).

**Barriers, drivers and policy needs:** While the demand-side flexibility of EVs can support the decarbonization of the electricity market, it may simultaneously lead to increased electricity consumption (Tehrani and Wang, 2015; Gilleran et al., 2021). This could be problematic because the integration of non-dispatchable renewables, combined with the electrification of multiple sectors, leads to increased power flows over the transmission grid, resulting in congestion and consequently higher redispatch costs (Loschan et al., 2023). Compared to the demand-side adjustment of load, large-scale implementation of bidirectional charging, though promising, is facing more barriers such as increased battery wear due to frequent charge-discharge cycles and limited availability of V2G-capable vehicles and bi-directional chargers, which remain expensive (Goncearuc et al., 2024).

Overall, the future flexibility potential is highly dependent on the development of preferred charging strategies for the different applications and mobility patterns of EVs, as well as expansion strategies for public charging infrastructure (*medium evidence, high agreement*). Realizing the flexibility potential of e-mobility in the electricity system will require a robust regulatory framework to address challenges while unlocking opportunities for grid stability and sustainability (Gonzalez Venegas et al., 2021; Sadeghian et al., 2022; Loschan et al., 2023).

## Mitigation strategies

The scientific consensus emphasizes that achieving decarbonization of the transport sector requires a comprehensive mix of awareness-raising, regulatory, infrastructure and fiscal measures (*high confidence*). Integrated policy packages that combine *push* measures (banning, limiting, or disincentivizing carbon-intensive travel) with *pull* measures (making sustainable alternatives like public transport and cycling infrastructure more feasible and attractive) are the most effective approach (e.g., Dugan et al., 2022; Koch et al., 2022; Hössinger et al., 2023; Heinfellner et al., 2024a) (for local policies, see Section 3.2.2).

**Avoiding travel:** The COVID-19 pandemic demonstrated the potential of teleworking to reduce commuting and teleconferencing to reduce business travel, particularly air travel. However, due to rebound effects, such as increased local errands on home-office days, existing evidence is inconclusive about the extent to which travel avoidance is feasible (Maier et al., 2022) (*medium confidence*).

Effective spatial and settlement planning (Section 3.2.2) has significant potential in the medium to long term to reduce the frequency and distance of trips, while promoting active transport modes (avoid and shift). Strategies include urban 'city of short distances'/'15-minute city' concepts in urban areas and the revitalization of town and village centers in rural or semi-urban regions. These initiatives often focus on reducing car-centric infrastructure through lanes restrictions, road closures, increased parking charges or decreased parking spaces while ensuring daily destinations (e.g., workplaces, shops, and public services) are accessible by walking, cycling, or public transport (see Jandl et al., 2024) (see Section 6.5.1). Regulatory measures such as speed limits and the elimination of minimum requirements for parking facilities further support these goals (*high confidence*). More broadly, promoting sufficiency through changes in lifestyle (i.e., consumption) and changes in social and cultural norms can enhance acceptance of these measures (see Section 5.6.2).

**Shifting away from private motorized vehicles:** Efforts to shift travel away from private motorized vehicles include reducing the cost and improving the attractiveness of alternative modes (*high confidence*). For public transport, this includes simplified and affordable fares, such as the regional/national versions of the 'Klimaticket' (BMK, 2023c), as well as improved quality (e.g., reliability, frequency, integrated schedules) and expanded spatial and temporal coverage. Demand-responsive transport (DRT) can address mobility gaps in remote areas, consistent with a 'mobility guarantee' approach that minimizes the need for car ownership (Laa et al., 2022). For international travel, advancing high-speed rail, intermodal connections, and addressing capacity constraints (e.g., night trains) are critical, although challenges remain in the medium term (*medium confidence*). Improving biking and walking infrastructure – especially for shorter trips, which make up the majority – remains vital in both urban and rural areas (e.g., ETH Zürich, 2023) (*high confidence*).

**Electric vehicles as key technological improvement option:** Travel demand that cannot be avoided or shifted must rely on low-emission technologies that are energy and cost efficient across their entire lifecycle. For passenger road transport, BEVs best meet these criteria when powered by 100 % renewable electricity (Hoekstra, 2019; Fritz et al., 2021, 2022; BMK, 2022b) (*robust evidence, medium agreement*). Financial incentives (subsidies, tax reductions), regulatory measures (low emission zones, e-taxi mandates, see also Ajanovic et al. (2021) for the case of Vienna), charging infrastructure, and policies that enable the installation of charging points in shared housing are essential (Kumar and Alok, 2020) (*high confidence*). Economies of scale are expected to further lower the purchase cost of BEVs, reducing the need for subsidies (Wicki et al., 2022). EU bans on diesel/gasoline car sales by 2035 remain the most effective lever to accelerate this shift. Alternative fuels such as e-fuels – synthetic fuels produced using renewable electricity, water, and carbon dioxide ($CO_2$) – and hydrogen are unlikely to play a significant role in passenger transport due to lower efficiency and higher costs – e.g., Morrison et al.

(2024) estimate $CO_2$ abatement costs of over $EUR_{2023}$ 600 per ton (GHG emissions reduced in $CO_2$ weight equivalent) for e-fuels versus less than $EUR_{2023}$ 150 per ton for BEVs (see Section 8.3.2). Strimitzer et al. (2022) conducted an efficiency comparison in terms of the distance that can be traveled using 10,000 kWh of renewable electricity, demonstrating the energy efficiency of BEVs at 74 %, far surpassing hydrogen fuel cell vehicles (30 %) and e-fuels (15 %). However, e-fuels are likely to play a critical role in decarbonizing air travel, particularly for large aircraft (*medium confidence*).

**Pricing and subsidies:** Pricing strategies, in line with the user-/polluter-pays principle are essential for achieving the goals of avoiding trips, shifting to sustainable modes, and relying on technological improvements (Angelini et al., 2022). For instance, the recent 'Maßnahmenbericht Mobilitätswende' shows that increasing the mineral oil tax and introducing road pricing have the highest GHG emission reduction potential among 13 policy measures examined (Heinfellner et al., 2024a). Currently, Austria's road transport cost coverage ratio – covering variable external (e.g., environmental) and infrastructure costs with tolls, taxes and fees charged to users – is only 21 %, which is one of the lowest in Europe (European Commission: Directorate-General for Mobility and Transport et al., 2019). Compared to bans, pricing policies have the advantage of generating tax revenues that can be used to counterbalance negative distributional effects, especially in rural car-dependent regions (Axhausen et al., 2021). A distinction can be made between generic pricing instruments such as carbon pricing (the ETS will be expanded to cover transport from 2027 onwards: ETS 2) (European Union, 2024), and more specific instruments such as city tolls, parking fees and taxes on car ownership. With sufficiently high prices, all of these instruments have a high potential for influencing travel behavior in such a way that substantial $CO_2$ emission reductions can be generated (*high confidence*). Removing counterproductive subsidies (e.g., for company cars, commuting, or hybrid SUVs) also has significant potential to reduce emissions (Peneder et al., 2022) (*high confidence*). Similarly, introducing taxes on kerosene or other flight charges could encourage a modal shift away from air travel and lead to innovations that benefit aircraft efficiency (*medium evidence, high agreement*).

**Exceptional challenges in reducing car modal share:** Reducing the car modal share in rural and semi-rural areas remains particularly challenging due to the perceived convenience and reliability of cars (*high confidence*). Spatial planning policies – such as minimum standards for public infrastructure, expansion of public transport, and investment in walking and cycling – can enable shifts in the modal split. Studies suggest that a significant proportion of the population is willing to switch modes under these conditions (Millonig et al., 2022; Peer et al., 2023). In the medium and longer term, these efforts could lead to a reduction in car ownership, especially among households with multiple cars (*medium confidence*).

## Scenarios

The Environment Agency Austria (EAA) presents possible trajectories for transport-related GHG emissions (Umweltbundesamt, 2023a). In the With Existing Measures (WEM) scenario, only measures (that were) bindingly implemented or legally fixed by January 1, 2022, are considered. These are insufficient to reverse unfavorable trends. The WEM scenario predicts an increase in passenger transport to 126.7 billion passenger kilometers by 2040 and an increase in motorization to 639 cars per 1,000 inhabitants. By 2040, 69 % of passenger kilometers would rely on motorized private transport, with only 56 % of the fleet electrified. This results in GHG emissions of 10 million $tCO_2eq$ in that year (Umweltbundesamt, 2023b).

In contrast, the EAA's Transition scenario models complete decarbonization of transport by 2040 using a backcasting approach. Measures are tailored in design and intensity to achieve climate neutrality by this deadline.

Motorization stabilizes at around 570 cars per 1,000 people, with the fleet almost entirely electrified by 2040. This eliminates GHG emissions from private transportation and meets climate neutrality targets. However, this requires about 23.4 TWh of renewable electricity (a 35 % increase from the WEM scenario), putting transport in competition with other sectors. Issues around equitable distribution of limited renewable energy remain unresolved, with the transport sector accounting for 20 % of energy use in the 'Transition' scenario by 2040.

## Governance and acceptability

Legal and institutional challenges – such as the insufficient design and enforcement of existing measures – often hinder effective policy implementation (Jandl et al., 2024) (see Section 6.5.1). In addition, a critical barrier to implementation remains the lack of public acceptance, especially for stringent policy instruments (see also Heinfellner et al., 2024a) (see Section 5.6.3). Public opposition is, however, not limited to strict regulations, as the debates around the '15-minute city' concept show (Caprotti et al., 2024). Strategies for improving public support include (*high confidence*):

- Policy packaging: Combining push and pull measures can mitigate negative distributional effects, such as those felt by rural residents relying on cars for commuting (Thaller et al., 2021; Dugan et al., 2022; Hössinger et al., 2023; Heinfellner et al., 2024a).
- Participatory approaches: Co-design and stakeholder engagement increase legitimacy and acceptance.
- Awareness and co-benefits: Informing the public about policies' benefits can build support (e.g., Peer et al., 2023).
- Strategic implementation: Timing, coalition-building, trials, and gradual rollouts increase acceptance. For example, Stockholm's temporary congestion charge became a permanent policy after public support increased post-trial (Schuitema et al., 2010; Heyen and Wicki, 2024).
- Address spillover effects: Avoid unintended consequences, such as Vienna's parking permit system ('Parkpickerl'), which initially shifted parking demand to adjacent districts until more comprehensive policies were enacted.
- Making sustainable travel the default: Designing sustainable travel options in such a way that they are more convenient to use than less sustainable travel options (Section 5.5.1).

Recent surveys suggest that Austrians may be more open to regulatory and pricing policies than previously thought, with a majority viewing most measures positively or neutrally (Hössinger et al., 2023; Heinfellner et al., 2024a). Lack of acceptance of technological options may also hinder progress towards decarbonization (*high confidence*). For example, a substantial portion of the Austrian population remains reluctant to adopt electric vehicles (Priessner et al., 2018).

## 3.4.3. Freight transport

### Status quo and trends

Like passenger transportation, freight transportation is a derived demand that results from the need to move goods. As a result, economic activity, typically measured by GDP, has historically been a reliable predictor of freight volumes and flows. However, changes in the structure of the economy – such as the growth in the service sector, changes in supply chains (e.g., just-in-time logistics), and policies affecting shippers and carriers – have weakened this correlation and reduced the accuracy of forecasts (Meersman and Van de Voorde, 2013; ITF, 2023). This decoupling is evident when comparing ton-kilometers per GDP unit across EU nations; Austria is in line with the EU average, but exceeds many Western European countries (Odyssee-Mure, 2022b). Despite this trend, the consensus points to continued growth in freight demand, driven in particular by the expansion of e-commerce.

**Emissions, modal split and freight demand:** Figure 3.10 shows the evolution of transport performance for road and rail since 1990. In particular, road transport performance has increased considerably over this time period.

Table 3.4 shows the freight transport demand for inland waterways, rail and road in 2023, categorized by transport type. Road freight transport reached a record high of 56,846,395 × 1,000 tkm in 2021, accounting for 71 % of the total freight transport share. By 2023, the road share increased slightly to 72 %. Rail's role in intermodal freight

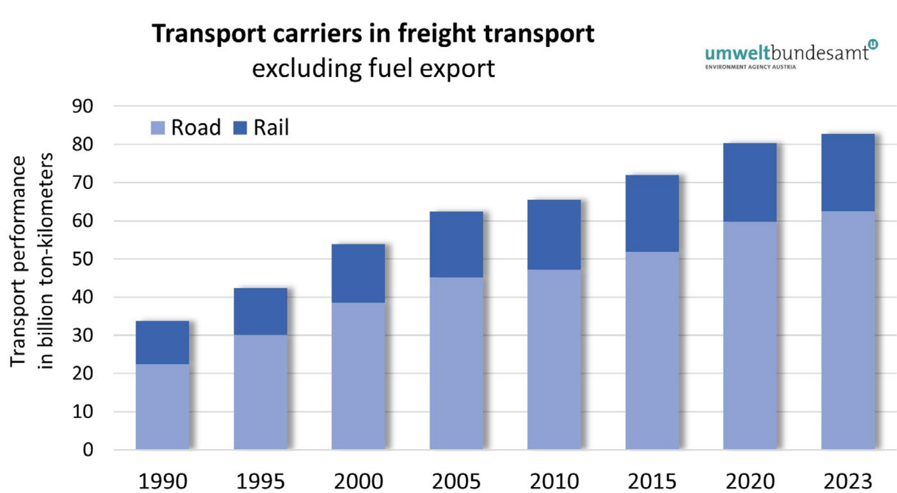



**Figure 3.10** Freight transport performance by rail and road in Austria (1990–2023) (Heinfellner et al., 2024b).

**Table 3.4** Modal split of freight transport (road/rail) by transport type (inland, import, export and transit) in Austria in the year 2023 [1000 tkm] (Statistik Austria, 2024d).

| Modal split in the year 2023 [1,000 tkm] | Inland | Import | Export | Transit | Total | |
|---|---|---|---|---|---|---|
| Inland waterway | 509,407 | 320,922 | 310,71 | 45,506 | 1,186,546 | 2 % |
| Rail | 3,948,293 | 4,921,328 | 3,516,192 | 7,819,358 | 20,205,170 | 26 % |
| Road | 18,034,181 | 8,725,596 | 8,614,571 | 19,754,058 | 55,128,407 | 72 % |
| Overall | 21,982,474 | 13,646,924 | 12,130,763 | 27,573,416 | 76,520,123 | 100 % |

transport is mainly facilitated by 14 inland container terminals across Austria (Schienen-Control, 2023; VABU, 2023).

The contribution of road freight transport to total GHG emissions from transport increased from 31 % in 1990 to 34 % in 2023, but declined significantly from 2022 to 2023 as Austria's economic output also declined. Fuel exports in commercial vehicles account for 12 % of these emissions (European Commission: Eurostat et al., 2023; Schuster et al., 2023; Heinfellner et al., 2024b). Among Austria's transport-intensive industries (e.g., mining, food, and waste), logistics activities account for about 12 % of their total GHG emissions (Miklautsch et al., 2022).

**Parcels and urban freight transport:** In 2020, approximately 290 million parcels were delivered in Austria, with parcel deliveries increasing by 9 % annually over the last decade. The Viennese chamber of commerce projects an increase to 339 million parcels by 2030 (WKO Wien, 2022). Despite this large volume, the associated GHG emissions have not been explicitly measured. Urban freight accounts for 10 % of urban road transport in Europe, with deliveries estimated to contribute 20 % of freight emissions – the same as maritime transport, although it represents only 3 % of freight activity compared to 70 % for shipping (ITF, 2023).

**Technological advancements:** There have been significant technological changes in the light- and heavy-duty vehicle markets in recent years. For heavy-duty electric trucks, recent studies show that electrified highways are economically feasible, but feasibility depends on international adoption, which seems unlikely. In addition, the construction of such electrified highways is expected to result in large GHG emissions (Qiu et al., 2022; Colovic et al., 2024) (*medium confidence*).

Battery-operated freight vehicles have been advancing in recent years: In 2024, battery trucks reached a 4 % market share among light-duty vehicles, which are often used for distribution and especially urban freight delivery, and a 1.6 % share among heavy-duty vehicles (i.e., larger truck classes) in Austria (AustriaTech, 2024). Scaling up this adoption will require improved charging infrastructure, especially along highways and at loading sites (*limited evidence, high agreement*).

Hydrogen-powered heavy-duty vehicles offer greater range than (existing) battery-operated vehicles and faster refueling (similar to diesel and gasoline). However, high hydrogen prices and limited filling stations (four in Austria) make them economically and logistically unattractive, and this is unlikely to change in the short to medium term (*medium confidence*).

Hydrotreated vegetable oil (HVO) is gaining traction as a transitional fuel due to the limited availability of heavy-duty battery electric trucks and related charging infrastructure. A 220-fold increase in HVO sales compared to 2022 levels occurred following Austria's new national fuel regulation in 2023, which promotes the use of renewable energy (Heinfellner et al., 2024b).

**Energy efficiency:** Low-carbon fuels, including biofuels and synthetic fuels, significantly reduce GHG emissions compared to standard diesel for heavy road vehicles (Benajes et al., 2024). However, compared to battery electric trucks, biofuels require 2–3 times more cumulative energy input (i.e., the sum of all primary energy inputs), while synthetic fuels (or e-fuels) require 5.5–6.5 times more, due to their energy-intensive production processes that use electricity to convert hydrogen and carbon dioxide into a usable energy source (Fritz et al., 2022). This is a major challenge given the expected increase in demand for renewable energy across all sectors (*medium evidence, high agreement*). Lifecycle assessments also indicate that battery electric trucks have the lowest cradle-to-grave GHG emissions (O'Connell et al., 2022) (*medium confidence*).

**Adaptation:** As discussed in Section 3.4.4 on infrastructure, the increasing likelihood of extreme weather events – such as landslides, floods, and tree falls – and their impacts on infrastructure negatively affect network connectivity and thus accessibility and reliability. With higher global warming levels, such events are expected to become even more frequent (see Section 3.2.3, Sections 1.4.1, 1.6.2, 1.7, and Cross-Chapter Box 1). Particularly in mountainous areas, where alternative routes or modes are not available, prolonged network disruptions can lead to high economic costs if goods are not delivered on time (e.g., Fikar et al., 2016) (*medium evidence, high agreement*). Supply chain diversification offers some potential to mitigate these risks (*medium confidence*).

## Mitigation strategies

The medium-term mitigation potential for freight transport is considered to be relatively high (*high confidence*). This potential can be divided into three key areas: Avoiding unnecessary freight movements, shifting to more sustainable transport modes, and exploiting technological improvements. A comprehensive policy addressing all three dimensions could include a dynamic road pricing system that takes into account usage, location, time of day and vehicle type and internalizes negative externalities, including not only GHG emissions but also local air pollution, accidents, noise and infrastructure costs (Marcucci et al., 2023) (*high confidence*). In Austria, less than one-fifth of these costs are currently covered by charges and tolls, despite the existence of a motorway toll system (European Commission: Directorate-General for Mobility and Transport et al., 2019).

**Avoiding and shortening trips:** Optimizing logistics and supply chains (e.g., reducing empty backhauls) can play a key role in reducing freight movements (*medium confidence*). Regionalization of production and distribution can also lead to shorter transport distances (*medium evidence, high agreement*). Adopting circular economy principles, which promote resource efficiency and product reuse, can help minimize the need to transport new goods (*medium confidence*). In urban areas, tailored approaches such as parcel boxes can further contribute to GHG emission reductions (*limited evidence, medium agreement*). However, while these measures could moderate the projected growth in freight volumes, an overall reduction would require strong pricing and/or regulatory measures (*medium confidence*).

**Shift from road to rail:** Shifting long-haul freight movements from road to rail has significant GHG emissions-savings potential given the low emission factors of railway operations in Austria (see Section 8.3.2 and the recent 'Maßnahmenbericht Mobilitätswende') (Heinfellner et al., 2024a). Despite the relatively high share of rail freight in Austria (27 %), increasing this share to the political target of 40 % by 2040 poses considerable practical challenges. These include the rigidity and limited capacity of the rail system, as well as first and last mile issues. Accessibility and expansion of rail infrastructure, terminals and sidings are critical, with the latter even declining in recent years. Strong policies, such as bans on road freight along corridors with sufficient rail capacity (limited to certain types of freight, times of day, or truck types), could enforce this shift. Improvements in rail speed, reliability, and predictability are also critical. To compensate for rail's higher costs, subsidies – e.g., for personnel or infrastructure usage fees – could be effective, especially in the absence of road freight charges that fully internalize the corresponding external costs (*medium evidence, high agreement*).

Rail modal shift is generally viable for trips over 250–300 km; shifts for shorter distances are usually unattractive for shippers and carriers. Due to Austria's geography, approximately 80 % of the longer trips start or end abroad. Achieving the 40 % modal share is therefore highly dependent on improving international connectivity, without which only a 34 % share is considered achievable (BMK, 2021b). Cross-border rail operations remain inefficient, hampered by waiting times, limited capacity, and unattractive, difficult-to-schedule services.

In addition, interconnectivity gaps also exist between rail networks and airports, seaports, and major inland waterways. The EU's efforts to address these issues are pronounced, as evidenced by initiatives such as the 'Fourth Railway Package' (European Commission, 2016) and the multimodal Trans-European Transport Network (TEN-T) 'core network' targeting major European axes by 2030 (and a more comprehensive network by 2050) (European Commission, 2020b). It is estimated that failure to complete the TEN-T would result in a loss of 1.8 % of potential economic growth and 10 million person-years of employment across the EU (Schade et al., 2015) (*medium evidence, high agreement*).

**Technological options:** There is great potential to shift road freight vehicles to low or zero emission technologies. EU regulations, including a Directive on the deployment of alternative fuel infrastructure (Directive 2014/94/EU), the 'Clean Vehicles Directive' (Directive (EU) 2019/1161), and a Regulation on $CO_2$ emission performance standards for new heavy-duty vehicles (Regulation (EU) 2019/1242), require manufacturers to reduce the fleet-wide average $CO_2$ emissions of their newly registered trucks per calendar year by 15 % by 2025 and 45 % by 2030 (compared to 2019 levels). These measures have already reduced the $CO_2$ intensity of the freight vehicle fleet, although growing freight demand has largely offset these gains (*medium evidence, high agreement*) (see Figure 3.8 and Figure 3.10).

The relatively young truck fleet in Austria (average age: 6.6 years (ACEA, 2023a), possibly a result of significantly lower toll fees for less polluting vehicles) underlines the potential for a rapid change in propulsion technology, which would lead to considerable GHG emission reductions. This can be seen as low-hanging fruit, and vehicle manufacturers can be seen as enablers of a faster transition. Battery-electric systems, particularly for distances under 300–500 km, offer feasible near-term solutions if supported by regulatory and infrastructure advancements. A key barrier is limited range and long charging times, which could be mitigated by systems that allow battery swapping (e.g., a 'stagecoach' model), especially for international routes (*medium confidence*).

Emissions from urban freight transport can be significantly reduced by establishing zero-emission zones in cities, effectively enforcing $CO_2$-free logistics in urban centers. Light-duty electric vehicles (range ~500 km, charging time ~30 minutes) have already already entered the market and could be complemented by (e-)cargo bikes for short-distance and special deliveries (*medium evidence, high agreement*).

### Scenarios

For the Austrian context, there is little evidence on decarbonization scenarios for the freight sector. Sedlacek et al. (2021) calculate two scenarios for the road freight sector, one corresponding to a WEM scenario and one that achieves carbon neutrality by 2040. The scenarios emphasize the role of technological progress in all vehicle categories. A Europe-wide strategy and policy framework is considered essential due to the international nature of freight transport. Despite significant transformation efforts, they conclude that the macroeconomic impact on Austria's GDP is expected to be small (*low confidence*).

## 3.4.4. Transport infrastructure

Infrastructure supports the physical mobility of goods and people and includes fixed structures (e.g., roads, railways, bicycle and pedestrian paths, inland waterways), access points (e.g., train stations, airports), and parking facilities (both on- and off-street). In 2022, Austria's transportation infrastructure included approximately 128,000 km of roads, 4,965 km of railways, 1,033 railway stations, 6 commercial airports, 8 inland waterway terminals, and 538 rail sidings. Statistics for local infrastructure, such as bicycle paths and parking spaces, are difficult to obtain, but notable examples include 280 km of tram lines and 80 km of subway networks.

Infrastructure can be characterized in terms of its capacity and technical specifications, which in turn affect its (perceived) quality, safety and resilience. Changes in infrastructure alter accessibility, typically affecting the flow of people and goods across routes and transport modes. Especially over time, infrastructure developments can reshape spatial patterns, such as residential and business locations and supply chain structures. For example, the expansion of (high quality) road networks has repeatedly been shown to induce urban sprawl and suburbanization (*robust evidence, medium agreement*) (see also Section 3.2).

The provision of transport infrastructure is associated with significant embodied GHG emissions (see also Section 4.2), which are often underestimated or ignored, leading to a severe undervaluation of the environmental impacts of transport (Facanha and Horvath, 2007; Chester and Horvath, 2008). A distinction can be made between direct and indirect effects:

- **Direct effects** result from energy consumption and associated GHG emissions for raw material extraction (mining) and production, transportation, production and construction of the transport infrastructure itself, maintenance and eventual disposal. Infrastructure construction requires substantial amounts of material (Haas et al., 2024) (*medium evidence, high agreement*).
- **Indirect effects** include increased fuel consumption of vehicles due to road surface irregularities, but also changes in travel behavior and freight transport movements induced by infrastructure improvements: In general, infrastructure improvements often increase travel activity, potentially increasing GHG emissions, especially in the case of road infrastructure expansions, where on average a 1 % increase in road kilometers leads to a corresponding 1 % increase in vehicle kilometers traveled (e.g., Garcia-López et al., 2022) (*medium confidence*). Similarly, the availability of convenient parking greatly increases the likelihood of car ownership and use (e.g., Hess, 2001) (*medium confidence*).

Infrastructure can exacerbate the effects of global warming, particularly in urban areas, by reinforcing the UHI phenomenon as described in Section 3.2.1, which is particularly relevant in densely populated areas. In addition, infrastructure covers a significant area of land, contributing to soil sealing and potentially increasing the negative impacts of extreme weather events such as heatwaves and heavy precipitation (see Section 3.2.3). Land-based infrastructure occupies 6.7 % of Austria's permanent settlement area (Umweltbundesamt, 2020). Among transportation modes, rail infrastructure uses 7 m² of land per passenger, compared to 100 m² per car user.

In addition to being a source of GHG emissions, infrastructure is also strongly affected by climate change and associated weather events – see also Section 3.2.3 for the urban context and Section 7.4.3 for infrastructure in alpine areas. The main weather hazards requiring adaptation are high temperatures and (excessive) precipitation (Fian et al., 2021; Palin et al., 2021) (*medium evidence, high agreement*).

In the following subsections, rail and road infrastructure, the dominant types in Austria, are analyzed in detail. Other infrastructure types also contribute to GHG emissions, but have a comparatively smaller network size and therefore a limited reduction potential. Nevertheless, some statistics and considerations for rail and road infrastructure can be adapted to broader application. For example, trams and subways share characteristics with rail infrastructure due to their rail-bound systems, while on-street parking is consistent with emission factors for road surfaces. A discussion on urban infrastructure planning can be found in Section 3.2.2.

Although local variations and dependencies make it challenging to generalize the need for infrastructure investments, adaptations, or even removal, evidence suggests that welfare benefits of additional infrastructure diminish at high levels of infrastructure availability (Virág et al., 2022a) (*limited evidence, medium agreement*).

## Railway infrastructure

As of 2023, Austria's rail infrastructure network covers 4,935 km, of which 2,262 km are double track (ÖBB-Holding AG, 2024). Among European countries, Austria ranks second in per capita investment in rail infrastructure, surpassed only by Switzerland (ITF, 2022). The investment plan of the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology allocates $EUR_{2023}$ 21.1 billion for the period 2024-2029 for new line construction, line expansion and electrification, freight terminals, digitalization, efficiency improvements, and park-and-ride facilities. The annual budgets include $EUR_{2023}$ 780 million for maintenance and $EUR_{2023}$ 838 million for reinvestment. Major cost-intensive ongoing projects include the Brenner Base Tunnel, the Koralm Tunnel and Semmering Base Tunnel, while further investment plans are guided by Austria's long-term expansion strategy, the 'Zielnetz 2040' (BMK, 2023a, 2024b).

Existing rail capacity is heavily utilized. In 2023, the Austrian Federal Railways 'ÖBB' handled 12.6 billion traveled passenger kilometers, which corresponds to 7,026 trains operated daily (ÖBB-Holding AG, 2024). In addition, freight transport accounted for 26.1 billion ton-kilometers. Maintenance work limits the extent to which freight transport movements can be shifted to night hours. Expanding rail capacity is complex and cost-intensive, especially for routes that cross mountains or urban areas, requiring costly tunnels and infrastructure. Austria's central location in Europe means that its trans-European connectivity relies heavily on investments from neighboring countries. Without adequate foreign investment, the shift of freight from road to rail is constrained, as intra-Austrian distances often fall below the 300 km threshold typically considered uneconomic for rail freight (see also Section 3.4.3).

The majority of the environmental impacts of railway infrastructure are caused by the rails, ballast, sub-ballast, and civil engineering structures (de Bortoli et al., 2020), with the track substructure being a critical factor (Cheng et al., 2020; Pons et al., 2020). The GHG emissions for ballasted railway tracks reported in this section are calculated based on a detailed bottom-up approach that considers all related upstream and downstream processes, including local conditions (traffic loads, radii, and elevation), used track components, specific supply chains, and emissions from trackwork machinery (Landgraf and Horvath, 2021; Landgraf et al., 2022). In addition, supply chains, asset lifetimes, and maintenance requirements throughout the infrastructure lifecycle are considered (Landgraf and Horvath, 2021) (*medium evidence, high agreement*).

In Austria, the focus is on maintaining and renewing the existing network rather than building new lines. In 2023, for example, 216 km of track were renewed, which corresponds to an annual rate of 2.3 % (ÖBB-Infrastruktur AG, 2024), while new track construction has averaged 12 km per year since 2008 (ÖBB-Holding AG, 2022). This continuous renewal rate offers high potential for innovation, as new solutions can be integrated swiftly into the existing network (*medium evidence, high agreement*).

Annual cradle-to-gate GHG emissions from rail infrastructure – based on the current infrastructure network, asset distribution and renewal rates – amount to 234,730 $tCO_2eq$, compared to 144,900 $tCO_2eq$ from passenger operations and 149,500 $tCO_2eq$ from freight operations in 2019. Tunnels and aerial structures (bridges) remain the largest contributors to emissions per kilometer (Chang and Kendall, 2011; Landgraf and Horvath, 2021) (*medium evidence, high agreement*).

Track construction and maintenance account for 55–60 % of GHG emissions within the Austrian rail network (Landgraf and Horvath, 2021). This share is relatively high compared to other countries (Banar and Özdemir, 2015; Jones et al., 2017) because, unlike most other foreign rail operators, ÖBB uniquely sources its traction power from renewable energy sources – 95 % hydropower and 5 % other renewables (ÖBB-Holding AG, 2022). This significantly reduced operational GHG emissions, but increases the relative share attributable to infrastructure.

*Mitigation strategies*

**Planning for future rail demand:** Overall, the shift towards rail is crucial to avoid environmental impacts in the transport sector, as emphasized by the European Green Deal's strategy to 'accelerate the shift to sustainable and smart mobility' (ERA, 2020). However, the development of transport infrastructure development should be limited to what is necessary, based on in-depth traffic volume simulations, which the ASI framework promotes.

**Shift to low-emission materials and fuels in rail infrastructure construction and maintenance:** The main further mitigation potential lies in shifting to low-emission materials and fuels (ÖBB-Holding AG, 2022). Key areas include steel and concrete production, the adoption of circular economy principles, and the use of fossil-free propulsion for heavy maintenance machinery and transport. In particular, as the extraction and processing of raw materials account for 18 % of the EU's total GHG emissions associated with the consumption of goods and services, climate-friendly procurement and processing practices are crucial (European Environment Agency, 2021a). In addition to further research and support (subsidies, financing) for the market entry of sustainable products, this can be achieved by quantifying and integrating environmental impacts into the public procurement process (BMK, 2021a; UNEP, 2021). This, in turn, may encourage contractors and manufactures to invest in environmentally efficient production processes and services (*medium confidence*).

**Efficiency improvements in rail infrastructure design, usage, and maintenance:** Railway infrastructure can be improved by increasing efficiency within the system. The further implementation of the 'European Train Control System' (ETCS) according to Austria's 'National Implementation Plan' (BMVIT, 2017) will increase the efficiency and capacity of the existing railway infrastructure. In addition, ÖBB has already taken a number of measures to mitigate lifecycle costs and GHG emissions (ÖBB-Holding AG, 2022). For example, ballast cleaning allows about 50 % of material to be reduced when reinvesting in existing rail infrastructure (Zeiner et al., 2021). Optimized maintenance planning and improvements in railway infrastructure design can also extend the service life of existing infrastructure (Landgraf and Horvath, 2021).

## Road infrastructure

In 2022, the Austrian road infrastructure consisted of 2,260 km of high-level roads ('Autobahnen' and 'Schnellstraßen'), 33,800 km of intermediate-level roads ('Landesstraßen' 'B' and 'L'), and about 92,000 km of low-level roads ('Gemeindestraßen'). Overall, more than 95 % of roads are built with asphalt pavements (bituminous bound, hot mix asphalt (HMA)) and less than 5 % with concrete pavements (cement bound, portland cement concrete (PCC)). However, about one third of the high-level road network is cement-bound. In comparison, Austria has a high-level road network that is 50 % larger per capita than the EU average and about 55 % larger than Germany's (VCÖ, 2024b).

In 2020, $EUR_{2023}$ 1,291 million were spent on the high-level road network, 46 % on new construction and 54 % on maintenance. For this, 7.4 million tons of asphalt mixture were produced, a decrease of 10 % from the peak year (2010), while 1.26 million tons of reclaimed asphalt were recovered for recycling. Of the recycled material, 70 % was reused in HMA, while 30 % was diverted to other uses or landfills (Blab et al., 2012; BMK, 2022c; EAPA, 2023).

GHG emissions from road infrastructure vary by material type. This can be assessed using a production-based material flow analysis, which includes the production of (raw) materials (bituminous binders, cement, mineral aggregates, additives), and the transport of materials. HMA production results in 40–50 $kgCO_2eq/t$, while PCC emissions range from 75–100 $kgCO_2eq/t$, as shown by Gruber and Hofko (2023) with calculations based on Gruber (2023). For HMA, raw materials contribute approximately 50 %, transportation 5 %, and production of asphalt mixture about 45 % of total GHG emissions. In contrast, PCC raw materials account for 95 % of the emissions, with transportation and production accounting for the remainder.

Overall, the impact of asphalt paved roads on GHG emissions is 0.4 % to 4 % of traffic-related emissions for the low- and high-level road network, respectively, while concrete roads contribute 0.6 % to 6.4 %, respectively (calculations based on Gruber, 2023). Due to continuous dynamic loading of road infrastructure by vehicle traffic, the road surface and structural properties deteriorate over time. As a result, top-layer lifetimes are typically 10-15 years before replacement. This deterioration includes increased surface roughness and increased longitudinal unevenness, leading to increased activation of vehicle damping systems, resulting in energy dissipation and thus increased fuel consumption. Recent studies estimate the potential GHG emission savings from improving the evenness of road surfaces to be between 5–15 % (Louhghalam et al., 2019). For example, road traffic on a 1 km long section of a 3-lane road with 27,000 vehicles per day, of which 10 % are heavy goods vehicles (HGVs), causes approximately 3,000 $tCO_2eq$ of GHG emissions per year. With a theoretical, rather pessimistic savings potential of 2.5 % by improving longitudinal evenness, 74 $tCO_2eq$ could be saved per year, which is roughly equivalent to the GHG emissions caused by the rehabilitation of the surface layer. Thus, in this case, the emissions from asphalt production could be offset by reduced fuel consumption already within the first year (Roxon et al., 2019). Even with an 30 % overall share of electric vehicles (cars and HGVs), the corresponding emissions savings potential would still be 59 $tCO_2eq$ per year (calculations based on Gruber and Hofko, 2023).

*Mitigation strategies*

**Avoidance of road infrastructure expansion:** Current planning and design standards for road infrastructure drive the need to expand the network and cross-sections of existing roads due to: (a) Future traffic volume growth – mandatory assumptions of a 2–3 % annual traffic growth result in larger, thicker structures, wider cross-sections, and sometimes additional lanes; (b) Design speed requirements – minimum design speed thresholds set for various road classes, increase space and material requirements, as speed limits affect the required curvature radii and lane widths; (c) Capacity thresholds – in periodic checks of existing roads, current capacity overload thresholds prioritize high user service levels over efficiency. Therefore, critically reviewing and adapting all standards and guidelines to minimize future expansions can not only reduce the need for material- and production-based GHG emissions, but also reduce land use and indirect emissions from further traffic attracted to overly capacious infrastructure (Anupriya et al., 2023) (*high confidence*).

**Shifting to low-emission materials in the construction and maintenance of road infrastructure:** Incentives in tendering processes can drive reductions in GHG emissions by incorporating best bid criteria that optimize road production and products not only economically and technically, but also ecologically (*medium evidence, high agreement*). Calculation tools to assess emission reduction potential based on material mix designs and production parameters are already available for the tendering process of the high-level road network operated by ASFINAG (an Austrian public corporation that plans, finances, builds, maintains and collects tolls for the Austrian highways) (ASFINAG, 2024). Dry storage of mineral aggregate, reclaimed asphalt pavement (RAP), and short transport distances have a significant positive impact on the GHG reduction potential of HMA, increasing its importance in achieving minimum overall energy consumption (Hofko et al., 2020) (*high confidence*). While the addition of RAP to HMA can reduce emissions, excessive RAP content can affect the durability of the road, reducing its service life while increasing the need for rehabilitation and therefore long-term energy consumption. There is currently no consensus on safe RAP limits, highlighting the need for further research to establish reliable thresholds and improve lifecycle analysis.

**Optimization of surface quality:** High surface quality (i.e., longitudinal evenness) improves not only the structural quality (technical lifetime) but also, as discussed above, fleet fuel consumption. Incorporating surface quality models into pavement management systems can therefore further reduce traffic-related GHG emissions (*high confidence*). Continuous assessment of longitudinal evenness is possible with simple means, as recent studies have shown (Gruber and Hofko, 2024).

## Risks and adaptation possibilities

Adaptation to increasing global warming levels is essential for transport infrastructure due to the risks posed by changing weather patterns and their consequences (see also Cross-Chapter Box 1), including infrastructure unavailability and reduced network resilience (*high confidence*). Temporary or prolonged unavailability can result in significant economic costs due to delays and necessary adjustments in routes and modes of transport caused by reduced travel time reliability, supply chain disruptions, and other logistical challenges. Urban areas face higher impacts due to denser populations and freight demand, while rural areas – although less affected (with the exception of tourism hotspots; see also Section 7.4) – may suffer severe disruptions due to the lack of alternative routes and modes (no redundancy) (*medium evidence, high agreement*). The complexity of infrastructure operations means that the response of the infrastructure to hazards is rarely linear (*medium evidence, high agreement*). Infrastructure damages can also increase the risk of accidents and potentially lead to loss of property (vehicles, cargo, etc.) if not detected in time, or if warnings are ignored.

In general, proactive adaptation safeguards infrastructure and ensures functionality under increasing global warming levels. Moreover, adaptation of rail and road infrastructure to climate change usually results in net macroeconomic benefits by balancing direct benefits and indirect benefits such as employment, even at rather low damage reduction potentials (Bachner, 2017) (*limited evidence, medium agreement*). So far, Austria's adaptation targets for climate change – as outlined in König et al. (2014) – have not been met in any of the relevant transport and infrastructure dimensions (see Table 48 in Balas et al., 2021) (*high confidence*).

**Heavy rain events:** Increased likelihood of shorter (*high confidence*) and longer (*low confidence*) heavy rainfall events can trigger pluvial and riverine flooding, rock falls, avalanches (rock and snow), and shallow slides, especially in narrow valleys (Huttenlau et al., 2010; Olsson et al., 2012; Löschner et al., 2017; Schlögl and Matulla, 2018; Unterberger et al., 2019). Consequences include infrastructure damage, disruption, and potentially safety issues. Prolonged heavy rain events can increase surface runoff due to increased soil saturation and cause structural failure of unbound base layers, necessitating premature reconstruction (*high confidence*). In addition, landslides can result from rain-induced deconstruction. Bridge scour and water damage to electronic equipment are other specific consequences associated with heavy rain events. Adapting standard practices with porous surface layers, slightly tilted surfaces (for water drainage), and slope stabilization increases resilience (see also Section 3.2.3 Urban water impacts). Surface elevation in vulnerable areas, such as valleys, creates safe escape routes during floods. Infrastructure improvements such as water retention basins manage excess water. In flood-prone areas, soil monitoring combined with an automatic warning system provides additional safety (see also Sections 1.4.1, 3.2.3 and 7.4.1). Urban water management concepts, such as the 'sponge city' concept, can improve safety during short heavy rain events and retain water from precipitation in soils under sealed surfaces by allowing water to locally percolate through porous surface layers (see also Section 3.2.3).

A recent example of such a heavy rain event occurred in Eastern Austria in September 2024. In addition to an estimated EUR 1.3 billion in damages to businesses and households, immense infrastructure damage occurred, the cost of which cannot yet be determined (as of 2024) (WIFO, 2024). It led to the closure of Austria's main railway line between Vienna and Salzburg ('Weststrecke') for nearly two months due to flooding that damaged tunnels, stations, and electronic systems. Despite being designed in the 1990s according to standards to statistically withstand 100-year flood extremes, the 2024 rainfall exceeded these magnitudes, with water levels equivalent to a 500- or 1000-year event. An example for which infrastructure costs have been quantified are the several heavy rain events in Styria in the summer of 2024, with a total estimated damage of $EUR_{2023}$ 34 million (ORF, 2024).

**Acute heat:** Increased acute heat can cause significant material damage. For road infrastructure, this includes premature failure of asphalt pavements due to excessive softening and permanent deformation (rutting) (Zhang et al., 2022) and failure of concrete pavements due to slab buckling (Kerr, 1994). Acute heat increases the risk of rail buckling, with thermal expansion being particularly problematic in narrow curves such as those often found in mountainous areas. These risks can be partially counteracted by changes in product design and construction techniques. Speed and weight restrictions on roads and railways, and the design of rail infrastructure to avoid narrow curves (e.g., tunnels) are other suitable short- and long-term adaptation measures.

In urban areas, adaptation strategies to reduce UHIs are of utmost importance (see Section 3.2.3 Integrated mitigation and adaptation strategies). Surface adaptations such as lighter-colored pavements and permeable structures are currently being studied to gain experience. Lighter colored surfaces increase reflection and reduce energy dissipation, resulting in faster cooling after sunset. However, during the day, higher reflectance can lead to higher local temperature maxima. Permeable structures contain less mass to act as a heat carrier, and water can be applied and partially stored during extreme temperature events to shift energy conversion from heating to evaporation (Myrup, 1969; Qin et al., 2024) (*high confidence*). However, changes in road surfaces can only provide partial solutions. Preserving and increasing the amount of natural shade is necessary and provides the most significant improvements to UHIs.

**Lack of precipitation:** Risks associated with a lack of precipitation primarily affect waterways, as lower water levels reduce freight carrying capacity. However, waterways are only a small part of the Austrian transportation network. In exceptional cases, dry soils can cause shrinkage cracks or even landslides, leading to infrastructure failures. Cost-effective adaptation options for these risks are limited.

*Regulation, governance, and planning aspects*

Beyond the physical adaptation of infrastructure, regulatory and governance frameworks will also need to evolve to meet the demands of building and operating transport infrastructure under changing climate conditions (e.g., see Table 48 in Balas et al., 2021). The acute need for action is underscored by the fact that infrastructure assets built today are expected to remain operational well beyond 2100, a timeframe that is often overlooked in current legislation (see, e.g., Siefer et al., 2019, on railway infrastructure regulations in Germany). Forward-looking scenarios and risk assessment tools, such as maps detailing changes in minimum and maximum surface temperatures and extreme precipitation probabilities, can guide the design of resilient infrastructure to accommodate changing climate patterns (Fasthuber, 2019; Esterl et al., 2022). In particular, the urgent need to re-evaluate flood risk statistics was further illustrated by the extreme flood event in the fall of 2024, which revealed significant gaps in existing predictive models and preparedness measures.

## Conclusion

Climate change is already impacting Austria's built environment and transport sector, with rising temperatures and extreme weather events threatening infrastructure. To ensure resilience and protect public welfare, adaptation strategies are essential, including improved water management, flood and landslide protection, and greening measures to mitigate heat stress. Soil sealing and excessive land take exacerbate these challenges, highlighting the need for permeable surfaces, sustainable drainage systems, and nature-based solutions. Resilient urban planning must incorporate these elements to ensure long-term sustainability.

Meanwhile, Austria's building and transport sectors remain major contributors to climate change, accounting for 70 % of national energy consumption and 38 % of greenhouse gas emissions in 2023, excluding emissions from electricity and district heat generation, which are attributed to the industrial sector. Electrification, driven by heat pumps and electric vehicles, is key to decarbonization, but its full potential depends on defossilizing and decarbonizing both electricity generation and district heating. Maximizing the benefits of the transition requires deep renovations of buildings, widespread adoption of heat pumps, and the use of low-emitting materials alongside circular design principles to minimize environmental impacts and resource consumption.

Compact urban development and reduced car dependency are also critical to reducing emissions, but urban heat island effects and strong preferences for single-family homes and car ownership pose challenges. Mitigation options include urban greening, prioritizing mixed-use neighborhoods, and improving public transport and active mobility infrastructure. Freight transportation is another hurdle, with rising demand and limited low-carbon alternatives delaying full decarbonization. Solutions include optimizing logistics and shifting long-distance transport to rail, while improving cross-border rail connectivity in line with EU transport policy. Dynamic road pricing and stronger incentives targeting the advancement of sustainable transport technologies, including low- and zero-emission trucks, could further accelerate emissions reductions.

Achieving a low-carbon future will require a combination of pull and push measures, including incentives for behavioral change, renewable energy adoption, and efficiency improvements. With a 43 % reduction in GHG emissions from 1990 to 2022, the building sector is already making progress. However, continued emphasis on emission avoidance, renewable solutions, and efficiency gains will remain critical to meeting climate goals. Through integrated planning, technological innovation, and behavioral shifts, Austria can foster more resilient, sustainable, and livable communities.

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