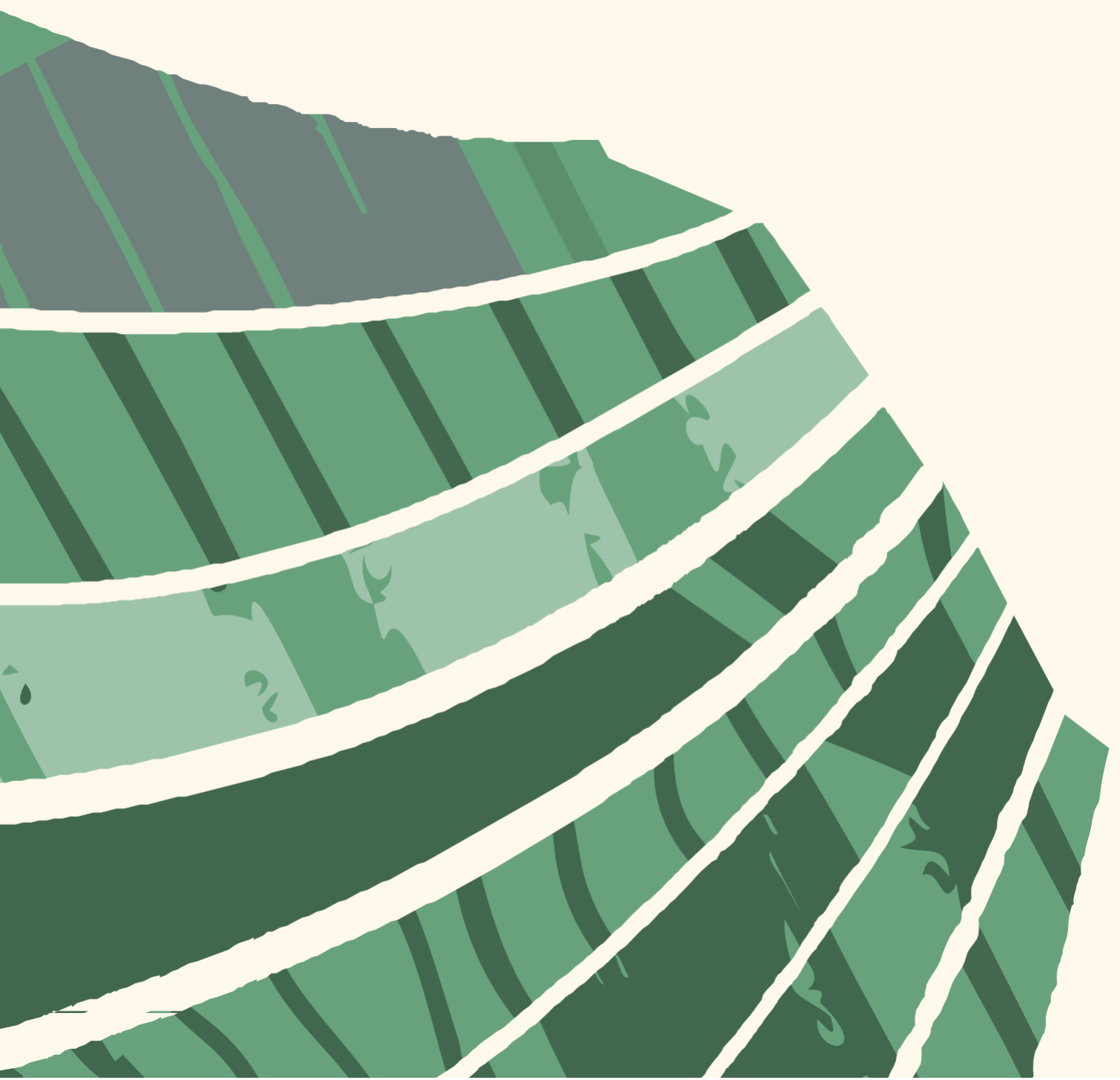


Appendix to Chapter 4

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



Second Austrian Assessment Report on Climate Change | AAR2

Appendix to Chapter 4

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

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4.A.1 Appendix to [Section 4.4](#)

Overview of Mitigation Options and Emission Reduction Potentials

There are several mitigation options in steel production and use across the Avoid, Shift and Improve dimensions (see Table 4.A. 1). Avoiding emissions can be achieved via using alternative materials downstream (e.g., wood as construction material for housing), increased material efficiency (lowering material use and extending lifetime of products) and circularity (recycling and product circularity). The shift dimension covers fuel switching (e.g., to biofuels for heat) and electrification of processes, such as a switch to the direct reduction (DR)-EAF route combined with hydrogen. Improve covers options of energy efficiency improvements of existing technologies and CCS/CCU.

There are multiple mitigation options in cement production across the Avoid, Shift and Improve dimensions (see Table 4.A. 1). Emissions can be avoided by switching to alternative materials in construction (e.g., wood as construction material for housing), reducing over-usage (increasing material efficiency) and circularity, by reducing the clinker to cement ratio and by introducing new binder materials. Within the shift dimension, emissions can be reduced via fuel switching and electrification, with the latter having emission reduction potential by up to 100 % when combined with CCS. Emission intensity can further be improved by increasing energy efficiency or employing CCS or CCU.

Several options exist for decarbonizing the chemicals industry (see Table 4.A. 1). To avoid emissions, consumption patterns and levels (e.g., less plastic products) could be reduced, material efficiency can be further improved (lower material use and extending lifetime of products) and product circularity and recycling increased. In the shift domain, electrification of processes, fuel switching to biofuels and the usage of hydrogen (e.g., for methanol production and ammonia synthesis) offer large emission reduction potentials. Hydrogen itself could be generated using methane pyrolysis (based on renewable electricity and biogas). Negative emissions could be accomplished in urea production (using low-carbon ammonia and captured CO₂, e.g., from cement) as well as in methanol from biomass production (Alton et al., 2022; Bashmakov et al., 2022).

Mitigation options for the paper industry are summarized in Table 4.A. 1. In general, this sector can be decarbonized easier than other industries, because it operates at low temperatures. In the avoid dimension, digitalization and recycling can reduce the demand for paper and virgin material itself. In the shift dimension emission can be reduced via fuel switching and electrification. Energy efficiency can be further improved and CCS with biomass (BECCS) could also reduce emissions substantially.

Overview of global trends in industry sectors steel, cement, chemicals, paper

Steel

Steel is a key material in our current economic system, as it is used for construction and infrastructure, transportation and machinery. Between 1960–2020 annual global crude steel production increased from 350 to 1,900 Mt (2.8 %/yr), with China being the largest producer at 1,060 Mt in 2020 (WSA, 2023). The production of steel is highly energy intensive. The dominant crude steel production route worldwide is the blast furnace-basic oxygen furnace (BF-BOF) route (WSA, 2023). It uses coke or coal to reduce the iron ore (in the BF), generating CO₂ process emissions which constitute the lion's share of emissions in steelmaking. Iron is then converted into steel in the BOF, where some carbon is absorbed to increase ductility. Secondary steel production, done via scrap smelting in electric arc furnaces (EAF), is by about 75 % less energy and emission intensive (Chiappinelli et al., 2021).

Cement

In terms of emissions and energy demand, cement is the most important sub-sector of the sector 'manufacture of other non-metallic mineral products.' Cement is a key material for construction of infrastructures and buildings as it serves as the 'glue' that gives concrete its stability. In 2022, globally 4.1 billion tons of cement were produced (CEMBUREAU, 2022). Emissions are estimated between 2.1–2.5 GtCO₂eq in 2019, making up 14–17 % of global industrial emissions, or 4 % of global total emissions (Bashmakov et al., 2022; IPCC, 2022). The production of cement is highly energy intensive. To produce one ton of clinker 1×10^{-6} TWh of energy is

needed (Material Economics, 2019). About 80 % of this energy is used in terms of thermal energy, the rest as electrical energy (Rahnama Mobarakeh and Kienberger, 2022). In Europe the most common production technology is the dry kiln technology, where high temperature heat (up to 1,500°C) is needed to decompose limestone (CaCO_3) into lime (CaO) and CO_2 . CO_2 emissions are mainly associated with clinker production and are occurring largely (60–70 %) in terms of process emissions. To provide heat, fossil fuels are used, with high shares of up to 80 % of (also mostly fossil) alternative waste fuels (Material Economics, 2019; Rahnama Mobarakeh and Kienberger, 2022).

Chemicals

The chemicals sector is very heterogenous in its processes and products. The most important processes in terms of climate mitigation are the production of ammonia, methanol, olefines (basic material for plastics production), nitric acid, urea and fertilizer (Alton et al., 2022). Particularly plastics, made from oil-based naphtha, are key products from the chemicals sector, which replaced less specialized traditional materials such as wood, metals, glass and cotton (Material Economics, 2019). The sector is highly energy intensive, with fossil resources as the dominant energy and feedstock source. Globally, the chemicals sector is responsible for 1.1–1.7 Gt $\text{CO}_2\text{eq/yr}$ (2019), which is 10 % of industrial emissions or 2.4 % of total global emissions (Bashmakov et al., 2022).

Paper and Pulp

For paper production, pulp, either from virgin wood fibers or from recycled material is needed. More than 90 % of demand is thermal energy, mainly for drying processes (Moya and Pavel, 2018; IEA, 2023). Pressurized steam is used for wood chipping, pulp production, cooking and drying (Bajpai, 2016), which is generated to a large extent from biomass, but also electricity and natural gas (Bashmakov et al., 2022; CEPI, 2023; IEA, 2023). The sector's emissions are mainly coming from biogenic CO_2 from feedstock, globally about 700–800 Mt/yr, and additional 200 Mt from fossil energy sources (Tanzer et al., 2021). The paper and pulp sector operates mainly at low temperature heat (<200°C) and is often equipped with combined heat and power units (Moya and Pavel, 2018), generating more than 50 % of its own electricity demand (CEPI, 2023).

Table 4.A. 1 Summary of mitigation options mapped into domains of Avoid, Shift and Improve (Sources: Pauliuk et al., 2013; Abdul Quader et al., 2016; Moya and Pavel, 2018; Chan et al., 2019; Material Economics, 2019; Zhou et al., 2019; Holappa, 2020; Fan and Friedmann, 2021; Alton et al., 2022; Rahnama Mobarakeh and Kienberger, 2022; Mowbray et al., 2023).

	Avoid	Shift	Improve
<i>Iron and steel</i>	- Material efficiency increase (lowering material use and extending lifetime of products) 48 % - Recycling with EAF [20 %]–87 % - Circular economy (product circularity) [35 %]	- Fuel switching to biofuel or electricity for heat demand [n/a] - Electrolysis for ironmaking (Ulcolysis, Ulcowin) [30–98 %] - Changing BF-BOF to DR-EAF with natural gas, syngas or methane [40 %] - Changing BF-BOF to DR-EAF with hydrogen [95 %]	- Energy efficiency improvement [15–20 %]; specifically for Austria: 6 % - BF-BOF with CCS 50 %–[80 %] - BF-BOF with CCU (in combination with biomass even negative emissions possible) - Hisarna with CCS [80 %]
<i>Chemicals</i>	- Material efficiency increase (lowering material use and extending lifetime of products [n/a] - Circularity (recycling) [n/a] - Circular economy (product circularity) [n/a]	- Electrification of compressors (in nitric acid production [80 %] - Electrification of heating systems (in urea synthesis) [90 %] - Electrification of steam production [90 %] - Electrification and use of waste heat [80 %] - Electrification of fertilizer production [n/a] - Methanol to olefin production (even negative emissions possible), with methanol being produced from hydrogen, biomass and (previously captured) CO₂ [45 %] - Low-carbon hydrogen-based ammonia synthesis [90–100 %] - Low-carbon hydrogen production of methanol [120 %] - Methane pyrolysis for hydrogen production, based on renewable electricity and biogas [90–100 %] - Urea from low-carbon ammonia and CO₂ [120 %] - Methanol production from biomass [120 %]	

<i>Paper and pulp</i>	• Fiber recycling [37 %] • Digitalization [n/a]	• Fuel switching, substituting NG by biomethane or H₂ [n/a] • Fuel switching, to biofuels combined with CHP [25 %] • Replacing fossil boilers by electric boilers [20 %] • Heat pump and waste heat recovery [40–90 %]	• Adoption of BAT, operational innovations, energy management [22 %] • CCS with biomass (BECCS) [98 %] • New drying techniques [20 %]
<i>Cement</i>	• Reducing clinker to cement ratio [process emissions: 10–30 % + decrease in fuel related emissions due to lower thermal energy consumption] • New binder material: Replacing clinker by new materials [40–100 %]; even negative emission possible	• Fuel switching from fossil fuels (coal) to biomass, waste [35–40 %] • Fuel switching to H₂; associated with technical challenges [n/a] • Switching to ‘cement electrolysis’ in combination with CCS/CCU • Electrification for heat generation, instead of fossil fuels [40 %] • Electrification for replacing combustion-based emissions, combined with CCS [95–100 %]	• Material efficiency and circular economic (optimization of cement use, recycling, increasing lifetime of buildings and infrastructure) [44 %] • Energy efficiency improvement and BAT [10–12 %] • Amine scrubbing-CCS [65 %] • Calcium looping-CCS/CCUS [95 %] • Oxyfuel-CCS [90 %]
<i>Other manufacturing</i>	• Longer lifetimes of non-energy-intensive equipment • Reuse of industrial components • Recycling of industrial byproducts and waste	• Electrification for low-heat generation • Combination of electrification and carbon-neutral gas for machinery and off-road vehicles in construction industry	• Cross-sectoral energy efficiency improvements in industrial support processes (e.g., lighting, heating) • Reuse and cascading of waste heat in industrial clusters

4.A.2 Appendix to [Section 4.5](#)**Table 4.A. 2** Climate change impacts on electricity demand and supply components in Austria (Fuchs et al., 2013; Hausl et al., 2014; Koch et al., 2016; Totschnig et al., 2017; Simoes et al., 2021).

Electricity demand or supply component	Change	Scenario period	Climate Scenario	Source	Geographical scope	Reference period
Hydropower	Between +4 and -4 %	2031–2050	Four representative climate simulations from the ENSEMBLES project	Wagner et al. (2017)	AT	Not applicable
Hydropower	-5 %	2021–2050	20 regional climate models	Fuchs et al. (2013)	Danube	Not stated
Hydropower	-12 %	2071–2100		Fuchs et al. (2013)	Danube	Not stated
Hydropower	Between -9 and -16 %	2036–2060	GLOWA-Danube REMO regional-baseline	Koch et al. (2016)	Danube	Not available
Hydropower	Between +5 and +15 %	2020–2040	Sixteen combinations of global and regional climate models	Simoes et al. (2021)	AT	1995–2014
Hydropower	Between +5 and +18 %	2040–2060		Simoes et al. (2021)	AT	1995–2014
Heating demand	Between -7 and -17 %	2041–2050	– DMI-HIRHAM5-ARPEGE – ETHZ-CLM	Hausl et al. (2014)	AT	1981–2010
Cooling demand	Up to +355 %	2041–2050	– SMHI-RCA-HadCM3Q3	Hausl et al. (2014)	AT	1981–2010
Solar power	Between 0 and +9 %	2020–2040	Sixteen combinations of global and regional climate models	Simoes et al. (2021)	AT	1995–2014
Solar power	Negligible	2040–2060		Simoes et al. (2021)	AT	1995–2014
Solar thermal, PV, ambient heat	Negligible	until 2050	– DMI-HIRHAM5-ARPEGE – ETHZ-CLM – SMHI-RCA-HadCM3Q3	Hausl et al. (2014)	AT	1981–2010
Solar power	Almost negligible	2051–2080	REMO-UBA RegCM3 Aladin-Arpege	Totschnig et al. (2017)	AT	1971–1989
Wind power	Almost negligible	2051–2080			AT	
Wind power	Between -4 and +4 %	2020–2040	Sixteen combinations of global and regional climate models	Simoes et al. (2021)	AT	1995–2014

Table 4.A. 3 Renewable energy potentials in Austria (and cost if available). Ordered in terms of technology and year.

Reference	Energy generation technology	Capacity density	Type of potential (e.g., technical)	Total potential ¹	Cost
European Commission, Joint Research Centre (JRC) (2021)	Biomass	Varying	Technical	29–72 TWh	
Baumann et al. (2021)	Biomethane	Varying	Technical	11 TWh ²	
Pöyry Austria GmbH (2018)	Hydropower	Varying	Technical	51 TWh (+11 TWh to current generation)	
Mikovits et al. (2024)	Solar PV – agri-PV	17–28 m ² /kWp	Technical agri-PV on 100 % of agricultural land	500–875 TWh	EURCent ₂₀₂₃ ~3.5–14/kWh
European Commission, Joint Research Centre (JRC) (2021)	Solar PV – ground mounted	170 Wp/m ²	Technical	63–223 GWp/62–218 TWh	
Kakoulaki et al. (2021)	Solar PV – ground mounted	5.5 m ² /kWp	Technical, only 3 % of agricultural land allowed	35 TWh	
Mikovits et al. (2021)	Solar PV – ground mounted	20 m ² /kWp	Technical on 100 % of agricultural land	1,614 TWh	
European Commission, Joint Research Centre (JRC) (2021)	Solar PV – rooftop	170 Wp/m ²	Technical	10–36 GWp/10–35 TWh	
Fina et al. (2020)	Solar PV – roof top	6 m ² /kWp	Economic competing with retail prices (i.e., self-consumption)	10 GW	Not stated
Kakoulaki et al. (2021)	Solar PV – rooftop	5.5 m ² /kWp	Technical	13 TWh	
Mikovits et al. (2021)	Solar PV – roof top	7 m ² /kWp	Technical	16 TWh	
Truhetz et al. (2012)	Wind power	Not documented	Technical	30 TWh	
European Commission, Joint Research Centre (JRC) (2021)	Wind power	Varying	Technical	11–62 GW/25–150 TWh	
Gass et al. (2013)	Wind power	Varying	Economic	26 GW	EURCent ₂₀₂₃ 12.53/kWh
Höltinger et al. (2016)	Wind power	Varying	Economic potential with stakeholder preferences	7–90 TWh	Supply curve

¹ Unless stated otherwise, the total potential is presented.² Additional potential to current use

BMK (2024)	Wind	Theoretical technical	228 TWh
BMK (2024)	Wind	Realizable (2030)	21 TWh

Table 4.A. 4 Costs of renewable energy technologies in Austria. Ordered in terms of technology and year.

Reference	Energy generation technology	Cost
Kost et al. (2021)	Biogas	EUR ₂₀₂₃ 94–248/MWh (LCOE)
BMK (2023)	Biogas	EUR ₂₀₂₃ 289/MWh (feed-in premium)
Kost et al. (2021)	Biomass	EUR ₂₀₂₃ 81–215/MWh (LCOE)
BMK (2023)	Biomass	EUR ₂₀₂₃ 170–227/MWh (feed-in premium)
Kost et al. (2021)	Photovoltaics	EUR ₂₀₂₃ 35–123/MWh (LCOE)
Kost et al. (2021)	Photovoltaics with storage	EUR ₂₀₂₃ 58–220/MWh (LCOE)
BMK (2023)	PV roof-top	EUR ₂₀₂₃ 107/MWh
		EUR ₂₀₂₃ 116/MWh (incl. integration costs)
		(LCOE)
BMK (2023)	PV ground-mounted grassland	EUR ₂₀₂₃ 93/MWh
		EUR ₂₀₂₃ 102/MWh (incl. integration costs)
		(LCOE)
BMK (2023)	PV ground-mounted agriculture double use	EUR ₂₀₂₃ 106/MWh
		EUR ₂₀₂₃ 115/MWh (incl. integration costs)
		(LCOE)
BMK (2023)	Run-of-river hydropower	EUR ₂₀₂₃ 111–174/MWh (feed-in premium)
Kost et al. (2021)	Wind	EUR ₂₀₂₃ 44–93/MWh (LCOE)
BMK (2023)	Wind	EUR ₂₀₂₃ 75/MWh
		EUR ₂₀₂₃ 84/MWh (incl. integration costs)
		(LCOE)

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