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The Economic Effects of Achieving the 2030 EU Climate Targets in the Context of the Corona Crisis

An Austrian Perspective

Karl W. Steininger, Jakob Mayer, Gabriel Bachner, Samuel Duelli, Elisabeth Frei, Wolf Grossmann, Raphaela Maier, Stefan Nabernegg, Keith Williges, Wolfgang Streicher, Fabian Ochs, Mara Magni, Alice Tosatto, Elisa Venturi, Alexander Passer, Helmuth Kreiner, Marco Scherz, Barbara Truger, Johanna Vogel, Ivo Offenthaler

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The Wegener Center for Climate and Global Change is an interdisciplinary, internationally recognized research and graduate education institute of the University of Graz that is pooling the University's expertise in Climate, Environmental and Global Change. It brings together research teams and scientists from fields such as geophysics and climate physics, meteorology, economics, geography, and regional sciences. At the same time close links are maintained and further developed with many national and international cooperation partners. The research interests range from monitoring, analysis, and modeling of climate and environmental change to the investigation of climate change impacts and the analysis of the human dimensions of these changes related to mitigation, adaptation, and loss&damage. (more information at www.wegcenter.at)



Alfred Wegener (1880–1930), after whom the Wegener Center is named, was founding holder of the University of Graz Geophysics Chair (1924–1930). In his work in the fields of geophysics, meteorology, and climatology he was a brilliant scientist and scholar, thinking and acting in an interdisciplinary way, far ahead of his time with this style. The way of his ground-breaking research on continental drift is a shining role model – his sketch on the relations of continents based on traces of an ice age about 300 million years ago (left) as basis for the Wegener Center Logo is thus a continuous encouragement to explore equally innovative ways: paths emerge in that we walk them (Motto of the Wegener Center).

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Lebe jetzt die Fragen. Vielleicht lebst du dann allmählich,
ohne es zu merken, eines Tages in die Antwort hinein.
Rainer Maria Rilke

Wir brauchen einen ganz anderen Mut!
Stefan Zweig

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Executive Summary

Steering the comprehensive and truly fundamental transformation is happening now

The overall global and EU economic framework has changed

In December 2020 the European Council agreed to increase the ambition of the EU 2030 climate target from the previous level of 40% of greenhouse gas emissions reduction by 2030 to at least 55% (relative to 1990). This comes at a time when low carbon and circular economy developments have become extremely dynamic around the globe. For example, in its December 2020 Net Zero Path Report, the UK Committee on Climate Change identified a significant decline in climate mitigation costs compared to that of its 2019 report, and consequently recommended a 78% greenhouse gas emission reduction by 2035 (relative to 1990) for the UK, markedly more ambitious than its 2019 recommendation. Based on this report, the Committee's director of analysis Mike Thomson concluded: "This program is going to boost activity and boost employment across the economy. […] We simply don't need fossil fuels to access cheap energy anymore. Any notion that we can't afford to tackle climate change is clearly nonsense" (RenewEconomy, 2020). Thus, while previously the focus has often been on the costs of greenhouse gas mitigation, the perspective has changed towards concern as to missing out on opportunities if an industrialized country like Austria does not actively participate in and shape this transformative development, and in this case could end up at a comparative disadvantage in economic terms – relative to other European countries as well as globally, endangering the country's strength as an industry location.

Against a range of uncertainties there are many win-win options in climate change mitigation

But other developments are also possible. If longer-term EU climate targets turn out to be unreliable and are not met, implementing them early will only pay off if such alternative developments have been carefully considered. Climate policy is a field of decision-making under uncertainty. Globally and in the long-term, climate change impacts (both observed and foreseen to substantially increase) constitute a strong indicator for ultimate global action in climate change mitigation. Yet, the speed of this global action is unknown. For Austria, there are many options in climate change mitigation that turn out to be win-win situations (both environmentally and economically) even under a wide range of EU and global developments.

Shaping the future: An analysis of required framework conditions and economic implications

This report spells out in detail how such a fundamental transformation could take place across all sectors, in terms of technologies, time scales, and measures, and emphasizes the necessary framework conditions to enable such a transformation. It then focuses on the respective economic implications of such pathways, in particular in the economic aftermath of the Corona crisis.

Overview: fourfold content of Executive Summary

This Executive Summary condenses the main findings of the report. It first sheds light on the changed global setting, then summarizes the core ingredients of an Austrian strategy, and, most importantly, prerequisites to be set, before macroeconomic implications are highlighted.

With a rich set of attractive solutions available the global transition framing has switched

An array of complementary and attractive solutions has become available

Promising climate change mitigation options have become available across the board, from organizational (e.g. new business models) and institutional (e.g. green banking regulations) to technological (e.g. breakthrough technologies, new materials and applications) and behavioral (e.g. climate friendly diets). Naming just a few breakthrough technologies, we are currently witnessing a tremendous decline in the cost of batteries in combination with much cheaper renewable electricity, additive production (3D-printing), automated driving, and blockchain technology employed in multidirectional energy markets. Neither of these developments will contribute to a climate neutral development by themselves or under currently lacking (institutional) framework conditions, but can strongly support and possibly only enable carbon neutrality, if well directed. We witness corresponding developments in behavior (e.g. the car no longer exists as a status symbol for most in younger generations), organizational developments (e.g. car sharing flourishing among an engaged population even in rural areas) and institutions (e.g. BlackRock, among the world's largest institutional investors, has turned its back on companies that don't conform to sustainability, fueling the so called "Great Reset" in capital markets). These developments bear huge potential for climate change mitigation and welfare enhancement. Markets have very visibly begun to reflect these upcoming transformations and the risk of stranding of fossil fuel-based assets.

Fundamental changes have repeatedly led into progressive socio-economic development

Fundamental socioeconomic changes develop in a well-known pattern visible in history. The 'Great British leap' in the 18th century, the 'Victorian Boom' in the early 19th century, the 'Belle Époque' of Europe, the 'Progressive Era' of the US in the late 19th century and the post-war golden age of mass production and the US-led revolution in ICT – all of them started with an 'installation period', where niche developments led to the questioning of accepted customs. In these situations, distress and disruption prevailed and many societal actors were set adrift, fighting the new and desperately looking for guidance. A critical mass built up, pushing society to a new turning point. The ensuing 'period of deployment' led to thriving societies. This rich history indicates that the current situation appears to be another such turning point, ushering in a green and thus-directed digital future. How consistently and stably a society can succeed in it – and at whose benefit and for what cost – clearly depends on the framing. For its successful implementation, such framing needs the broadest possible basis, with co-development by all concerned groups of actors.

Responsible dialogue between all stakeholder groups concerned - far beyond the traditional discussion - is an essential prerequisite

The transformation task is enormous. It can be solved by bringing together all the different perspectives and facts from which good and innovative solutions will emerge. The focus in such dialogues needs to be on the solution, and while not getting stuck on winners and losers, paying attention to the distribution in the solution.

A traditional discussion format, as it usually aims at a competition for the better arguments, leads to winners and losers and only one or a few who prevail. However, we do not find solutions by looking back and trying to preserve what already exists, but by looking forward and courageously allowing new things to happen. To do this, we need well-prepared and responsibly designed dialogue platforms (forums of stakeholder engagement). In this regard, we can build on a tradition of best practice

examples in Austria. For example, the scientific community has been initiating such dialogues on national issues since the mid-2010s, e.g. in the context of EU-funded Horizon 2020 research projects, with the involvement of all stakeholder groups concerned. Many shared "aha" experiences have led to new approaches to solutions. Such dialogues enable diversity and lead us all out of classic "silos"; in them, it is important to ensure a high quality of exchange and a certain commitment and thus co-responsibility of all participants. By structuring this exchange in such a way that solutions emerge, it becomes clear that it is the genuine dialogue between all those involved that facilitates change or makes it possible in the first place, also in terms of awareness and mutual understanding, especially in terms of how otherwise losers are dealt with. And it is this mutual understanding above all that is needed here.

A comprehensive strategy emerging from a holistic dialogue approach can ensure solutions and form the basis for a successful transformation

A comprehensive strategy starts from a holistic focus on needed or desired services

Austria will not reach enhanced climate targets simply by wishing it. Utmost focus of governments at each level (federal, provincial, municipal, and accommodation at the European level) as well as of all societal actors is required to scale up policy across every sector. To be successful, a set of instruments not only has to address

- avoiding activities where substitutable,
- shifting remaining activities to environmentally benign structures and
- improving the emissions balance of the latter ones,

but it must be the result of an overall strategy, comprehensively addressing the substantial transformation challenge. Such a strategy necessarily has to adhere to

- inverse argumentation that starts from the very service (or functionality) we are actually requiring for satisfying our human needs (i.e. to no longer focus on supplying energy, but on the ultimate service we seek, e.g. access to goods or people, and the ways this can be supplied),
- integrate the different options to supply these services, to allow for flexible and lucid choices (e.g. by establishing intermodal hubs, rather than addressing all transport modes separately) and
- innovate along the whole (possibly international) economic value added chain (e.g. by taking advantage of digitalization in managing variable renewable supply, storage, and demand management), thereby overcoming any end-of-pipe only solution approach.

Focus of this report is on industry, energy, buildings and transport

In Austria, certain sectors do have an outsized contribution to the greenhouse gas (GHG) emissions balance, and thus we focus on them and their interaction in particular. We focus explicitly on industrial, energy, building and transport sector emissions, as these together accounted for nearly 90% of total Austrian GHG emissions in 2019, and on these sectors emission intensive activities in particular. For the necessary direction of available measures across these sectors see Chapter 4, for their detailed implementation in the model analysis see Chapter 5.

Economic implications crucially depend on whether Austria can put in place the required framework conditions before the window of opportunity closes

Barriers keep us from flourishing via the transformation

While many climate-benign options have become available cost-efficiently, the required up-front investments are still subject to implementation gaps, such as misperceptions of future savings, renter-owner differences in incentives to invest, or financial, institutional or knowledge barriers, unclear responsibilities or vested interests. When conquered due to new framework conditions, this investment would come with ongoing savings in fuel costs, and a range of sustained benefits: reduced overall operating cost, reduced emissions that benefit health and the environment, intangible benefits such as higher living comfort due to new building standards, and a strengthening of the industry location Austria.

Framework conditions are crucial

We thus find that the economic implications of such a transformation crucially depend on the process and content of how the economic and energy policy framework is now set (spelled out in detail below). We further find that the Corona crisis opens a window of opportunity where stepping up the climate target can address both crises and comes at much lower costs, compared to a sequential addressing or to a situation without the current economic underutilization of productive capacities. Conversely, if recovery measures contribute to an even further fossil lock-in, social costs would rise significantly.

Setting the adequate prerequisites is indispensable

The core transformation steps in industry, commerce and society cannot be successful if the required framework conditions are set too late or not at all.

Prerequisites for the industry transformation

In climate neutral industrial development, Austria can be successful in economic terms, if and only if

- reliable medium and long-term framework conditions on climate and energy are set, which allow for sound managerial decision-making

Only then are climate-benign decisions also economically sustainable (and thus possible). This includes

- stable carbon market framing and predictability, based on comprehensive planning, acknowledging the EU internal market as well as international competitiveness,
- reliable renewable energy (in terms of availability, security, affordability and price reliability, the latter e.g. by the establishment of carbon contracts-for-difference to fund CO_2 market price differences relative to a previously set pathway),
- expansion of infrastructure (in particular for electricity, green gas, hydrogen), including the timely establishment of a needed regulatory and legal framework for such infrastructure expansion, and
- creation of markets for green products.

Based on these framework conditions,

- dialogue fora for common development of circular economy implementation need to be operated to enable coordination of value-added chains across different (also legal) economic entities.

Recognizing that the climate policy challenge is a public good problem with free riders that cannot be solved by the market under insufficient framework conditions, innovation needs to be fostered in a competitive environment in the transition phase with

- public funds, such as an Austrian Industrial Innovation and Transition Fund (AIITF), which can exploit a leverage of both private investors and EU funds for significant up-front investments. Such a fund should also support investments in new industrial facilities necessary to produce new, 'greener' products at scale using new, climate-friendly production processes.

To foster the development of Austrian leadership in emerging low-carbon technologies, the entire set of innovation and export policy instruments should be employed as appropriate,

- from an expansion of existing R&D subsidy programmes and additional tax incentives for climate-neutral R&D as well as start-up funding in this area,
- via continuous updates to the regulatory framework, including to technology standards, to ensure it supports low-carbon innovations and their diffusion,
- to strengthening the best-bidder principle in public procurement as well as export promotion instruments and international networking initiatives, especially those targeting small and medium-sized enterprises in low-carbon technology fields.

Prerequisites for the energy transformation

If the energy transformation is to be achieved within the envisaged time horizon, energy market regulation needs to be established to both

- address demand and
- to include adequate incentives to substantially enhance renewable supply across all energy carriers required (electricity, green gas, hydrogen),

and

- the respective infrastructure for generation, transmission and/or storage needs to be not only put in place in time, but also available in a spatially-specific manner at the very industrial production locations relying on it.

Austria needs to

- develop and follow a clear strategy of reliable renewable energy supply based on the two complementary sources of origin, domestic and foreign.

As in particular seasonal variation of solar cannot be adequately compensated by other renewables, not only domestic storage is crucial, but also a strategy based on energy trade, including foreign supply of direct (electricity) or indirect (e.g. hydrogen) solar energy to Austria (and corresponding exports). This has to be settled early and to be adjusted to the respective European and global efforts to allow for the necessary planning reliability.

Prerequisites for the building transformation

Given the overall limits of domestic availability of renewable electricity and (district) heat and in light of the competing further demand for it, notably by industry and transport, thermal renovation of buildings is indispensable to achieve the overall climate targets, as this report shows. Also, the change from gas- or oil-based heating systems to heat pumps is

(often) only technically feasible in combination with deep thermal renovation and generally only recommended in combination with it. However, with increasingly carbon-free electricity and district heating and a mere physical carbon accounting, the incentives for deep renovation decrease, which thus have to be implemented by adequate direct regulation (respective coding or incentives for deep renovation).

The success of shifting the building sector to climate neutrality depends on

- a clearly stated, reliable and long-term strategy including specific milestones and a well-defined timeframe to serve as a basis for actors in the sector. This needs to include incentives to develop technological solutions to replace (decentralized) oil and gas and e-boilers with renewable energy sources or heat pumps across all application areas. Such incentives must overcome economic investment barriers for rented buildings or flats, address ownership structures of mixed housing with multiple owners, and overcome the financing barrier due to immediate upfront investment but only long-term energy cost savings. For example, an overall surcharge could finance a private household investment subsidy fund.
- New buildings need to be built to a higher energy efficiency standard than currently required. A change in domestic standards is necessary to reduce the energy demand of new buildings (net zero energy buildings standard or passive house level).
- Comprehensive (i.e. deep) refurbishment needs to increase significantly (achieving the highest possible reduction in (external) energy demand). For the full phase-out until 2040, the change of the remaining fossil-based systems needs to be compulsory, and the initialization of that path needs to start now.
- All surface areas with sufficient solar radiation (roofs, building surfaces) need to be taken advantage of for photovoltaic systems installations.
- Actors in the building sector need to be incentivized to not only reduce buildings' operational emissions and energy demand, but also to reduce embodied emissions in building materials and components under a life-cycle perspective.

Prerequisites for the transport transformation

The

- development and implementation of effective energy- and transport- (and thus cost-) saving spatial planning

is as crucial as

- a revision of the direct incentive system, choosing an adequate combination of economic, command and control and information policies that ensures climate neutrality (from a reform of counterproductive support measures, via price and registration regulation instruments, up to public awareness).

For the shift in the vehicle stock, the phasing out of fossil-fueled combustion engines and simultaneously phasing-in of alternative vehicles demands

- an extension of adequate infrastructure.

Relevant policy has to

- provide incentives to investors to allocate capital, with various financing concepts available, e.g. direct support from public spending, or private-public-partnerships (PPPs) in infrastructure construction.

With a reframed financial system that fosters the integration of aspects such as Environmental Social Governance (ESG) considerations in a consistent manner, new – and in the long-term reliable – sources for financing the transition would become available for both transport and building infrastructures, with the latter at least as strong as the former governing mobility patterns. Such new sources are even more crucial as certain tax revenue components (such as excise tax on fossil fuels, 'Mineralölsteuer') will decline if the current tax system prevails.

Preconditions in the European and international context

Austria cannot solve the transition to a net-zero-emission future on its own. Beyond the obvious field of international regulation, aviation, for example in road transport vehicles of foreign freight companies account for more than half of the ton-kilometers driven in Austria. A strategy in which other countries are not involved will lead to inefficient investments and infrastructure development. Hence, a common strategy on at least a regional level (with neighboring countries), or better on a European level is needed.

For industry, which is exposed to international competition, an internationally-uniform greenhouse gas price would provide sufficient legal and planning security. Without such a price, a combination of measures would be required. First, at the EU level, measures such as carbon pricing at the EU's external border relating to production outside of EU borders (administratively easiest might be free carbon allowances within the EU, but relating to declining certificate quantities and implied rising costs a thus accommodated supplementary Carbon Border Adjustment Mechanism), as well as market access rules for products and related international agreements need to be foreseen. These could be supplemented at the national level by e.g. creation of markets for green products, export or investment promotion or differential compensation for energy costs. For energy- and/or emission-intensive industries, the availability of renewable energies and compatible substitute fuels needs to be ensured – both at the EU level (internal energy market) and at the national level through corresponding strategy implementations, infrastructure investments and international agreements.

The specification of the full list of prerequisites – beyond their summary here – against the respective background is given in Chapter 7.

In the following, we analyze the economic implications of such a transition. *Throughout we presuppose below that adequate framework conditions have been set as a prerequisite in due time.*

Economic implications of stepping up the EU 2030 Climate targets are manifold

Stepping up climate targets is connected to impacts enhancing economic activity…

Stepping up the European 2030 climate target and seeking to achieve climate neutrality by 2040 for Non-ETS sectors (transport, agriculture, waste, low-energy intensive production) and by at least 2050 for sectors regulated at the European level (energy and energy-intensive industry) involves a transition that implies a multitude of short- and long-run effects on the Austrian economy.

While – if wisely set – the transition will unambiguously enhance welfare (in both the narrower consumption definition but also in its broader meaning of e.g. comfort and health benefits), a range of effects tends to also enhance immediate economic activity, most notably:

- The (quicker) switch to a renewable resource base reduces the substantial amount of fossil energy imports (currently about € 8 billion/anno[1]) and shifts expenses for energy services to additional domestic value added.
- The transition fosters a modernization and sustainability-directed digitalization of the economy, enhancing both productivity and international competitiveness.

Such a transition requires a substantial amount of directed additional investments. If such investment does not fully crowd out other investment – especially in a post-Covid situation of strongly underutilized capacity, crowding out will be very low, if it exists at all –

- such investment will create additional value added, employment, and respective household income already in the short-term.

...as well as to such reducing

Correspondingly, other effects tend to reduce domestic activity (and possibly welfare during a transitional phase), such as:

- At the firm level, enhanced investment expenditures and possibly rising unit cost for energy may in the short-term result in reduced international competitiveness and thus challenge exports beyond the EU. An adequate policy framework can mitigate these losses, especially competition with foreign (not climate friendly) supply on markets within the EU, e.g. by appropriate EU level border carbon adjustment policies.
- At the household level, higher low-carbon investment (e.g. higher expenses for renovation of buildings) increases credit expenditures and in that respect reduces consumption temporarily. Possible energy poverty or otherwise regressive policy implications can be avoided, e.g. by adequate transition/bonus funds or refund schemes.
- The restructuring of the electricity sector might lead to a higher electricity price, which could reduce household consumption in the short term. Adequate market regulation (e.g. low-priced base demand) can avoid unintended distributional consequences.

These various economic implications and effects all work simultaneously, and partially in opposite directions, and work differently at the firm, sector, household, national and global level, as well as differently in time. Most notably we expect positive effects to unfold sustainably in the long term, whereas negative economic effects are likely to be more relevant in the short term. This could imply a trade-off of consumption possibilities across generations.

Therefore, a dynamic, multi-sector, multi-regional macroeconomic modeling approach has been employed to shed light on the respective quantitative relevance of each of these forces and the resulting net overall implications.

[1] If not indicated otherwise, all monetary values in this report are given at the price basis 2018, i.e. in $€_{2018}$.

A scenario approach for the quantification of economic effects is applied

To evaluate the macroeconomic effects of increasing the stringency of climate mitigation targets in the EU and especially in Austria, we utilize a scenario approach. In this study we make use of two main scenarios. First, we construct a baseline grounded in the former EU policy of 40% emissions reductions by 2030 compared to 1990 (and, crucially, also incorporating estimated effects of the recent pandemic on near-term growth and economic activity). Second, resembling the recent target revision of the EU council, we establish an enhanced scenario, which examines the changes necessary to reach an at least 55% EU-wide emissions reduction.

The "EU40" Baseline scenario

The "EU40" Baseline scenario describes the evolution of the economy under existing measures and trends (see Chapter 5 and the Appendices C to H for full details) and includes climate policies to reach both the EU 2030 target of greenhouse gas emission reductions of -40%, relative to 1990 and Austrian climate neutrality by 2040.

The "EU55" Enhanced scenario

The "EU55" enhanced scenario builds upon the EU40 Baseline in terms of generic socio-economic parameters but adds on top a multitude of additional and earlier climate change mitigation measures and strengthens existing policies. We further differentiate the EU55 Enhanced scenario in the following way:

a. EU55-seq: policy measures in response to the Covid-19 crisis and to the climate crisis are implemented sequentially; i.e. starting with generic economic stimulation measures and only later implementing specific enhanced climate change mitigation measures.

b. EU55-sim: enhanced climate change mitigation measures are at the same time policy measures in response to the Covid-19 crisis, i.e. measures are implemented simultaneously. This setup describes the strategy to channel the now available large amounts of (public) funds into climate-neutral investments, rather than into sole and generic economic stimulus.

Enhanced climate-oriented investment can address both the economic and climate crisis

Aligning private and public investments after Covid-19 addresses the climate and economic crises

Austrian actors are preparing and advancing low-carbon solutions (e.g. electrification, hydrogen-based production, and circular economy approaches). Stepping up the European 2030 climate targets implies an earlier implementation of these mitigation options. Economy-wide macroeconomic simulation shows that this is connected to significant economic implications. The direction is governed by the relevant framework conditions and the current window of opportunity. With the post-Covid recession, it is expected that at least for the early transition years of such an upscaling, no relevant crowding out of investments will take place, as production facilities are underutilized and financial investors seek (green) investment projects.

Automatic economic stabilizers (e.g. unemployment benefits, ad valorem tax revenues, etc.) lack comprehensiveness and profoundness to address this underutilization. Hence, governments step in by bolstering effective demand in order to ameliorate the worst effects of unprecedented lock-down measures. Such public investment – even more so at the high levels which occur – is only justified economically if it fosters long-term

sustainable structures, and thus needs to be channeled into climate neutral (infra)structures and away from fossil energy. Thereby policy can do best when addressing both crises at the same time – the climate and economic crises.

A combination of indicators is used to shed light on overall implications

Over the last decades mankind has learned that not only labor and production capital create value added and welfare, but that human wellbeing also crucially depends on the quality of natural services (ecosystem services, such as productive use of natural resources and amenities enjoyed)[2], yet one main economic indicator, gross domestic product (GDP), still only reflects the former. As a consequence, if economic resources are devoted to improving or maintaining environmental quality (or reducing environmental costs), as climate mitigation is, or enhancing non-marketed services (higher comfort in renovated buildings) this will increase *actual* productivity (enhancing environmental and comfort services). But when measured against the traditionally defined GDP, it might *reduce* productivity, as then some additional output or value is not reflected. In the following we nevertheless do utilize GDP as one indicator, because it is strongly correlated with employment, but also because it is still used broadly in public discussion. We stress, however, to be careful in its interpretation. And we complement our analysis with a welfare indicator that seeks to more comprehensively depict welfare dimensions neglected by GDP.

Temporary window of opportunity turns transformation costs into benefits

For an EU55 consistent climate policy in Austria (and relative to a scenario where we remain on the former policy trajectory of 40% emissions reduction by 2030), macroeconomic model simulation indicates a higher GDP for Austria in the mid-2020s due to an earlier investment cycle (see Figure ES.1, solid green line). The increase is also due to post-Covid underutilization of capital, which can be activated by stimulus. If (hypothetically) full crowding out would be assumed (dashed green line), traditionally measured GDP would decline. This implies that the current recession provides a framework under which climate-friendly investments are particularly connected to additional and near-term high economy-wide benefits, clearly visible also in terms of GDP. Note that our comparison scenario EU40 (as well as EU55) includes climate neutrality in Austria by 2040. Relative to EU55, the comparison scenario EU40 would thus have larger climate-relevant investments in the 2030s. With earlier climate policy (EU55) some of these investments occur sooner (i.e. already in the 2020s), with the thus implied additional economic activity of this fraction occurring already in the 2020s rather than in the 2030s (solid green line). In the period thereafter – starting in 2040, with less investment difference – accumulated learning effects of early European (ETS) and Austrian (non-ETS) implementation and lower operating costs of climate-friendly technologies imply a GDP higher than in the EU40 scenario.

[2] Complementing the influential Stern Review on the economics of climate change, published in 2007, in 2021 "The Economics of Biodiversity: The Dasgupta Review" (also commissioned by the UK government) has become available, and is discussed in the field to be of at least the same level of relevance (Dasgupta, 2021).

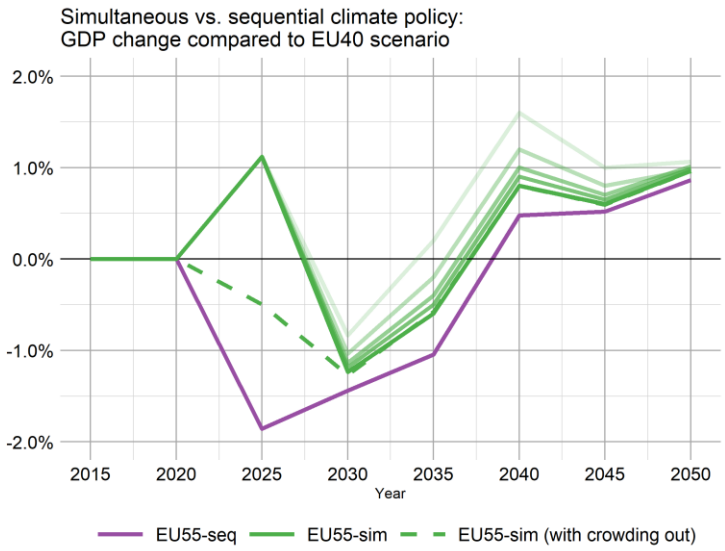


Figure ES.1 Economic impacts of EU55 climate policy in Austria, GDP (traditionally measured, not reflecting environmental and non-market productivity gain) deviation relative to EU40 development (used here as reference) under simultaneous policy (solid green line), with less than the most conservative parameter settings (fading colored green lines), with hypothetical full crowding out (dashed green line), and under sequential policy (purple line).

Sensitivity analysis indicates rising economic activity throughout the transition period

For the main EU55 quantification (solid green line) we have chosen parameters such as to report a conservative estimate, e.g. high-cost carbon-neutral technologies with learning rate parameters below what our literature review finds, or energy efficiency gains at the low end of the spectrum. Changing any of these assumptions results in higher (traditional) GDP estimates, particularly so later in the transition phase (fading green colored pathways in Figure ES.1).

The macroeconomic evaluation applied studies the effects of a deviation of EU55 policy scenarios from a baseline scenario EU40. Put differently, the depicted EU55 deviations to EU40 (as shown in Figure ES.1) occur on top of the economic development under EU40. The EU40 development itself is connected to substantial uncertainties, not the least due to the pandemic and its aftermath. Sensitivity analysis shows that qualitative results of the deviation between EU55 and EU40 are robust to a range of different possible baseline (EU40) growth assumptions.

In Figure ES.2 we show one possible GDP development of EU40 and how EU55 deviates from it. This *absolute* development of Austrian GDP is depicted for a rather conservative baseline scenario (EU40) and contrasted with GDP of the EU55 simultaneous policy scenario. Table ES.1 indicates respective annual growth rates including "x_i" as an expected positive addend capturing a range of possible EU40 baseline scenarios. The longer-term growth rates are taken from the IIASA Shared Socioeconomic Pathway (SSP) database. Under current expectations of moderate trend growth – and under the condition that the prerequisite framework conditions are met – the stricter target of EU55 involves a short- and long-term boost for Austria's real GDP. Note that for EU55 some of the growth occurs earlier than otherwise, which becomes visible in higher GDP up to the late 2020s, where climate change mitigation ambition of EU55 is higher than in EU40. This is followed by a period in

which ambition is relatively lower in EU55 (as compared to EU40, with some of this periods EU40 investments having been advanced to the 2020s already under EU55), and again with long term gains of choosing EU55 instead of EU40. In a nutshell, this shows that higher ambition means higher GDP, even in its traditional form, if the adequate framework conditions for climate policy are set.

The deviation in economic activity due to advanced climate policy

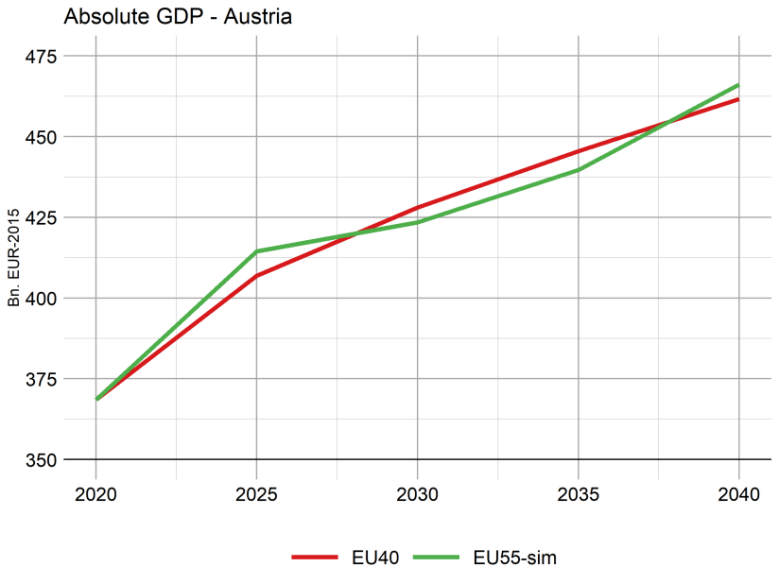


Figure ES.2 Gross domestic product – conservative baseline (EU40) development and deviation due to EU55 pathway.

Table ES.1 Annual GDP growth rates (x_i indicates post Covid-19 and long-term uncertainty)

Period	EU40	EU55-sim
2021-25	$x_1 + 2.0\%$	$x_1 + 2.4\%$
2026-30	$x_2 + 1.0\%$	$x_2 + 0.4\%$
2031-35	$x_3 + 0.8\%$	$x_3 + 0.8\%$
2036-40	$x_4 + 0.7\%$	$x_4 + 1.2\%$

These GDP pathways hold for the case of a simultaneous climate and economic policy package in the aftermath of the Covid-19 pandemic.

Postponing climate policy action is unwise and expensive

Sequential action is costlier because only a shorter time frame would be available for achieving the same stricter target and investments in long-lived emission-intensive capital stock would bear the risk of stranding (Figure ES.1, solid purple line). From a national perspective, these results indicate that a simultaneous implementation of climate mitigation measures and Covid-19 response measures clearly outperform a sequential strategy throughout the modelled time horizon from now until 2050.

Contributions to macroeconomic development differ by sectoral policies

Exploring the deviation of the Austrian wide GDP development (from its EU40 development) under an enhanced policy in single sectors only, we find that the policy package for electricity is associated with additional positive GDP impacts, particularly during the recovery. While the unit-

cost of electricity slightly increases with stricter targets, a set of further components including increased energy efficiency and more rapid structural change dominate and cause GDP (even in traditional definition) to rise. The retrofitting of cement facilities with carbon capture applications happens more rapidly than in the EU40 baseline, provides a by-product hydrocarbon to other industries, and generates positive contributions to the recovery. Relative to the EU40 scenario, following the EU55 pathway implies that part of the positive GDP effects are advanced already to the 2020s, such that the positive effect in the 2030s is then only somewhat smaller.

In non-ETS sectors the policy package in buildings can take advantage of underutilization (with an even higher GDP in mid 2020s), while the only policies modelled in the transport package (infrastructure and vehicle stock investment) also net-increase transport cost. For a detailed discussion of sector results see Chapter 6.

A stricter climate target performs better also in terms of traditional GDP

Macroeconomic model simulations support the availability of cost-efficient climate mitigation. We here compare the cumulative GDP effect of the measures connected to the EU55 target for the period 2020-2050 with measures for achieving the earlier European target of 40% emission reduction by 2030. As stated above, only if necessary preconditions are set (i.e. availability of renewable energy at sufficient levels and competitive prices, fair market access or border adjustment rules as long as no globally uniform CO_2 price is guaranteed, national framework conditions for transition) can such a path become reality, resulting in annual Austrian GDP rise, which until 2050 is on average +0.2% higher per year.

Stepping up the climate target comes with significant co-benefits

Climate policy comes with a range of welfare improvements. For example, enhanced building quality raises living comfort, more active mobility implies significant health benefits (increased biking and walking reduces incidence of illness, in particular cardiovascular illnesses), and electrolysis improves steel quality – even beyond the directly intended benefit of climate change mitigation. Most of these co-benefits are difficult to measure or transform to a uniform indicator, including a monetary one. However, in one area of co-benefits, air quality improvements, such a harmonized measure is available from comparatively robust quantifications. We therefore indicate the order of magnitude of co-benefits of climate policy due to concurrently induced air-quality improvements; more specifically, only the health benefits implied. As shown in Figure ES.3, air quality health co-benefits amount to at least annually €0.8 bn. (1 bn.) by 2030 for EU40 (EU55) policy and rise to €2 bn. by 2050. The earlier co-benefits of bringing forward climate policy are clearly evident in the 2020s and 2030s, as climate neutrality is also assumed in the EU40 scenario.

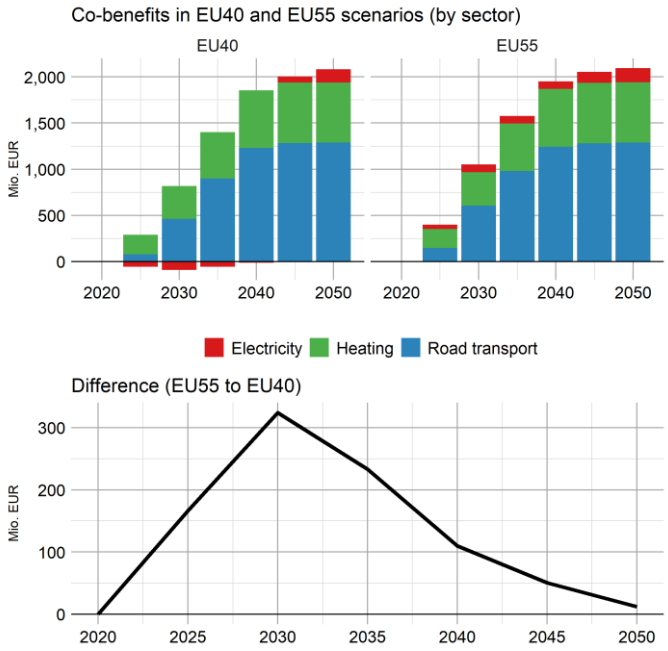


Figure ES.3 Air quality health co-benefits of EU40 and EU55. Top row: absolute by sector. Bottom: absolute difference EU55 relative to EU40.

A stricter near-term climate target avoids expensive fossil lock-in in the buildings sector and enhances technological leadership in Austrian strongholds

With the former EU40 target translated to the buildings sector in Austria, a lock-in of fossil-fuel-based heating systems would likely have taken place. Achieving a decarbonized buildings sector by 2040 would then come with (massive) additional upfront investment and stranding of capital assets as in 2030 fossil fuel-based heating systems would still be maintained and would need to be replaced before their end of life in 2040. Targeting net carbon neutrality in Austria's building sector by 2040, reduction measures must start without delay and with "2040-ready" components. The more stringent EU55 scenario is consistent with this 2040 target and avoids the additional post-2030 costs of a fossil lock-in of the buildings sector.

Competitive advantage in decarbonizing technologies for buildings

With the decarbonization of the buildings sector in Austria, the deployment of technologies such as low-carbon building components, heat recovery and heating systems will become necessary. In all of these areas Austria has already built-up a competitive advantage and with a more stringent policy target, could further strengthen its position on the international market. While for structural building components necessary technologies are already on the market, there is a need especially for development of small, decentralized heat pump systems for apartments in multi-family houses (including ventilation, heating, cooling and domestic hot water production) as well as large scale heat-pump systems. In the EU55 scenario, such technological solutions will be demanded in large quantities within the next few years. Investing in the development of such technologies would allow Austria to not only supply to its own domestic demand but could generate a technology leader position on the international market.

Austria is well-positioned in key low-carbon technologies to exploit new export opportunities

Strongholds in rail technologies, steel and cement industries, and buildings technologies

An analysis of Austria's current performance in emissions-reducing innovations and related export fields shows that the country can build upon areas of strength not only in buildings technologies, such as heat pumps, bioenergy combustion, nearly zero-energy buildings or passive houses, but also in rail transport as well as low-carbon technologies for the steel and cement industries. In these areas, Austria is well-positioned to exploit new export opportunities that more stringent climate targets create by increasing international demand for climate-neutral products and processes. In other key transition technologies, targeted innovation and export policy instruments should be considered to maintain or further develop Austria's international competitiveness. Examples include electric vehicle technologies such as batteries and charging technologies as well as energy generation from solar PV and wind.

Renewable electricity presents global challenges for Europe and at the same time offers opportunities in digitalization and green industry development

Demand for renewable electricity rises significantly in Austria

During the transition towards climate neutrality, many areas of the Austrian economy will be undergoing an electrification (mobility, heating, electrolysis-based hydrogen for industrial use, etc.). With a current (2019) national electricity demand at 72 TWh, our analysis shows that by 2030 electricity demand in Austria will rise by 17 to 20 TWh, plus the significant demand for new routes in industry and for domestically-produced hydrogen for Carbon Capture and Use processes. Each of the latter could add an equivalently sized additional demand on their own. For these latter industry sectors, and starting the analysis from the final service supplied, it quickly becomes evident that there are many options to achieve climate neutrality. Ceilings in buildings, for example, due to lucid shuttering formwork can be produced with 40-60% less concrete (and thus cement), while increasing bearing strength and offering additional functionalities as activated building components for energy storage (which allow new fields of generation of value added for respective enterprises). If a significant share of the (global) climate neutrality in these sectors is based on (renewable) electricity – and if Austria takes advantage of its position to acquire an over-proportional share of it (i.e. if the current strong competitive position in branches like steel and cement is safeguarded) – domestic demand for affordable (industry competitive) renewable electricity will clearly exceed domestic supply in a fully transformed economy. A long-term available potential not significantly beyond 100 TWh will be confronted by a long term (2050) demand – depending on which scenario comes true – of up to 145 TWh. With a policy in accordance with the EU 55% emission reduction (or higher) by 2030 electricity demand will most likely already by 2030 exceed domestic renewable supply.

There are benefits of trade in (renewable) electricity

The very same excess demand for energy has been prevalent in the past and Austria has focused on and benefited from its comparative advantages, for instance, by importing cheap fossil resources and exporting high-quality steel products in turn. Similarly, the benefits of trade are capable of more than compensating for the outlined domestic shortages of renewable energy. The comparative advantage in selected industrial production for Austria tends to be higher than the one in energy supply, and gains in value added in this case occur for both trading

partner countries (industrial and energy production, export and import country). Choices still have to be made in terms of the form in which renewable energy is imported in Austria, either directly as electricity, bound in energy carriers (such as green hydrogen), or bound in intermediate products (such as iron pellets), and the respective shares of each of these elements. It is likely – and promising – that some share will be renewable electricity imports (and corresponding exports, possibly balancing imports across seasons).

Renewable electricity to become a global market

Global powers, notably China, are pushing the global electricity market through new technologies and with sophisticated software. As this electricity will be affordable, due to the new capabilities of batteries and direct current transmission lines of firm supply, and green, customers all over the world will buy it, also in Europe. This is a signal for Europe to speed up its activities in the field of green electricity as much as it can, i.e. pursue the most ambitious goals for climate mitigation, in order to give a strong incentive to industries, and embed this in a strong program for sustainable digitalization.

Renewable electricity as a lifeline for green European industry

It goes without saying that an electricity grid that connects billions of prosumers also poses a strong challenge for development of new software. Ambitious projects in the field of renewable electricity will also constitute a lifeline for a green European industry.

Das Wichtigste im Überblick

Die Steuerung der umfassenden und wirklich grundlegenden Transformation findet jetzt statt

Die globalen und EU-weiten wirtschaftlichen Rahmenbedingungen haben sich grundlegend verändert

Im Dezember 2020 einigte sich der Europäische Rat darauf, die Ambition im EU-Klimaziel für 2030 von bisher 40 % Treibhausgasreduktion bis 2030 auf mindestens 55 % (bezogen auf 1990) zu erhöhen. Dies kommt zu einer Zeit, in der Entwicklungen zur Klimaneutralität und Kreislaufwirtschaft rund um den Globus extrem dynamisch wurden. So hat beispielsweise das UK Committee on Climate Change in seinem Bericht "Net Zero Path" vom Dezember 2020 sowohl einen weiteren signifikanten Kostenrückgang im Klimaschutz gegenüber seinem Bericht von 2019 festgestellt als auch – als Konsequenz davon – eine Treibhausgasemissionsreduktion von 78 % bis 2035 (im Vergleich zu 1990) für Großbritannien empfohlen, was deutlich ehrgeiziger ist als seine Empfehlung aus dem Vorjahr. Basierend auf diesem Bericht kommt Mike Thomson, der Analysedirektor des Komitees, zu dem Schluss: "This program is going to boost activity and boost employment across the economy. […] We simply don't need fossil fuels to access cheap energy anymore. Any notion that we can't afford to tackle climate change is clearly nonsense." (RenewEconomy, 2020) Während also früher oft die Kosten des Klimaschutzes im Vordergrund standen, hat sich die Perspektive dahingehend geändert, dass Chancen verpasst werden, wenn nicht aktiv und gestaltend an dieser transformativen Entwicklung teilgenommen wird, und in diesem Fall sogar wirtschaftliche Nachteile entstehen können – sowohl im Vergleich zu anderen europäischen Ländern als auch global, was die Stärke des Wirtschaftsstandorts Österreich gefährden würde.

Gegenüber vielen Unwägbarkeiten gibt es viele Win-Win-Optionen im Klimaschutz für Österreich

Aber auch andere Entwicklungen sind möglich. Sollten sich längerfristige EU-Klimaziele als unzuverlässig erweisen und nicht erreicht werden, lohnt sich eine frühzeitige Umsetzung nur, wenn solche alternativen Entwicklungen sorgfältig abgewogen wurden. Klimapolitik ist ein Feld der Entscheidungsfindung unter Unsicherheit. Global und langfristig gesehen sind die Auswirkungen des Klimawandels (sowohl die beobachteten als auch die als deutlich zunehmend erwarteten) ein starker Indikator für letztlich weltweit wirksame Klimapolitik. Die Geschwindigkeit dieses globalen Handelns kann jedoch unterschiedlich ausfallen. Für Österreich gibt es jedenfalls viele Optionen im Klimaschutz, die sich als Win-Win-Situationen (sowohl ökologisch als auch ökonomisch) erweisen, auch unter ganz unterschiedlichen EU- und globalen Entwicklungen.

Die Zukunft gestalten: Eine Analyse erforderlicher Rahmenbedingungen und wirtschaftlicher Implikationen

Im vorliegenden Bericht wird detailliert dargelegt, wie eine grundlegende Transformation konsistent über die Sektoren hinweg stattfinden könnte, mit welchen Technologien, Maßnahmen, in welchen Zeitskalen und unter welchen Rahmenbedingungen eine solche Transformation erst möglich wäre. Er konzentriert sich in weiterer Folge auf die jeweiligen ökonomischen Implikationen solcher Pfade, insbesondere in einer Zeit der wirtschaftlichen Nachwirkungen der Corona-Krise.

Zur Orientierung: die vier Themen in diesem Überblick

Dieser Kurzüberblick fasst die wichtigsten Ergebnisse des Berichts zusammen. Er beleuchtet zunächst das veränderte globale Umfeld und identifiziert anschließend die Kernbestandteile einer österreichischen

Transformations-Strategie sowie vor allem die zu setzenden Voraussetzungen, ohne die eine solche Transition nicht gelingen kann. Abschließend werden die makroökonomischen Implikationen beleuchtet.

Mit einer breiten Verfügbarkeit attraktiver Lösungen hat sich der globale Transformationsrahmen verschoben

Eine Reihe von einander ergänzenden und attraktiven Lösungen ist verfügbar geworden

Vielversprechende Optionen für den Klimaschutz wurden insbesondere in der letzten Dekade breit verfügbar, von organisatorischen (z. B. neue Geschäftsmodelle) und institutionellen (z. B. ökologisierte Bankenregulierung) bis hin zu technologischen (z. B. bahnbrechende Technologiesprünge, neue Materialien und Anwendungen) und verhaltensbezogenen (z. B. klimafreundliche Ernährung). Einige aktuelle bahnbrechende Technologiesprünge sind beispielsweise: ein enormer Rückgang der Batteriekosten in Kombination mit viel billigerem erneuerbarem Strom, additive Produktion (3D-Druck), automatisiertes Fahren oder Blockchain-Technologie, die in Energiemärkten mit dezentraler Produktion eingesetzt wird. Keine dieser Entwicklungen wird von sich aus oder unter den derzeit fehlenden (institutionellen) Rahmenbedingungen zu einer klimaneutralen Entwicklung führen, jede kann aber die Klimaneutralität stark unterstützen, ja vielfach erst ermöglichen, wenn eine gute Gestaltung erfolgt. Entsprechende Entwicklungen sind auch im Verhalten zu beobachten (z. B. ist das Auto für die meisten jungen Menschen kein Statussymbol mehr), in der Organisation (z. B. floriert das Carsharing unter einer engagierten Bevölkerung auch in ländlichen Gebieten) und in den Institutionen (z. B. hat sich Black Rock, einer der weltweit größten institutionellen Investoren, von Unternehmen abgewandt, die nicht der Nachhaltigkeit verpflichtet sind, und damit den sogenannten "Great Reset" hin zur nachhaltigen Veranlagung an den Kapitalmärkten noch weiter beschleunigt). Diese Entwicklungen bergen ein enormes Potenzial für den Klimaschutz und die Steigerung der Wohlfahrt. Die Märkte haben sehr deutlich begonnen, diese Veränderungen und das Risiko von Stranded Assets (Wertverlust von Beteiligungen an Unternehmen aus dem fossilen Bereich) einzupreisen.

Grundlegende Veränderungen haben immer wieder zu einer fortschrittlichen sozioökonomischen Entwicklung geführt

Grundlegende sozioökonomische Veränderungen traten in der Geschichte wiederholt auf und wiesen jeweils ein bestimmtes Muster auf. Der "Great British Leap" im 18. Jahrhundert, der "Victorian Boom" im frühen 19. Jahrhundert, die "Belle Époque" Europas, die "Progressive Era" der USA im späten 19. Jahrhundert und das goldene Nachkriegszeitalter der Massenproduktion sowie die von den USA angeführte Revolution in der Informations- und Kommunikations-technologie – sie alle begannen mit einer "Einführungsphase", in der sich Nischenentwicklungen daran machten, akzeptierte Gewohnheiten in Frage zu stellen. In dieser Situation herrschten durchaus auch Verstörung, ja Verzweiflung, und viele gesellschaftliche Akteure nahmen die Chancen nicht aktiv wahr, ja bekämpften das Neue. Schließlich bildete sich eine kritische Masse, die die Gesellschaft an einen neuen Wendepunkt führte. Die darauffolgende "Phase der Entfaltung" führte zu prosperierenden Gesellschaften. Diese reichhaltige geschichtliche Erfahrung deutet darauf hin, dass die aktuelle Situation einen weiteren solchen Wendepunkt darstellen dürfte, der eine grüne und solcherart gelenkt digitale Zukunft einläutet. Wie reibungslos eine Gesellschaft dahin gelangen kann und zu wessen und wie großen Nutzen bzw. Kosten,

hängt eindeutig von der Art der Neugestaltung der gesellschaftlichen, institutionellen und politischen Rahmenbedingungen ab. Für ihre erfolgreiche Implementierung braucht diese Rahmung eine möglichst breite Basis, die Mitentwicklung durch alle betroffenen Akteursgruppen.

Ein verantwortungsvoller Dialog zwischen allen betroffenen Akteursgruppen – weit über die traditionelle Diskussion hinaus – ist eine wesentliche Voraussetzung

Die Transformationsaufgabe ist enorm. Sie kann gelöst werden, indem alle unterschiedlichen Perspektiven und Fakten zusammengeführt werden, aus denen sich gute und innovative Lösungen ergeben werden. Den Fokus in solchen Dialogen gilt es auf die Lösung zu legen, nicht bei Gewinnern und Verlierern stecken zu bleiben, sondern in der Lösung auch auf die Verteilung zu achten. Ein traditionelles Diskussionsformat, wie es üblicherweise auf einen Wettbewerb um die besseren Argumente abzielt, führt zu Gewinnern und Verlierern und nur zu einem oder wenigen, die sich durchsetzen. Lösungen finden wir aber nicht, indem wir zurückblicken und versuchen, das Bestehende zu bewahren, sondern indem wir nach vorne schauen und mutig Neues zulassen. Dazu brauchen wir gut vorbereitete und verantwortungsvoll gestaltete Dialog-Plattformen (Foren des Stakeholder-Engagements). Dabei können wir auf eine Tradition von Best-Practice-Beispielen in Österreich aufbauen. So initiiert etwa die Wissenschaft seit Mitte der 2010er Jahre solche nationalen Dialoge, z. B. im Rahmen von EU-finanzierten Horizon 2020-Forschungsprojekten, unter Einbindung aller betroffenen Akteursgruppen. Viele gemeinsame „Aha"-Erlebnisse haben zu neuen Lösungsansätzen geführt. Solche Dialoge ermöglichen Vielfalt und führen uns alle aus klassischen "Silos" heraus, es gilt darin eine hohe Qualität des Austausches und eine gewisse Verbindlichkeit und damit Mitverantwortung aller Beteiligten sicherzustellen. Mit einer Strukturierung dieses Austausches, sodass sich Lösungen ergeben, wird sichtbar: Es ist der echte Dialog zwischen allen Beteiligten, der Veränderungen erleichtert oder überhaupt erst ermöglicht, auch im Bewusstsein und im gegenseitigen Verständnis, gerade auch darin wie mit andernfalls Verlierern umgegangen wird. Und dieses gegenseitige Verständnis ist es vor allem, was hier gebraucht wird.

Eine umfassende Strategie, die aus einem ganzheitlichen Dialog-Ansatz hervorgeht, kann Lösungen sicherstellen und die Grundlage für eine erfolgreiche Transformation bilden

Eine umfassende Strategie geht von der tatsächlich erwünschten Dienstleistung aus

Österreich wird die nachgeschärften Klimaziele nicht einfach allein durch den Wunsch danach erreichen. Es bedarf der vollen Aufmerksamkeit der Regierungen auf allen Ebenen (Bund, Länder, Gemeinden sowie der Abstimmung auf europäischer Ebene) sowie aller gesellschaftlichen Akteure (von Unternehmen über NGOs bis zur Zivilgesellschaft), um die Politik in allen Bereichen verstärkt zu gestalten. Das Maßnahmenpaket muss nicht nur darauf abzielen

- Aktivitäten zu vermeiden, wo sie ersetzbar sind,
- die verbleibenden Aktivitäten in umweltfreundliche Strukturen zu verlagern und
- die Emissionsbilanz letzterer zu verbessern,

sondern kann nur erfolgreich sein, wenn es aus einer Gesamtstrategie hervorgeht, die die substanzielle Transformationsherausforderung umfassend angeht. Eine solche Strategie muss notwendigerweise

- die Argumentationskette umkehren und nicht bei der Bereitstellung von Energie beginnen, sondern an der eigentlichen Dienstleistung (oder Funktionalität) ansetzen, die letztlich

unsere Bedürfnisse stillt (z. B. den Zugang zu Gütern oder Menschen und die Möglichkeiten, diesen Zugang zu gewährleisten),

- die verschiedenen Optionen zur Erbringung dieser Dienstleistungen integrieren, um flexible und situationsangepasst gute Entscheidungen zu ermöglichen (z. B. durch die Einrichtung intermodaler Drehscheiben („Hubs“) anstatt alle Verkehrsträger nur einzeln zu regeln) und
- Innovation entlang der gesamten (möglicherweise internationalen) wirtschaftlichen Wertschöpfungskette fördern (z. B. durch die Nutzung der Digitalisierung in der Integration von variabler erneuerbarer Energieerzeugung, der Speicherung und der Nachfragesteuerung), wodurch ein reiner End-of-Pipe-Lösungsansatz überwunden wird.

Der Fokus dieses Berichts liegt auf Industrie, Energie, Gebäude und Verkehr

In Österreich tragen einzelne Sektoren überproportional zur Treibhausgas-Emissionsbilanz bei, weshalb wir uns primär auf diese, deren emissionsintensive Aktivitäten und ihr Zusammenwirken konzentrieren. Wir analysieren explizit die Sektoren Industrie, Energie, Gebäude und Verkehr, und ihre Emissionen, da diese zusammen fast 90 % der gesamten Treibhausgas-Emissionen in Österreich im Jahr 2019 ausmachten. Die erforderliche Richtung der quer über diese Bereiche verfügbaren und möglichen Maßnahmen wird im Detail in Kapitel 4 spezifiziert, deren Implementierung in der ökonomischen Modellanalyse in Kapitel 5.

Die wirtschaftlichen Implikationen hängen entscheidend davon ab, ob Österreich die notwendigen Rahmenbedingungen schaffen kann, bevor sich das günstige Zeitfenster schließt

Barrieren halten uns davon ab, von der Transformation zu profitieren

Während nunmehr viele klimaschonende Optionen kosteneffizient verfügbar sind, stehen den erforderlichen Investitionen andererseits weiterhin Umsetzungsbarrieren gegenüber, wie z. B. Fehleinschätzungen über zukünftige Einsparungen, unterschiedliche Anreize für Mieter und Eigentümer zu investieren oder andere finanzielle, institutionelle oder Wissensbarrieren, unklare Zuständigkeiten oder in anderer Weise verzerrte Interessen. Wenn diese Barrieren durch veränderte Rahmenbedingungen überwunden werden können, würden die Investitionen mit laufenden Einsparungen bei den Brennstoffkosten und einer Reihe von dauerhaften Vorteilen einhergehen: reduzierte Gesamtbetriebskosten, reduzierte Emissionen, die der Gesundheit und der Umwelt zugutekommen, immaterielle Vorteile wie höherer Wohnkomfort aufgrund neuer Gebäudestandards und einer Stärkung des Wirtschaftsstandorts Österreich.

Rahmenbedingungen sind entscheidend

Die vorliegende Analyse zeigt, dass die ökonomischen Implikationen einer solchen Transformation entscheidend davon abhängen, wie die wirtschafts- und energiepolitischen Rahmenbedingungen jetzt gesetzt werden (diese werden im Folgenden im Detail erläutert). Es zeigt sich zudem, dass die Corona-Krise ein Window of Opportunity öffnet, in dem die Erhöhung des Klimaziels und Maßnahmen der Umsetzung beide Krisen adressieren können und zwar zu viel geringeren Kosten als wenn dies sequentiell oder ohne die aktuelle wirtschaftliche Unterauslastung erfolgen würde. Umgekehrt würden die sozialen Kosten deutlich steigen, wenn Konjunkturmaßnahmen so gesetzt würden, dass sie zu einem weiteren fossilen Lock-in beitragen.

Die Schaffung der entsprechenden Voraussetzungen ist unabdingbar

Die zentralen Transformationsschritte in Industrie, Gewerbe und Gesellschaft können nicht erfolgreich sein, wenn die notwendigen Rahmenbedingungen zu spät oder gar nicht gesetzt werden

Voraussetzungen für die Transformation der Industrie

In der klimaneutralen Industrieentwicklung kann Österreich wirtschaftlich erfolgreich sein, wenn, und zwar nur wenn

- verlässliche mittel- und langfristige Rahmenbedingungen zu Klima und Energie gesetzt werden, die wirtschaftlich fundierte unternehmerische Entscheidungen ermöglichen

Nur dann sind klimaschonende Entscheidungen auch wirtschaftlich nachhaltig (und damit möglich). Dazu gehören

- zuverlässige Rahmenbedingungen und Berechenbarkeit des Emissionsmarktes, basierend auf gesamthafter Planung unter Berücksichtigung des EU-Binnenmarktes als auch der internationalen Wettbewerbsfähigkeit,
- verlässliche erneuerbare Energien (in Bezug auf Verfügbarkeit, Sicherheit, Wettbewerbsfähigkeit und Preissicherheit, letzteres z. B. durch die Etablierung von Carbon Contracts-for-Difference um Differenzen zu einem verlässlichen CO_2-Preispfad auszugleichen),
- der Ausbau der Infrastruktur (insbesondere für Strom, grünes Gas, Wasserstoff), einschließlich der rechtzeitig gesetzten regulatorischen und rechtlichen Rahmenbedingungen für diesen Infrastrukturausbau, sowie
- die Forcierung von Märkten für nachhaltige Produkte.

Basierend auf diesen Rahmenbedingungen

- gilt es Dialogforen zur gemeinsamen Entwicklung der Umsetzung der Kreislaufwirtschaft zu betreiben, um eine Abstimmung der Wertschöpfungsketten über (auch rechtlich) eigenständige Wirtschaftseinheiten (Unternehmen) hinweg zu ermöglichen.

Gegeben, dass die klimapolitische Herausforderung ein Öffentliches Gut-Problem mit Trittbrettfahrerverhalten darstellt, das unter unzureichenden Rahmenbedingungen nicht durch den Markt allein gelöst werden kann, können Innovationen in der Übergangsphase in einem wettbewerbsorientierten Umfeld dann nach Österreich geholt werden, wenn sie gefördert werden mit

- öffentlichen Mitteln, wie z. B. einem Österreichischen Fonds zur Industriellen Innovation und Transformation (Austrian Industrial Innovation and Transition Fund, AIITF), der eine Hebelwirkung sowohl in Hinblick auf private Investoren als auch für EU-Mittel erzielen kann, um die erheblichen Vorabinvestitionen finanzieren zu können. Ein solcher Fonds kann auch zur Förderung von Investitionen in neue industrielle Anlagen zur Herstellung nachhaltiger Produkte mittels neuer, klimafreundlicher Prozesse genützt werden.

Um die Entwicklung österreichischer Technologieführerschaft in kohlenstoffarmen Zukunftstechnologien zu unterstützen, gilt es das gesamte Instrumentarium der Innovations- und Exportpolitik entsprechend zu nutzen,

- vom Ausbau bestehender F&E-Förderprogramme und zusätzlicher steuerlicher Anreize für klimaneutrale F&E sowie Start-Up-Finanzierung in diesem Bereich,
- über kontinuierliche Aktualisierungen des regulatorischen Rahmens, inklusive Technologiestandards, um sicherzustellen, dass er kohlenstoffarme Innovationen und deren Diffusion unterstützt,
- bis hin zur Stärkung des Bestbieterprinzips in der öffentlichen Beschaffung sowie von Instrumenten zur Exportförderung und internationalen Vernetzungsinitiativen, insbesondere solcher, die auf kleine und mittelgroße Unternehmen im Bereich kohlenstoffarmer Technologien abzielen.

Voraussetzungen für die Energiewende

Soll die Energiewende im nunmehr avisierten Zeitfenster gelingen, so ist dafür unabdingbar nicht nur

- die Nachfrageseite zu adressieren, sondern auch
- den Energiemarkt zu reformieren, um mit ausreichenden Anreizen die Versorgung durch erneuerbare Energie über alle benötigten Energieträger hinweg (Strom, grünes Gas, Wasserstoff) deutlich zu erhöhen,

und

- die entsprechende Infrastruktur für Erzeugung, Übertragung und/oder Speicherung nicht nur rechtzeitig aufzubauen, sondern auch räumlich spezifisch an den darauf angewiesenen (industriellen) Produktionsstandorten verfügbar zu machen.

Österreich benötigt

- eine klare Strategie sowie deren Umsetzung für eine zuverlässige Versorgung mit erneuerbarer Energie, die beide komplementären Herkunftsquellen, das Inland und das Ausland, integriert.

Da insbesondere die saisonalen Schwankungen der besonders preisgünstigen Solarenergie nicht ausreichend durch andere erneuerbare Energien kompensiert werden können, ist nicht nur die inländische Speicherung entscheidend, sondern auch eine Strategie zum Handel mit Energie, einschließlich der ausländischen Lieferung von direkter Solarenergie (Strom) oder indirekter (z.B. Wasserstoff) nach Österreich (und entsprechender Exporte). Dies gilt es frühzeitig zu klären und an die jeweiligen europäischen und globalen Bestrebungen anzupassen, um die notwendige Planungssicherheit zu ermöglichen.

Voraussetzungen für die Transformation im Bereich Gebäude

Angesichts der insgesamt begrenzten Verfügbarkeit von erneuerbarem Strom und (Fern-)Wärme im Inland und angesichts der sich verstärkenden Konkurrenz durch steigende weitere Nachfrage, insbesondere aus Industrie und Verkehr, ist die thermische Sanierung von Gebäuden unverzichtbar, um die Klimaziele insgesamt zu erreichen, wie dieser Bericht zeigt. Auch der Umstieg von gas- oder ölbasierten Heizsystemen auf Wärmepumpen ist (oft) nur in Kombination mit einer angemessenen thermischen Sanierung technisch machbar und in der Regel auch nur in Kombination mit dieser zu empfehlen. Mit zunehmend kohlenstofffreiem Strom und Fernwärme sinken jedoch bei rein physikalischer Kohlenstoffbilanzierung die Anreize für tiefgreifende Sanierungen, die somit durch eine adäquate direkte Regulierung

(entsprechende Normen oder finanzielle Anreize für tiefgreifende Sanierungen) umzusetzen sind.

Der Erfolg der Umstellung des Gebäudesektors auf Klimaneutralität hängt ab von

- einer klar formulierten, verlässlichen und langfristigen Strategie mit konkreten Meilensteinen und einem klar definierten Zeitrahmen, die den Akteuren des Gebäudebereichs als Entscheidungsgrundlage dient. Diese muss Anreize zur Entwicklung technologischer Lösungen für den Ersatz von (dezentralen) Öl- und Gas- und E-Boilern durch erneuerbare Energien oder Wärmepumpen in allen Anwendungsbereichen schaffen und dabei wirtschaftliche Investitionshemmnisse überwinden für vermietete Gebäude oder Wohnungen, Eigentumsstrukturen bei Wohngebäuden mit mehreren Eigentümern und Finanzierungshürden aufgrund von sofortigen Investitionskosten, aber nur langfristigen Energiekosteneinsparungen. Aus einem pauschalen Aufschlag kann beispielsweise ein Fonds für Investitionszuschüsse für private Haushalte gespeist werden.

Um den Energiebedarf von Neubauten zu reduzieren (Netto-Nullenergiegebäude-Standard oder Passivhausniveau), gilt es:

- neue Gebäude mit einem höheren Energieeffizienzstandard zu bauen als derzeit gefordert (eine entsprechende Änderung der Gebäudestandards ist notwendig),
- sicherzustellen, dass umfassende (d. h. tiefgreifende) Sanierungen deutlich zunehmen (Erreichen der höchstmöglichen Reduzierung des (externen) Energiebedarfs). Für den vollständigen Ausstieg bis 2040 ist dafür der verpflichtende Wechsel der verbleibenden fossilen Systeme zentral und der Start für diesen Weg ist jetzt zu setzen,
- alle Flächen mit ausreichender Sonneneinstrahlung (Dächer, Fassadenflächen) für die Installation von Photovoltaikanlagen zu nutzen,
- die Akteure im Gebäudesektor dazu anzuhalten, nicht nur die betriebsbedingten Emissionen und den Energiebedarf von Gebäuden zu reduzieren, sondern auch die grauen Emissionen ("embodied emissions") in Baumaterialien und Bauteilen aus einer Lebenszyklusperspektive zu verringern.

Voraussetzungen für die Transformation des Verkehrs

Die

- Gestaltung und Umsetzung einer effektiven energie- und verkehrssparenden (und damit kostensparenden) Raumplanung

ist ebenso entscheidend wie

- eine Überarbeitung des direkten Anreizsystems in zu wählender Kombination aus finanziellen, ordnungsrechtlichen und informatorischen Maßnahmen, die gemeinsam das Erreichen der Klimaneutralität sicherstellen (von der Reform kontraproduktiver Fördermaßnahmen, über Preis- und Zulassungsinstrumente bis zu bewusstseinsbildenden Maßnahmen).

Für das Umstellen des Fahrzeugbestandes, den Ausstieg aus fossil betriebenen Verbrennungsmotoren und den gleichzeitigen Einstieg in

alternative Fahrzeuge ist ein

- Ausbau einer angemessenen Infrastruktur erforderlich.

Dafür ist notwendig

- Anreize für Investoren zu schaffen, Kapital bereitzustellen, wobei verschiedene Finanzierungskonzepte zur Verfügung stehen, z. B. direkte Unterstützung aus öffentlichen Mitteln oder Private-Public-Partnerships (PPP) für den Infrastrukturbau.

Mit einem neu gestalteten Finanzsystem, das Aspekte wie Environmental Social Governance (ESG) Kriterien auf konsistente Weise integriert, würden neue und langfristig verlässliche Quellen zur Finanzierung des Übergangs sowohl für die Verkehrs- als auch für die Gebäudeinfrastruktur zur Verfügung stehen, wobei letztere mindestens so stark wie erstere das Mobilitätsverhalten bestimmt. Solche neuen Quellen sind umso wichtiger, als einzelne Komponenten des Steueraufkommens (wie z. B. die Mineralölsteuer, sollte das derzeitige Steuersystem beibehalten werden) zurückgehen werden.

Voraussetzungen im europäischen und internationalen Kontext

Österreich kann den Übergang zu einer Netto-Null-Emissions-Zukunft nicht allein lösen. Jenseits der Felder mit offensichtlichem Bedarf nach internationaler Regulierung wie der Luftfahrt, sind z. B. im Straßenverkehr im Ausland zugelassene Fahrzeuge für mehr als die Hälfte der in Österreich gefahrenen Tonnenkilometer verantwortlich. Eine Strategie, an der andere Länder nicht beteiligt sind, führt zu ineffizienten Investitionen und Infrastrukturausbau. Daher ist eine gemeinsame Strategie zumindest auf regionaler Ebene (mit Nachbarländern), besser noch auf europäischer Ebene erforderlich.

Für die gegenüber dem internationalen Wettbewerb exponierte Industrie würde eine international einheitliche Treibhausgasbepreisung ausreichende Rechts- und Planungssicherheit bieten. Solange diese nicht verwirklicht ist, benötigt es eine Kombination aus Maßnahmen: dies zunächst auf Ebene der EU (wie Treibhausgasbepreisungsausgleich an der EU-Außengrenze in Bezug auf die Produktion außerhalb der EU (administrativ am einfachsten könnten Gratiszuteilungen von Emissionsrechten im Inneren sein, und bezogen auf die aus verringerten Zertifikatsmengen resultierenden Mehrkosten darauf abgestimmt ergänzend ein Carbon Border Adjustment Mechanism), Marktzugangsregeln für Produkte und diesbezügliche internationale Abkommen), sowie (oder gegebenenfalls ergänzt) auf nationaler Ebene (wie Schaffung von Märkten für grüne Produkte, Export- oder Investitionsförderung, Differenzausgleich für Energiekosten). Für die energie- und/oder emissionsintensive Industrie sind insbesondere auch die Verfügbarkeiten erneuerbarer Energien und dazu kompatibler Ersatzbrennstoffe gesichert zu gewährleisten – sowohl auf Ebene der EU (Energie-Binnenmarkt) wie national durch entsprechende Strategie-Umsetzungen, Infrastrukturinvestitionen und internationale Abkommen.

Eine über diese Kurzfassung hinausgehende, vollumfängliche Darstellung der erforderlichen Rahmensetzungen und deren jeweilige Begründung gibt Kapitel 7.

Im Folgenden analysieren wir die wirtschaftlichen Implikationen einer klimaneutralen Transformation. *Dabei gehen wir im Folgenden davon aus, dass rechtzeitig adäquate Rahmenbedingungen geschaffen wurden.*

Die wirtschaftlichen Auswirkungen der Anhebung der EU-Klimaziele für 2030 sind vielfältig

Die Anhebung der Klimaziele ist mit unmittelbar wirtschaftsfördernden Wirkungen verbunden...

Die Anhebung des europäischen 2030-Klimaziels und das Streben nach Klimaneutralität bis 2040 für die Sektoren, die nicht dem europäischen Emissionshandel unterworfen sind (Landwirtschaft, Verkehr, Abfall, nicht-energieintensive Produktion) und bis spätestens 2050 für die auf europäischer Ebene im Emissionshandel regulierten Energie- und energieintensiven Sektoren erfordert einen Übergang, der eine Vielzahl von kurz- und langfristigen Auswirkungen auf die österreichische Wirtschaft mit sich bringt.

Während der Übergang – wenn er klug gesetzt wird – eindeutig die gesellschaftliche Wohlfahrt steigert (dies sowohl in deren engerem Verständnis als Konsum als auch im weiteren Sinn, etwa bezogen auf Gesundheits- und Annehmlichkeitsvorteile), gibt es eine Reihe von Effekten, die auch die Wirtschaftsleistung im Inland erhöhen, insbesondere:

- Der (schnellere) Umstieg auf eine erneuerbare Ressourcenbasis reduziert die erheblichen fossilen Energieimporte (derzeit ca. 8 Mrd. €/Jahr[3]) und verlagert diese Ausgaben für Energiedienstleistungen auf zusätzliche heimische Wertschöpfung.
- Der Übergang fördert eine Modernisierung und eine auf Nachhaltigkeit ausgerichtete Digitalisierung der Wirtschaft, wodurch sowohl Produktivität als auch internationale Wettbewerbsfähigkeit erhöht werden.

Ein solcher Übergang erfordert erhebliche zusätzliche gezielte Investitionen. Wenn solche Investitionen andere Investitionen nicht vollständig verdrängen – insbesondere in einer Post-Covid-Situation mit stark unterausgelasteten Kapazitäten wird die Verdrängung sehr gering sein, wenn sie überhaupt vorhanden ist –

- werden solche Investitionen bereits kurzfristig zusätzliche Wertschöpfung, Beschäftigung und entsprechende Haushaltseinkommen schaffen.

...sowie auch mit diese zunächst reduzierenden

In gegengleicher Richtung reduzieren andere Effekte tendenziell die inländische Wirtschaftsleistung (und möglicherweise die gesellschaftliche Wohlfahrt während einer Übergangsphase), wie insbesondere:

- Auf Unternehmensebene können erhöhte Investitionsausgaben und möglicherweise steigende Energiekosten kurzfristig zu einer verringerten internationalen Wettbewerbsfähigkeit führen und damit den Export über die EU-Grenzen hinaus gefährden. Ein angemessener politischer Rahmen kann diese Verluste abmildern, insbesondere den Wettbewerb mit ausländischen (nicht klimafreundlichen) Angeboten auf den Märkten innerhalb der EU, z. B. durch eine auf EU-Ebene gesetzte Klima-Ausgleichsabgabe an der EU-Außen-Grenze.
- Für private Haushalte erhöhen gestiegene klimarelevante Investitionen (z. B. höhere Ausgaben für die Renovierung von Gebäuden) die Ausgaben für Kredite und reduzieren insofern

[3] Wenn nicht anders angegeben, sind alle monetären Werte in diesem Bericht zur Preisbasis 2018 angeführt, somit in €$_{2018}$.

vorübergehend möglicherweise den Konsum. Mögliche Energiearmut oder anderweitig regressive Folgewirkungen klimapolitischer Maßnahmen können durch staatlichen Ausgleich gezielt vermieden werden, z. B. durch angemessene Transformationsfonds, Bonussysteme oder allgemeine Rückerstattungssysteme.

- Die Umstrukturierung des Stromsektors könnte zu einem höheren Strompreis führen, was den Verbrauch der Haushalte kurzfristig reduzieren könnte. Eine adäquate Marktregulierung (z.B. Stufentarife) kann unbeabsichtigte Verteilungsfolgen vermeiden.

Diese verschiedenen ökonomischen Folgewirkungen und Effekte wirken alle gleichzeitig, teilweise gegenläufig, und wirken auf Unternehmens-, Sektor-, Haushalts-, nationaler und globaler Ebene unterschiedlich, auch zeitlich verschieden. Vor allem erwarten wir, dass sich positive Effekte langfristig entfalten, während negative ökonomische Effekte eher kurzfristig relevant sein dürften. Dies könnte einen Trade-off der Konsummöglichkeiten über Generationen hinweg bedeuten.

Daher wurde ein dynamischer, multisektoraler, multi-regionaler makroökonomischer Modellierungsansatz gewählt, um die jeweilige quantitative Relevanz jeder dieser Kräfte sowie die daraus resultierenden Netto-Gesamtauswirkungen beleuchten zu können.

Es wird ein Szenario-Ansatz zur Quantifizierung der wirtschaftlichen Auswirkungen angewendet

Um die makroökonomischen Auswirkungen einer Anhebung der Klimaschutzziele bis 2030 in der EU und insbesondere in Österreich zu bewerten, verwenden wir einen Szenario-Ansatz. In dieser Studie finden zwei Hauptszenarien Verwendung. Erstens hinterlegen wir ein Basisszenario, das auf der früheren EU-Politik einer 40%igen Emissionsreduktion bis 2030 im Vergleich zu 1990 basiert (und, was entscheidend ist, auch die geschätzten Auswirkungen der jüngsten Pandemie auf das kurzfristige Wachstum und die wirtschaftliche Aktivität berücksichtigt). Zweitens erstellen wir abgestimmt auf die jüngste Zielrevision des Europäischen Rats ein erweitertes Szenario, das die Folgewirkungen der zur zumindest 55 % Emissionsreduktion erforderlichen Änderungen untersucht.

Das "EU40" Basisszenario

Das "EU40"-Basisszenario beschreibt die Entwicklung der Wirtschaft unter den bestehenden Maßnahmen und Trends (siehe Kapitel 5 und die Anhänge C bis H für vollständige Details) und beinhaltet die Klimapolitik, um einerseits das bis vor kurzem gültige EU-Ziel für 2030 zu erreichen, d.h. die Treibhausgasemissionen um 40 % im Vergleich zu 1990 zu reduzieren, andererseits innerösterreichische Klimaneutralität bis 2040.

Das erweiterte Szenario "EU55"

Das erweiterte Szenario "EU55" baut in Bezug auf die allgemeinen sozioökonomischen Parameter auf dem EU40-Basisszenario auf, fügt jedoch eine Vielzahl zusätzlicher Maßnahmen zur früheren Eindämmung des Klimawandels hinzu sowie setzt bestehende Politiken stringenter an. Wir differenzieren das erweiterte Szenario "EU55" wie folgt:

a. EU55-seq: Politische Maßnahmen als Reaktion auf die Covid-Krise und die Klimakrise werden sequentiell umgesetzt, d. h. beginnend mit generischen Maßnahmen zur konventionellen wirtschaftlichen Stimulierung und erst später werden spezifische

Maßnahmen zur früheren Abschwächung des Klimawandels umgesetzt.

b. EU55-sim: Maßnahmen zur früheren Abschwächung des Klimawandels sind gleichzeitig politische Maßnahmen als Reaktion auf die Covid-Krise, d. h. die Maßnahmen werden gleichzeitig umgesetzt. Dieses Setup beschreibt die Strategie, das derzeit ohnehin hohe Ausmaß der Verwendung an (öffentlichen) Geldern in klimaneutrale Investitionen zu lenken, anstatt in ungerichtete allgemeine Konjunkturmaßnahmen.

Verstärkte klimaorientierte Investitionen können sowohl der Wirtschafts- als auch der Klimakrise begegnen

Ausrichtung privater und öffentlicher Investitionen nach Covid-19 zur Bewältigung der Klima- *und* Wirtschaftskrise

Österreichische Akteure bereiten klimaneutrale Lösungen vor und treiben diese voran (z. B. Elektrifizierung, wasserstoffbasierte Produktion und Ansätze der Kreislaufwirtschaft). Die Nachschärfung der europäischen Klimaziele für 2030 impliziert eine frühere Umsetzung dieser Minderungsoptionen. Unsere gesamtwirtschaftliche Modell-Simulation zeigt, dass dies mit erheblichen ökonomischen Implikationen verbunden ist. Die Richtung wird dabei von den jeweiligen Rahmenbedingungen und dem aktuell günstigen Zeitfenster bestimmt. Mit der Post-Covid-Rezession wird erwartet, dass zumindest für die ersten Übergangsjahre eines solchen Hochskalierens kein relevanter Verdrängungseffekt von Investitionen eintritt, da Produktionsanlagen nicht ausgelastet sind und Finanzinvestoren (auch und vermehrt grüne) Investitionsprojekte suchen.

Automatische wirtschaftliche Stabilisatoren (z. B. Arbeitslosengeld, Umsatz-Steuereinnahmen etc.) sind nicht umfassend und tiefgreifend genug, um die bestehende Unterauslastung zu beheben. Daher müssen die Regierungen einspringen, indem sie die effektive Nachfrage stärken, um die schlimmsten Auswirkungen der beispiellosen Lock-Down-Maßnahmen abzumildern. Solche öffentlichen Investitionen sind – erst recht auf den aktuell hohen Niveaus – ökonomisch nur dann gerechtfertigt, wenn sie langfristig nachhaltige Strukturen fördern, und gilt es diese daher in klimaneutrale (Infra-)Strukturen und weg von fossiler Energie zu lenken. Dabei kann die Politik beste Erfolge erzielen, wenn sie beide Krisen gleichzeitig angeht – die Klima- und die Wirtschaftskrise.

Eine Kombination von Indikatoren wird verwendet, um die Gesamtauswirkungen zu beleuchten

In den letzten Jahrzehnten hat die Menschheit gelernt, dass nicht nur Arbeit und Produktionskapital Wertschöpfung und Wohlfahrt schaffen, sondern dass das menschliche Wohlbefinden auch entscheidend von der Qualität der natürlichen Ressourcen und ihrer Dienstleistungen (Ökosystemleistungen, wie z. B. der produktiven Nutzung natürlicher Ressourcen und der genossenen Annehmlichkeiten) abhängt[4], dennoch spiegelt ein Hauptwirtschaftsindikator, das Bruttoinlandsprodukt (BIP), immer noch nur die ersteren wider. Wenn also wirtschaftliche Ressourcen zur Verbesserung oder zum Erhalt der Umweltqualität (oder zur Senkung der Umweltkosten) eingesetzt werden, wie es beim Klimaschutz der Fall ist, oder nicht-marktliche Dienstleistungen erhöhen (wie höherer Wohnkomfort in sanierten Gebäuden oder bessere

[4] Diesbezüglich in einem ausgezeichneten Überblick zusammenfassend wurde - den einflussreichen Stern Review zur Ökonomie des Klimawandels aus 2007 ergänzend - soeben "The Economics of Biodiversity: The Dasgupta Review" verfügbar, auch in diesem Fall beauftragt durch die Regierung des Vereinigten Königreichs (UK), und in der Fachwelt als mindestens so signifikant für die zukünftige Diskussion erachtet (Dasgupta, 2021).

Gesundheit), wird dies die tatsächliche Produktivität erhöhen (Verbesserung der Umwelt- oder nicht-marktlichen Leistungen). Aber gemessen als Beitrag zum traditionell definierten BIP kann es die Produktivität verringern, da ein Teil des zusätzlichen Outputs bzw. der zusätzlichen Leistungen darin nicht reflektiert wird. Im Folgenden weisen wir dennoch das BIP als einen der Indikatoren aus, unter anderem auch weil es stark mit der Beschäftigung korreliert, aber auch, weil es in der öffentlichen Diskussion immer noch weit verbreitet ist. Wir weisen jedoch darauf hin, dass bei seiner Interpretation Vorsicht geboten ist. Und wir ergänzen diesen Indikator durch einen Wohlfahrtsindikator, der versucht, vom BIP vernachlässigte Wohlfahrtsdimensionen umfassender abzubilden.

Temporäres Zeitfenster verschiebt Transformationskosten zu Vorteilen

Für eine EU55-konsistente Klimapolitik in Österreich (und relativ zu einem Szenario, in dem wir auf dem früheren Politikpfad von 40 % Emissionsreduktion bis 2030 bleiben), zeigt die makroökonomische Simulation ein höheres BIP für Österreich in der Mitte der 2020er Jahre aufgrund eines früheren Investitionszyklus (siehe Abbildung DW.1, durchgezogene grüne Linie). Der Anstieg ist auch auf die Unterauslastung des Kapitals nach der Covid-Krise zurückzuführen, die durch Stimulus verringert oder beseitigt werden kann. Würde man (hypothetisch) ein vollständiges Crowding Out annehmen (gestrichelte grüne Linie), könnte das traditionell gemessene BIP zurückgehen. Dies impliziert, dass die aktuelle Rezession einen Rahmen bietet, unter dem klimafreundliche Investitionen insbesondere mit zusätzlichen und auch kurzfristig hohen gesamtwirtschaftlichen Vorteilen verbunden sind, die sich deutlich im BIP zeigen. Zu beachten ist, dass das verwendete Vergleichsszenario EU40 (ebenso wie EU55) auch Klimaneutralität in Österreich bis 2040 beinhaltet, und insbesondere in den 2030er Jahren besonders hohe klimarelevante Investitionen aufweist. Bei früherer Klimapolitik (EU55) erfolgen einige dieser Investitionen vorgezogen (d.h. bereits in den 2020er Jahren), wobei die dadurch generierte zusätzliche wirtschaftliche Aktivität dieses Teils somit bereits in den 2020er Jahren (und nicht erst in den 2030er Jahren) erfolgt (durchgezogene grüne Linie). In der Zeit danach – ab 2040, mit weniger Investitionsdifferenz – implizieren die akkumulierten Lerneffekte der frühen europäischen (im Rahmen des ETS) und österreichischen (im Bereich der Nicht-ETS-Sektoren) Implementierung und die niedrigeren Betriebskosten klimafreundlicher Technologien ein höheres BIP als im EU40 Szenario.



Abbildung DW.1 Ökonomische Auswirkungen der EU55-Klimapolitik in Österreich, Abweichung des BIP (traditionell gemessen, ohne Berücksichtigung des ökologischen und nicht-marktlichen Produktivitätsgewinns) relativ zur EU40-Entwicklung (die hier als Referenz herangezogen wird) unter simultaner Politik (durchgezogene grüne Linie), mit weniger als den konservativsten Parametereinstellungen (verblassend grün gefärbte Linien), mit hypothetischer vollständiger Verdrängung (gestrichelte grüne Linie), sowie unter sequentieller Politik (lila Linie).

Sensitivitätsanalyse zeigt steigende wirtschaftliche Aktivität während der gesamten Übergangszeit

Für die Hauptquantifizierung EU55 (durchgezogene dunkle grüne Linie) wurden Parameter gewählt, die eine konservative Schätzung wiedergeben, z. B. kostenintensive kohlenstoffneutrale Technologien und Lernraten für diese, die unter jenen liegen, die unsere Literaturübersicht ergibt, oder Energieeffizienzgewinne am unteren Ende des Spektrums. Die Änderung auch nur einer dieser Annahmen führt zu höheren BIP-Werten (in traditioneller Definition), insbesondere später in der Übergangsphase (verblassend grün gefärbte Pfade).

Alle Abweichungen im Szenario EU55 zu EU40 treten zusätzlich zur wirtschaftlichen Entwicklung im Szenario EU40 selbst auf, wobei letztere mit substanziellen Unsicherheiten verbunden ist, nicht zuletzt aufgrund der Pandemie und ihrer Folgen. Die in dieser Studie angewandte makroökonomische Bewertung identifiziert daher die Abweichungen zu einem Basisszenario EU40, wobei die qualitativen Ergebnisse der Abweichung zwischen EU55 und EU40 robust gegenüber einer Reihe verschiedener möglicher Basisentwicklungen sind.

Abbildung DW.2 zeigt eine mögliche BIP-Entwicklung für EU40, sowie die Abweichung im Szenario EU55 davon. Die Entwicklung des BIP in absolutem Niveau ist hier für ein eher konservatives Basisszenario EU40 dargestellt und der BIP-Entwicklung im EU55-simultanen Politik-Szenario (EU55-sim) gegenübergestellt. Tabelle DW.1 zeigt die korrespondierenden jährlichen Wachstumsraten mit "x_i" als erwartet positivem Summanden, der die Breite möglicher EU40 Basisszenarien widerspiegelt. Die längerfristigen Wachstumsraten wurden der IIASA-Datenbank für gemeinsame sozioökonomische Entwicklungspfade (shared socioeconomic pathways, SSP) entnommen. Unter den derzeitigen Erwartungen des SSP2-Trendwachstums sowie unter der Bedingung, dass die erforderlichen Rahmenbedingungen rechtzeitig

gesetzt werden, bedeutet das strengere EU55 Ziel einen sowohl kurz- als auch langfristigen Schub für das reale BIP Österreichs, wobei ein Teil dieses Wachstums auch ein vorgezogenes ist. Letzteres wird in einem höheren BIP bis in die späten 2020er Jahre sichtbar, in denen die Klimaschutzambitionen unter EU55 höher sind als im Szenario EU40. Darauf folgt eine Periode, in der die Ambitionen unter EU55 relativ niedriger sind (im Vergleich zu deren Niveau in EU40, weil einige der Investitionen bereits in die 2020er Jahre vorverlegt wurden), und wiederum mit langfristigen Vorteilen durch die Wahl einer EU55 Politik anstelle einer gemäß EU40. Zusammengefasst zeigt dies, dass die höhere Ambition ein höheres BIP bedeutet, auch in dessen traditioneller Definition, freilich nur wenn die entsprechenden Rahmenbedingungen für die Klimapolitik zuvor gesetzt werden.

Die Abweichung in der ökonomischen Aktivität durch vorgezogene Klimapolitik

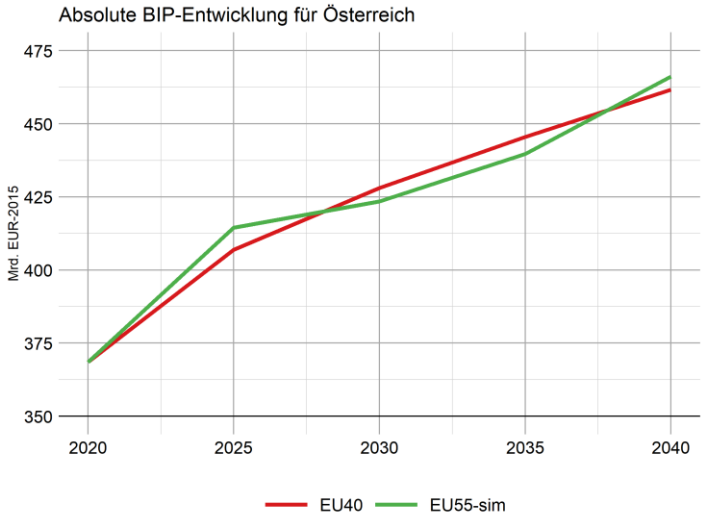


Abbildung DW.2 BIP-Entwicklung (absolut, real) - eine konservative Basisentwicklung (EU40) und die Abweichung davon durch den EU55 Pfad.

Tabelle DW.1 Jährliche BIP-Wachstumsraten; x_i weist auf die post-Covid-19 und Langfrist-Unsicherheiten hin

Periode	EU40	EU55-sim
2021-25	$x_1 + 2.0\%$	$x_1 + 2.4\%$
2026-30	$x_2 + 1.0\%$	$x_2 + 0.4\%$
2031-35	$x_3 + 0.8\%$	$x_3 + 0.8\%$
2036-40	$x_4 + 0.7\%$	$x_4 + 1.2\%$

Diese BIP-Pfade gelten für den Fall eines gleichzeitigen klimapolitischen und wirtschaftspolitischen Maßnahmenpakets im Anschluss an die Covid-19-Pandemie.

Aufschieben von klimapolitischen Maßnahmen ist unklug und teuer

Sequentielles Agieren wäre somit kostenintensiv, da nur ein kürzerer Zeitrahmen für dasselbe strengere Ziel verfügbar wäre und die zu Beginn getätigten Investitionen in langlebigen emissions-intensiven Kapitalbestand das Risiko vorzeitiger Abschreibungen tragen würde. Aus nationaler Sicht zeigen diese Ergebnisse, dass eine gleichzeitige Umsetzung von Klimaschutzmaßnahmen und Covid-19-

Wiederaufbaumaßnahmen eine sequenzielle Strategie deutlich übertrifft, und zwar über den gesamten modellierten Zeithorizont von heute bis 2050.

Beiträge zur makroökonomischen Entwicklung differieren nach sektoralen Politiken

Betrachtet man die Richtung der Veränderung des österreichweiten BIP (gegenüber seiner Entwicklung im EU40-Szenario) bei einer Politik in nur einzelnen Sektoren, so stellt man fest, dass das Politikpaket für elektrischen Strom mit zusätzlichen positiven BIP-Effekten verbunden ist, insbesondere während der Erholungsphase. Während die Stückkosten für Strom bei strengeren Zielen leicht ansteigen, dominieren eine Reihe weiterer Komponenten, darunter eine höhere Energieeffizienz und ein schnellerer Strukturwandel, und bewirken einen Anstieg des BIP (auch in der traditionellen Definition). Erfolgt die Nachrüstung von Zementanlagen mit Anwendungen zur Kohlenstoffabscheidung schneller als im EU40-Basisszenario, stellt das Nebenprodukt Kohlenwasserstoff anderen Industrien zur Verfügung und generiert positive Beiträge zur Erholung. Gegenüber dem EU-40 Szenario wird im EU55-Szenario ein Teil dieses positiven Effekts in die 2020er Jahre vorgezogen, und fällt der positive Effekt in den 2030er Jahren dadurch dann nur mehr etwas geringer aus.

In den Nicht-ETS-Sektoren kann das Maßnahmenpaket im Gebäudebereich von der Unterauslastung profitieren (es ergibt sich ein noch höheres BIP Mitte der 2020er Jahre), während die einzigen modellierten Maßnahmen des Verkehrspakets (Investitionen in die Infrastruktur und den Fahrzeugbestand) auch zu einer Nettoerhöhung der Verkehrskosten führen. Für eine detaillierte Diskussion der Sektor-Ergebnisse siehe Kapitel 6.

Ein strengeres Klimaziel schneidet auch in Bezug auf das traditionelle BIP besser ab

Makroökonomische Modellsimulationen unterstützen die Aussage, dass kosteneffektive Klimaschutzoptionen verfügbar sind. Wir vergleichen hier den kumulativen BIP-Effekt für den Zeitraum 2020-2050 der mit dem EU55-Ziel verbundenen Maßnahmen mit jenem zur Erreichung des früheren EU-Ziels von 40%. Wie zuvor festgehalten, kann dieser Pfad nur unter der Voraussetzung beschritten werden, dass die erforderlichen Rahmenbedingungen gesetzt wurden (Verfügbarkeit ausreichend erneuerbarer Energien zu wettbewerbsfähigen Preisen, fairer Marktzugang bzw. Grenzausgleichsregeln solange kein global einheitlicher CO_2-Preis gewährleistet ist, nationale Rahmenbedingungen für die Transition), und erhöht sich dann mit der Verfolgung des EU55-Ziels das österreichische BIP; es ist im Durchschnitt bis 2050 um +0,2% per anno höher.

Die Erhöhung des Klimaziels ist mit erheblichen Zusatznutzen verbunden

Klimapolitik geht mit einer Reihe von Wohlfahrtsverbesserungen einher. Zum Beispiel erhöht eine verbesserte Gebäudequalität den Wohnkomfort, eine aktivere Mobilität bringt erhebliche gesundheitliche Vorteile mit sich (mehr Radfahren und zu Fuß gehen wirkt Zivilisationskrankheiten, insbesondere auch Herzkreislauferkrankungen, entgegen) und die Elektrolyse verbessert die Stahlqualität – sogar über den direkt beabsichtigten Nutzen des Klimaschutzes hinaus. Die meisten dieser Co-Benefits lassen sich nur schwer messen oder auf einen gemeinsamen Nenner bringen (anhand eines einheitlichen Indikators messen, insbesondere auch eines monetären). In einem Bereich der Co-Benefits, der Verbesserung der Luftqualität, ist ein solch einheitliches Maß jedoch aufgrund vergleichsweise robuster Quantifizierungen verfügbar. Wir geben daher die Größenordnung der Zusatznutzen der Klimapolitik aufgrund von gleichzeitig induzierten Luftqualitätsverbesserungen an,

genauer gesagt, nur die dadurch implizierten gesundheitlichen Vorteile. Wie in Abbildung DW.3 gezeigt, belaufen sich die gesundheitlichen Zusatznutzen der Luftqualitätsverbesserung auf mindestens 0,8 Mrd. € pro Jahr. (1 Mrd. €) bis 2030 für die EU40 (EU55) Politik und steigen bis 2050 auf 2 Mrd. € an. Die Co-Benefits des Vorziehens der Klimapolitik zeigen sich deutlich in den 2020er und 2030er Jahren, während bis 2050 auch im EU40 Szenario Klimaneutralität unterstellt wird.

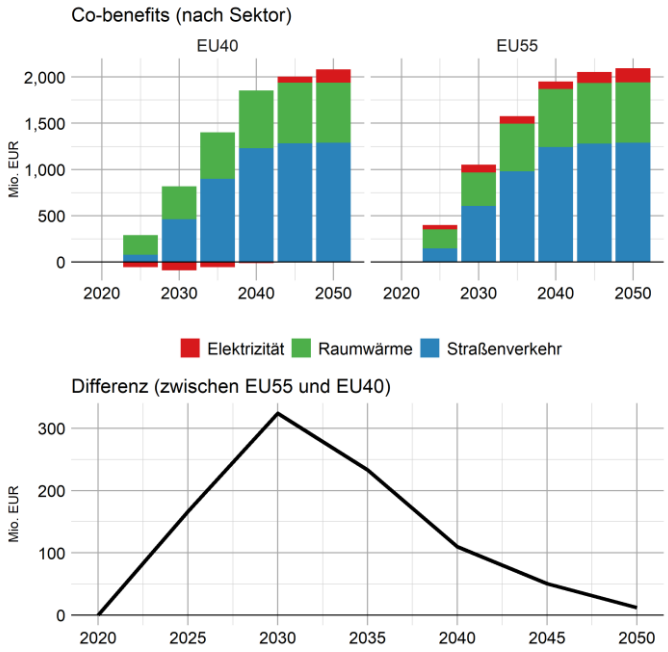


Abbildung DW.3 Zusatznutzen aus dem Bereich Gesundheit durch Luftqualitätsverbesserung in den Szenarien EU40 und EU55. Obere Reihe: absolut nach Sektor. Unten: absolute Differenz EU55 relativ zu EU40.

Ein strengeres kurzfristiges Klimaziel vermeidet teuren fossilen Lock-in im Gebäudesektor und stärkt die Technologieführerschaft in österreichischen Stärkefeldern

Wäre das frühere EU40-Ziel direkt auf den Gebäudesektor in Österreich umgelegt worden, so hätte wahrscheinlich ein Lock-in von fossilen Heizsystemen stattgefunden. Das Erreichen eines dekarbonisierten Gebäudesektors bis 2040 wäre dann mit (massiven) zusätzlichen Investitionen und einem "stranding of capital assets" verbunden, da im Jahr 2030 noch fossile Heizsysteme in Betrieb gewesen wären und vor Ende ihrer Nutzungsdauer im Jahr 2040 ersetzt hätten werden müssen. Mit dem Ziel der Netto-Kohlenstoffneutralität im österreichischen Gebäudesektor bis 2040 müssen Reduktionsmaßnahmen ohne Verzögerung und mit "2040-ready"-Komponenten beginnen. Das strengere EU55-Szenario ist mit diesem 2040-Ziel konsistent und vermeidet die zusätzlichen post-2030 Kosten eines fossilen Lock-in im Gebäudesektor.

Wettbewerbsvorteil bei klimaneutralen Technologien für Gebäude

Mit der Dekarbonisierung des Gebäudesektors in Österreich wird der Einsatz von Technologien wie kohlenstoffarmen Gebäudekomponenten, Wärmerückgewinnung und Heizungssystemen notwendig werden. In all diesen Bereichen hat Österreich bereits einen Wettbewerbsvorteil aufgebaut und könnte mit einer strengeren politischen Zielsetzung seine Position auf dem internationalen Markt weiter stärken. Während für

bautechnische Komponenten die notwendigen Technologien bereits auf dem Markt sind, besteht vor allem Entwicklungsbedarf bei kleinen, dezentralen Wärmepumpensystemen für Wohnungen in Mehrfamilienhäusern (inklusive Lüftung, Heizung, Kühlung und Warmwasserbereitung) sowie bei großtechnischen Wärmepumpensystemen. Im EU55-Szenario werden solche technologischen Lösungen in den nächsten Jahren in großen Mengen nachgefragt werden. Investitionen in die Entwicklung solcher Technologien würden es Österreich ermöglichen, nicht nur den eigenen Bedarf im Inland zu decken, sondern könnten eine technologische Führungsposition auf dem internationalen Markt generieren.

Österreich ist bei kohlenstoffarmen Schlüsseltechnologien gut positioniert, um neue Exportchancen zu nutzen

Stärkefelder in der Bahntechnik, der Stahl- und Zementindustrie sowie der Gebäudetechnik

Eine Analyse der aktuellen Leistungsstärke Österreichs bei emissionsreduzierenden Innovationen und den damit verbundenen Exportfeldern zeigt, dass das Land nicht nur bei Gebäudetechnologien, wie Wärmepumpen, Biomassefeuerungen, Nearly Zero Energy Buildings oder Passivhäusern, sondern auch im Schienenverkehr sowie bei kohlenstoffarmen Technologien für die Stahl- und Zementindustrie auf Stärken aufbauen kann. In diesen Bereichen ist Österreich gut positioniert, um neue Exportchancen zu nutzen, die durch strengere Klimaziele entstehen, indem die internationale Nachfrage nach klimaneutralen Produkten und Prozessen steigt. In anderen wichtigen Übergangstechnologien sollten gezielte Instrumente der Innovations- und Exportpolitik erwogen werden, um die internationale Wettbewerbsfähigkeit Österreichs zu erhalten bzw. weiter auszubauen. Beispiele sind Elektrofahrzeugtechnologien wie Batterien und Ladetechnologien sowie die Energieerzeugung aus Photovoltaik und Wind.

Erneuerbarer Strom stellt Europa vor globale Herausforderungen und bietet gleichzeitig Chancen in der Digitalisierung und der Entwicklung einer grünen Industrie

Nachfrage nach erneuerbarem Strom steigt in Österreich deutlich an

Im Zuge der Transition zur Klimaneutralität werden viele Bereiche der österreichischen Wirtschaft elektrifiziert (Mobilität, Heizung (Wärmepumpe), elektrolysebasierter Wasserstoff für die industrielle Nutzung, etc.). Bei einer aktuellen (2019) nationalen Stromnachfrage von 72 TWh zeigt unsere Analyse, dass die Stromnachfrage in Österreich bis 2030 um 17 bis 20 TWh steigen wird, zuzüglich der signifikanten Nachfrage durch neue Verfahren in der Industrie und durch im Inland produzierten Wasserstoff für Carbon Capture and Use-Prozesse, die für sich genommen bereits im gleichen Zeitraum jeweils noch einmal eine gleich große zusätzliche Nachfrage aufweisen könnten. Für die letztgenannten Bereiche und auf Basis der letztlich nachgefragten Dienstleistungen wird schnell deutlich, dass es viele Optionen gibt, um Klimaneutralität zu erreichen. Decken in Gebäuden können z. B. durch feingliedrige Schalungen mit 40-60% weniger Beton (und damit Zement) hergestellt werden, bei gleichzeitiger Erhöhung der Tragfähigkeit und zusätzlichen Funktionalitäten als aktivierte Bauteile zur Energiespeicherung. Wenn ein signifikanter Anteil der (globalen) Klimaneutralität in diesen Sektoren auf (erneuerbarem) Strom beruht – und Österreich seine Position nutzt, um sich einen überproportionalen Anteil daran zu sichern (d.h. die bestehende starke Wettbewerbsposition

in Sparten wie Stahl und Zement auch in Zukunft absichert), wird die heimische Nachfrage nach konkurrenzfähigem erneuerbarem Strom das heimische Angebot in einer vollständig transformierten Wirtschaft jedenfalls deutlich übersteigen. Einem langfristig verfügbaren heimischen Potential von nicht wesentlich über 100 TWh steht dann langfristig (2050) eine Nachfrage – je nach Szenario – von bis zu 145 TWh gegenüber. Bei einer Politik gemäß der EU-Emissionsreduktion von 55% (oder höher) wird die Elektrizitätsnachfrage höchstwahrscheinlich auch bereits im Zeithorizont bis 2030 das dann verfügbare Angebot übersteigen.

Es gibt Vorteile des Handels mit (erneuerbarem) Strom

Derselbe Nachfrageüberhang nach Energie war auch in der Vergangenheit gegeben und Österreich hat sich auf seine komparativen Vorteile konzentriert und davon profitiert, indem es beispielsweise billige fossile Ressourcen importiert und im Gegenzug hochwertige Stahlprodukte exportiert hat. In ähnlicher Weise können komparative Außenhandelsvorteile die skizzierten heimischen Engpässe bei erneuerbaren Energien mehr als kompensieren. Der komparative Vorteil in spezifischen industriellen Produktionsbereichen liegt für Österreich über jenem in der Energiebreitstellung, und es treten in diesem Fall Wertschöpfungsgewinne für beide Handelspartner (Industrielle Produktion, Energieproduktion; Export- bzw. Import-Land) auf. Es bleibt zu entscheiden, in welcher Form in Österreich erneuerbare (Solar-)Energie importiert wird, direkt als Strom, gebunden in Energieträgern (z. B. grüner Wasserstoff) oder gebunden in Zwischenprodukten (z. B. Eisenpellets), und wie hoch der jeweilige Anteil an diesen Elementen ist. Es ist wahrscheinlich – und vielversprechend –, dass ein gewisser Anteil erneuerbare Stromimporte sein werden (und entsprechende Exporte, die möglicherweise die Importe über die Jahreszeiten hinweg ausgleichen).

Erneuerbarer Strom wird zu einem globalen Markt werden

Globale Mächte, allen voran China, treiben den globalen Strommarkt durch neue Technologien und mit ausgefeilter Software voran. Da dieser Strom aufgrund der neuen Möglichkeiten von Batterien und Gleichstromübertragungsleitungen einerseits stabil, zudem erschwinglich und grün sein wird, werden Kunden auf der ganzen Welt ihn kaufen, auch in Europa. Dies ist ein Signal für Europa, seine Aktivitäten auf dem Gebiet des grünen Stroms so weit wie möglich zu beschleunigen, d. h. die ehrgeizigsten Ziele für den Klimaschutz zu verfolgen, um der Industrie einen starken Anreiz zu geben, und dies in ein starkes Programm für eine nachhaltige Digitalisierung einzubetten.

Erneuerbarer Strom als Lebensader für die grüne europäische Industrie

Es versteht sich von selbst, dass ein Stromnetz, das Milliarden von Prosument*innen miteinander verbindet, auch eine starke Herausforderung für die Entwicklung neuer Software darstellt. Ehrgeizige Projekte im Bereich des erneuerbaren Stroms werden auch eine Lebensader für eine grüne europäische Industrie darstellen.

1 Introduction

As part of the European Green Deal, the European Commission and the European Parliament had proposed to step up Europe's ambition for its 2030 climate targets, in December 2020 the European Council agreed to revise its climate target to an at least 55% reduction of greenhouse gases by 2030 (relative to 1990). This leads to important questions with respect to economic consequences on an EU-wide scale, but also on the national scale: What would the economic consequences be for the specific Austrian case? How – in economic terms – could Austria best meet its respective potentially new targets, especially in the context of the Corona crisis and its aftermath? What are the potential economic risks of remaining on the current policy path, given that the long-term targets of achieving climate-neutrality require substantial structural changes and strong policy interventions that are well set in a timely manner?

The goal of this study, commissioned by the Austrian Federal Ministry of Digitalization and Economic Affairs, is to provide a scientific analysis of the economy-wide effects of enhanced climate targets for Austria. It derives recommendations, including on the necessary framework conditions in Austria and beyond its borders that are needed to enable a welfare enhancing achievement.

We find that the economic implications of such a transformation crucially depend on the process and content of how the economic and energy policy framework is now set. We further find that the Corona crisis opens a window of opportunity, in which stepping up the climate target can address both crises at much lower costs than waiting for later. Moreover, we find that the core transformation steps in industry, commerce and society cannot be successful if the required framework conditions are set too late or not at all.

In the latter case, the EU's stepping up of climate ambition could even trigger a detrimental vicious cycle: The new normative pressure to change would then be coupled with incertitude ("we don't know how to make it") which would foster fear. This in turn – when lacking the necessary empowerment – could result in only a symbolic coping, i.e. re-assessing the situation as one not requiring any action. In other words, just stepping up the targets without increasing solution competence would be counterproductive.

This report seeks to contribute to avoiding such a vicious cycle and on the contrary to switch the discussion to one leading to a virtuous cycle and successful transformation. To encourage such a discussion, we here supply one basis for it, spelling out in detail how such a fundamental transformation could take place across all sectors, in terms of technologies, time scales, policy measures, and under which framework conditions. Given the sheer dimension of this transformation and challenge, we will not succeed in Austria if not all actor groups seek to contribute their expertise and – after mutually accommodating their perspectives – align behind a common target.

The report is structured as follows. Chapter 2 indicates the demands on a successful strategy to achieve climate neutrality and translates the GHG emission reduction target from the EU to the national level. Chapter 3 sets the economic stage of the Covid-19 aftermath. Chapter 4 identifies the core policy package elements across sectors, while Chapter 5 reports how these were translated into sector and macroeconomic modeling. Chapter 6 reports economic implications of climate neutrality pathways for different 2030 stringency levels. Chapter 7 identifies the core framework conditions that need to be set, and the final chapter discusses overall results and summarizes the main conclusions.

Throughout the report, all monetary values are given at the price basis 2018, i.e. in €$_{2018}$.

This report derives from a collaboration of research groups from the University of Graz, the University of Innsbruck, the Technical University of Graz, and the Environmental Agency Austria and was prepared during a given project duration time of 2 ½ months. An earlier version of this report served as one basis to foster the indispensable dialogue among industries and its many branches, the various actors in the fields of energy, transport and engineering, advocacy, public administration at

the federal, provincial, municipal and local levels, research, science and consultancy. This report benefited from the feedbacks of and discussion among 86 participants in a workshop on January 21st, 2021, of 69 participants in a workshop on January 28th and of 14 participants in one on February 2nd, for all of which we are very thankful. In parallel, within the scientific review, this report benefitted from extremely helpful comments by four international reviewers, by some of them at even multiple occasions for report versions at different stages, as well as by series of in-depth comments by colleagues from our own research groups, which we thankfully acknowledge.

We are looking forward to further and commonly explore transition pathways for Austria to ensure that a shared vision to the overall benefit of our country can be developed and ultimately materialize.

2 A Transformed Economy

> Probleme kann man niemals mit derselben Denkweise lösen, durch die sie entstanden sind.
> Albert Einstein

The challenges of transformation, societal goals and systemic strategies to achieve them

Mankind over the last decades has increasingly observed that the current system of production is eroding its very (natural) basis, an erosion taking place at a larger scale and higher speed than ever observed in human history. We note that the concept of planetary boundaries indicates that human activity is already acting outside what can be sustained for many of these boundaries (phosphor and nitrogen cycle, biodiversity) or is on a collision course (climate change) (Rockström et al., 2009; Steffen et al., 2015). The global community has both identified the corresponding challenges and agreed upon global targets to be achieved in order to avoid catastrophic outcomes: the Sustainable Development Goals (United Nations General Assembly, 2015), and for two areas specified in further detail: combating climate change (the Paris Agreement (UNFCCC, 2015) within the UN Framework Convention on Climate Change, (United Nations, 1992)) and combating desertification (United Nations, 1994).

The European Commission and Parliament has issued analogous suggestions to change course within Europe and the European Council has recently (on Dec 11, 2020) agreed to step up the EU climate targets to reach at least 55% greenhouse gas emission reduction by 2030, well beyond its earlier target of a 40% reduction (relative to 1990). We here focus on addressing the climate challenge and in particular the effects of the necessary increase of climate targets (European Commission, 2020a, 2020b).

Given the ultimate objective of our economic system to support mankind's welfare, this can also best direct our perspective on how to shape the transformation. Ultimately, we are interested in the services, sometimes called "functionalities," supplied by the economic system.[5] These "functionalities" include meeting basic needs, such as shelter, food, and access to people, goods and locations. It is helpful to reflect on these ultimate functionalities when designing a system transformation, as this allows a system-oriented approach. The aim of such an approach is to shift towards an economic system requiring significantly fewer (financial and material) resources, yet more clever design and value added, both during the transformation itself and after it has been accomplished, while keeping all functionalities satisfied. Taking the example of the transport sector, most of us do not see the ultimate purpose as spending each day driving 45 minutes in a private car, but rather on having access to our breakfast supply, workplace, or leisure location (the "ultimate functionality"). But the latter can be organized in very different ways. A change in spatial planning could grant access to a larger share of the population's demands by walking or biking, or a combination of these and public transport, thus reducing the aggregate amount of car mileage driven and accordingly reducing "mobility expenses". Recent experiences due to Covid-19 lockdowns have brought into focus the practicality and limits of videoconferencing to substitute for some in-person

[5] This concept builds upon the Human Needs Theory of Max-Neef (Max-Neef et al., 1991), the capabilities approach of Nussbaum and Sen (Nussbaum, 2000; Sen, 1999) and "A Theory of Human Need" by Doyal and Gough (Doyal and Gough, 1991); in the climate mitigation context Lamb and Steinberger (Lamb and Steinberger, 2017) developed a corresponding framework. The focus is on abilities or 'functionings' (rather than material goods (alone)). The classical and neoclassical basic economic concepts this builds upon are shortly reviewed in Appendix A.

meetings and thus also substitute for physical mobility. The remaining physical mobility, in a carbon neutral world, beyond walking or (e-)biking will be renewable energy based – likely electric – in a tram, train, or (electric) car (Wolkinger et al., 2012).

These are the three strategies that can best guide the transformation (Schleicher et al., 2018; Schleicher and Steininger, 2018, 2017), with founding work for the energy sector developed in (Köppl et al., 2011):

- **Inversion** focuses on the functionalities (or system services) relevant to prosperity, then follows the necessary value chains to their origin and thus reverses the sequence and consideration of associated decisions and evaluations. The strategy emphasizes starting our thinking at the ultimate objective we are interested in, and then proceed backwards, asking how such an objective can be supplied, progressing up value chains. For the mobility example: "How can we ensure access?"
- **Integration** discovers synergies through designs in systems instead of restricting our focus on their individual components. For the mobility example: "Which intermodal designs, based on respective hubs, are possible?"
- **Innovation** sets out on a conscious search for renewal and change in all areas that affect business and lifestyle, including technological and business models. For the mobility example: "What video-conference-enhancing framework conditions are advisable, what low-carbon power units can be developed, what sharing concepts for cars and bikes work?"

A recent perspective that has inspired the current Austrian government program (Bundeskanzleramt Österreich, 2020) denotes four levels of integrative climate policy: level 1 focuses on decarbonization by means of the substitution of fossil energy, level 2 on carbon management considering life cycle analyses (at the product level), level 3 focuses on the above three strategies (inversion, integration and innovation) in order to identify potentials of synergy in the supply of ultimate functionalities by analyzing the full value chain of supplying functionalities. The final level 4 emphasizes an integrative perspective on both energy and material flows to foster a circular economy, building upon the many potentials of fully integrating processes and products. Activities at none of these levels can be dismissed. To prepare for a climate-neutral Austria, we thus must ensure that we do not stop at levels 1 or 2 but move to integrate also levels 3 and 4 as soon as possible. This perspective adds the explicit focus of integrating material and energy flows in a circular economy to the strategy focus indicated above.

The occurrence of significant turning points, that we are to approach currently, is not new in socio-economic history. Repeatedly the same stylized pattern has been visible. From the 'Great British leap' in the 18th century to the 'Victorian Boom' in the early 19th century, from the 'Belle Époque' of Europe and the 'Progressive Era' of the US in the late 19th century to the post-war golden age of mass production and the US-led revolution in ICT – all of them started with an 'installation period', where niche developments led to the questioning of accepted customs. In these situations, distress and disruption prevailed and many societal actors were set adrift, fighting the new and desperately looking for guidance. A critical mass built up, pushing society to a new turning point. The ensuing 'period of deployment' led to thriving societies (Perez, 2016). The recent past indicates that the current situation is such a turning point ushering in a green and thus directed digital future.

Near term transition trajectory: The Austrian Effort Sharing target 2030

Current EU climate policy in force targets a 40% reduction in overall GHG emissions by 2030 (relative to 1990). However, recent decisions to move the EU towards climate neutrality by 2050 has led to stepping up the 2030 target. The European Commission has suggested a reduction of at least 55% (European Commission, 2020b) and the European Parliament voted to even recommend an ambitious 60% (European Parliament, 2020). The EU Council of Prime Ministers agreed on a reduction of GHG emissions by at least 55% by 2030 in December 2020. This enhanced target also brings the EU closer to its Paris commitments as well, as a 55% target is in line with its likely fair

share (given an equal share based on population) of emissions of a global carbon budget to reach a well below 2°C goal, but still falls short of achieving a 1.5°C goal (at a high likelihood) (Steininger et al., 2020b). Only a more ambitious target (65%) would align with the more ambitious limit in temperature rise.

Like the current 40% target, also the new goal will not be evenly distributed across countries and sectors. Sectors falling under the purview of the EU Emissions Trading System (ETS) will be covered under an EU-wide reduction target, due to the nature of the EU trading mechanism. However, outside of the ETS, so-called 'effort sharing' sectors will need to reach national reduction targets, and the way in which an overall EU wide 55% reduction target is distributed could have a large impact on eventual national allocations. Until now, effort sharing reductions have been divided across countries with consideration of primarily the capability aspect, reflected by national GDP per capita, but also further provisions. For Austria, this translated to a 36% reduction in non-ETS emissions by 2030, compared to 2005 levels.

New and more ambitious targets, however, could be based upon a number of economic, technical, or ethical considerations, as most recently described in (Steininger et al., 2020b), who provide a simple tool for use in developing likely distributions of the updated target, which we use as a starting point for developing non-ETS Member States allocation scenarios for this work.

For splitting the overall GHG emission reduction target into the ETS-sector and remaining sectors, we use the assumptions implemented in the Impact Assessment of the European Commission of Stepping up Europe's 2030 climate ambition of September 2020 (European Commission, 2020c). For an overall 55% GHG emission reduction target by 2030 (relative to 1990) this implies a 63% reduction target for the ETS sector (relative to the first year the ETS was effective, 2005, and without coverage of any further sector integration (such as transport) into ETS as currently discussed). Expressed in the ETS share in overall GHG emissions in 2030, this translates to a 35% share of ETS in overall emissions, with the remaining 65% being emitted by the non-ETS sectors of the individual member states. Depending on the approach towards effort sharing adopted in negotiations of EU member states, the final outcome in terms of Austrian non-ETS emissions target could most likely range between 48% and 52% reduction by 2030 (relative to 2005), compared to the currently effective target of 36% reduction.

For an overall EU 55% GHG emission reduction target (relative to 1990) we thus define an "Enhanced non-ETS emission reduction scenario" which is likely to result from the allocation and effort sharing negotiations. Under such a scenario, we assume a reduction of Austrian non-ETS emissions of 50% relative to 2005 as a central value, the median value of likely scenarios as shown in Figure 2.1. This results in a 2030 emissions target for Austria of at most 28 million tons of CO_2eq. for effort sharing sectors. Such a target would put Austria on a linear trajectory to approach carbon neutrality by 2040 and would be compatible with 2°C Paris targets (under the same equal-per-capita distribution of the global budget assumption as mentioned above), although likely falling outside 1.5°C goals[6].

For an overall EU 50% GHG emission reduction target, the ETS emissions target would fall to 59% by 2030, with corresponding non-ETS target ranges for Austria between 42% and 47%, and a central value of 31.3 million tons (or a 44.5% reduction compared to 2005). For a more stringent 60% GHG emission reduction target, the ETS target would rise to 67% of 2005 emissions by 2030, and non-ETS emissions for Austria would need to reduce between 54% and 59%. In this case, the median estimate of 2030 non-ETS emissions would be 24.9 million tons, or a 55.8% reduction compared to 2005.

[6] Given the large uncertainties in calculating global carbon budgets, a 55% target would fall within the range of uncertainty of a 1.5 degree goal with 50% likelihood, as well as the 66% likelihood, but that only barely, and is very far from the median scenario for each of those targets, while it is correspondingly much closer to matching the likely trajectory needed to meet a well-below 2 degree goal (Steininger et al., 2020b).

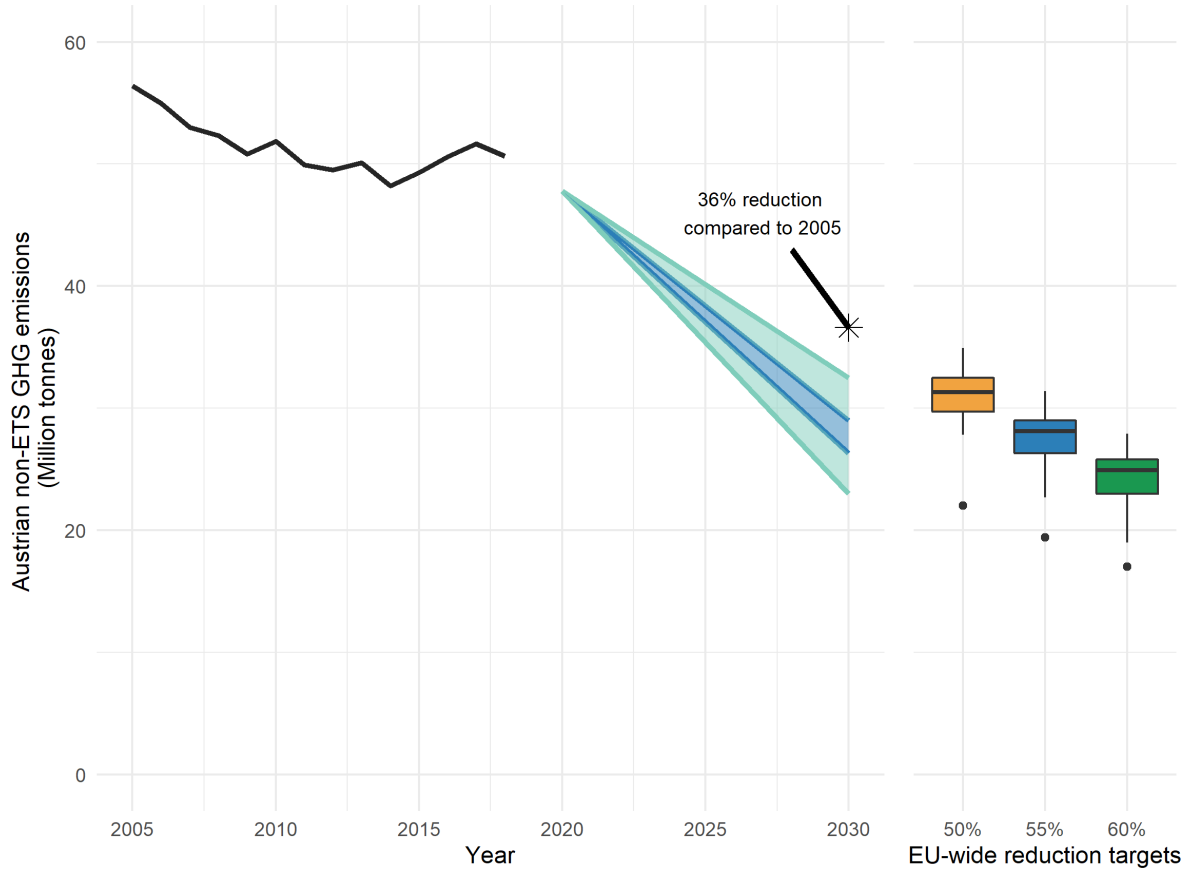


Figure 2.1. Range of possible 2030 targets for Austrian non-ETS ("effort sharing") emissions, based on the potential outcomes of deliberations to distribute a 50, 55, or 60% EU-27 GHG emission reduction target. The blue range indicates possibilities likely under a 55% reduction target, which we take as the starting point of our "Enhanced" scenario. The turquoise range (left panel) illustrates the potential spread of Austrian budgets for EU reductions between 50 and 60%. For the line chart on the left, the grey star indicates the previous target under 40% EU-wide reductions. In the box and whisker plot (right), the black lines within the boxes indicate median values, and the points indicate extreme outliers.

3 Economic Development and Climate Policy after Corona

Estimates of the size of Covid-19's impact on the Austrian economy understandably vary widely, due to the limitations of forecasting effects of a still further evolving pandemic. Nevertheless, for outlining a quantification of climate policy impacts in a (post-) Covid-19 world, a consistent scenario of the future economic baseline conditions due to Covid-19 effects is needed. In this section, we provide a cursory overview of the hypothesized future state of macroeconomic indicators compiled from various sources and define the assumptions on which we base our climate policy economic impact modeling. We also touch upon lessons to be learned from the crisis in terms of policymaking and the possible upsides for future actions on climate change mitigation.

The economic challenge

Defining possible future scenarios due to the current situation is difficult beyond normal economic forecasting due to the massive additional uncertainty surrounding the pandemic. As conditions in Austria and elsewhere change, projections adapt and evolve to provide a more apt picture, but some commonalities have emerged in terms of broad effects. Of the literature surveyed for this work (Baumgartner et al., 2020a, 2020b; IHS, 2020; International Monetary Fund, 2020; Poledna et al., 2020; Ragacs et al., 2020; Schiman, 2020), coinciding with most estimates in other regions of the world, the effects of the pandemic and associated lockdowns and distancing is expected to sharply reduce growth in 2020, with estimates of yearly GDP growth for Austria ranging between -7.7 and -4%. Similarly, unemployment rose significantly, with 2020 estimates for Austria between 5.4 to 5.5%, an increase of around 1% from the previous year.

Similar concordance can be seen in the estimates of future effects, e.g. into 2021 and beyond. While early studies (Poledna et al., 2020; Ragacs et al., 2020) did not take into account the possibility of a second lockdown, in comparison to more recent estimates (such as (Baumgartner et al., 2020a; International Monetary Fund, 2020)) all predict that following the massive downturn of 2020 GDP growth will return to positive levels in 2021, coinciding with a slight lowering of unemployment. Given the second lockdown, growth for 2021 is predicted to be much lower than the 4% from early 2020 estimates, or close to zero (Baumgartner et al., 2020a, 2020b) but will still be positive for the year. Regardless of a rebound in 2021, growth will not be large enough to return most countries and particularly Austria to its pre-Covid forecast predictions; GDP will likely not return to such levels until 2022 or beyond (Baumgartner et al., 2020b; Poledna et al., 2020).

However, it should be reiterated that uncertainty abounds. Projections made in the summer of 2020 do not take into account the stalling recovery due to resurgence of Covid-19 cases and the new lockdowns that many European countries faced in the end of 2020 and early 2021.

The period of lockdowns for Austria beginning in November 2020 and lasting on and off until mid-February 2021 resulted in a forecast GDP reduction for the year of 7.3 percent (Schiman, 2021). Despite ending the year in lockdown, effects were not unduly large, due to both the strong recovery during the summer period and the lack of interruption of e.g. international supply chains, in contrast to the first lockdown (Schiman, 2021). The most recent COVID measures have affected primarily service sectors, resulting in less macroeconomic effects than initial measures. Given the status of COVID policies in late February 2021, the latest scenario modeling from WIFO (a 'no policy change' scenario) projects that a rise in economic output in Austria could be seen within the first quarter of 2021, but the substantial and rapid rebound in economic activity following the first round of severe lockdowns may not hold true in the future, as relaxing of measures will likely be more conservative than in the spring of 2020. Other unknowns, particularly relevant for a recession focused mainly in service sectors – as opposed to conventional recessions which heavily affect production of goods – involve the extent of global spillovers from lessened demand and weak tourism, the latter a particular concern for Austria; the full extent of winter tourism impacts due to shuttering of hotels and a lack of foreign guests is not yet known. As international tourism will

likely only slowly return to pre-COVID levels, recovery in the service sector could be dampened further as a result.

Even so, given the current state of COVID incidence and the measures to contain its spread, it is forecast that GDP growth will return to positive levels in 2021, with a yearly change up to 4.5% compared to 2020. Due to a further surge of the virus, emerging new variants and the corresponding policy change, at the time of publication of this report (end of February 2021) current forecasts are revised downwards (Badelt, 2021). In terms of the labor market, the recovery is not projected to be as swift, with unemployment falling in 2021 by 5.4% compared to 2020, but still sitting at 28.5% above 2019 values, a deficit predicted to last into 2022 and beyond (Schiman, 2021).

Scenario assumptions used in this work

The macroeconomic modeling undertaken here in a thus adapted computable general equilibrium framework requires a number of assumptions as to growth paths, sectoral activity, the effect of investments, unemployment etc. (namely without additional climate policy), for both Austria and the rest of the world. While there have been a number of applicable estimates for Austria produced before the second lockdown, they do not apply a consistent methodology including other world regions which is needed to determine export / import demand and prices in the model. Additionally, they likely overestimate the GDP and employment shock in the current year, while similarly overstating the rebound in early 2021, as early works did not anticipate the strong rebound in summer 2020 nor the second lockdown in November.

As such, we rely on the recent International Monetary Fund global forecast for 2020, which applies a consistent approach using the latest national data available as of October 2020. While not explicitly taking a second lockdown into account, the study does err on the side of caution with regard to the resurgence of Covid-19 cases, particularly in Europe. Globally, IMF predicts -4.4% growth for 2020, rebounding to +5.2% in 2021, which reflects the continued but likely diminishing effect of social distancing and the pandemic as therapies likely become available in 2021. Beyond 2021, growth is expected to slow down, not returning to previous growth paths for 2020 to 2025. Increased output gaps (the difference between actual and potential economic output) will persist beyond into 2021 and could be particularly pronounced in Europe (e.g. Spain: -7.6%, Italy: -5.5%, France: -4.75%, and Germany -3.6% for 2020-2021, as compared to -1.6%, -1.7%, -2%, 0.5% respectively for years 2022-2023).

Austria is expected to follow the same general trends in the main IMF scenario; 2020 GDP could fall by -6.7%, with a rebound of +5.4% in 2021, with unemployment rising to 5.8% in 2020, and only partially recovering job losses in 2021 with a rate of 5.5% (both rates expressed in Eurostat terms). Medium-term forecasts see slowing growth to 2025, with a projected rate of 1.6%, meaning a languishing return to pre-Covid levels.[7]

Silver linings – opportunities for climate policy

While the crisis has presented an enormous challenge for Austria and the rest of the world, there are positive aspects to note, particularly regarding future climate policymaking. The rapid and aggressive response to the pandemic can be viewed as a potential example of the lengths governments can go to in order to solve pressing global issues. In Austria alone, the initial crisis management fund laid out in March was allocated EUR 38 billion (almost 10% of 2019 GDP) to provide loans and subsidies for self-employed workers, funds for fixed costs for vulnerable companies, tax deferrals and bonuses for new – and notably, explicitly climate-friendly – investments. This represents just a small portion of government action, with government providing employment support ("Kurzarbeit"), loan guarantees, as well as removing barriers to Covid-compliant workplaces (particularly with regards to extension of deadlines and easing of customs related regulations) (KPMG, 2020). In the second lockdown of the fall 2020, the government has pledged to reimburse affected businesses at a rate of

[7] Given this uncertainty in the actual size of the current impact on GDP and employment, the numbers used in this evaluation may – retrospectively – evidently differ from the ones actually observed.

80% of their revenues based on the corresponding month in 2019. This alone is estimated to cost up to 2 billion EUR (Baumgartner et al., 2020a).

And Austria is not alone in the rapid and aggressive response; recent work has shown that the global Covid-19 recovery packages massively outpace the needed investment to put the globe on a path to meeting aggressive climate goals (Andrijevic et al., 2020). Such measures, in Austria and abroad, demonstrate that the hurdles to effective climate policy can be crossed; similar aggressive and comprehensive policies to put the country and the globe on a low-carbon trajectory do not seem as unrealistic and demanding when put into context by the policies of the pandemic.

Beyond the demonstration of the lengths to which governments can go when given adequate motivation, Corona relief measures can also have positive effects in terms of climate change. Emphasis on reducing dependencies on global supply chains and instead improving the robustness of local production, would lead to reduced transport demand and costs as well as carbon leakage. At the same time, recovery funds promoting innovation (e.g. grants and bonuses for climate-friendly or zero-impact initiatives) are directly applicable to climate policy, which should encourage innovation at home to improve competitiveness and find new solutions to reduce emissions (Köppl et al., 2020).

For 2020, the Covid-19 induced reduction in economic activities is estimated to have reduced GHG emissions by about 9% (relative to 2019) (Umweltbundesamt, 2021). However, at least in 2020 this reduction was not yet due to a structural economic change, and thus is only temporary. Some of the measures set (enhanced tax breaks for green investment) have likely contributed to a future structural change, but further substantial efforts are indispensable to reach both the significant 2030 climate targets and the climate neutrality target for 2040.

4 Core Policy Package Elements to Achieve Carbon Neutrality

Lebe jetzt die Fragen. Vielleicht lebst du dann allmählich,
ohne es zu merken, eines Tages in die Antwort hinein.
Rainer Maria Rilke

In order to fulfill a more ambitious 55% reduction goal of the EU (relative to 1990) Austria will, as laid out in Chapter 2, likely need to reduce GHG emissions in non-ETS sectors by 50% in 2030, compared to 2005. Such a stricter target at the EU level and its translation to Austria will of course require stronger and/or faster reductions in both non-ETS (or effort sharing) sectors (accounted for at a national level) and ETS sectors (with the target accounted for at the European level). Since GHG emissions have fallen only moderately since 2005, this requires a substantial reduction over the 10 remaining years from now (2021), with respective significant action in every aspect of life. Every economic sector as well as the population at large will have to participate in this effort and will be exposed to the effects of a transformational policy package. This being said, certain sectors do have an outsized contribution to the emissions balance for the country, and thus we focus on them in particular, and rely on broad, cross-cutting measures to address what area specific policies may neglect.

Thus, we focus explicitly on the energy and industrial sectors (mainly covered by ETS), as well as the transport and building sectors (under national, so called "effort sharing" responsibility), as they together accounted (both directly and indirectly e.g. via the transport and building sectors use of energy) for 89.5% of total GHG emissions in 2019 (excluding Land Use, Land-Use Change and Forestry (LULUCF)) (Anderl et al., 2021). As climate policy in Europe involves multiple jurisdictions (EU, countries, subnational regions), initiatives at the individual jurisdiction level may overlap with the wider European system, in particular the European ETS. For example, a national initiative to foster e-mobility will reduce domestic transport emissions (to date a non-ETS sector) but enhance electricity demand (an ETS sector); or domestic support programs for renewable energy will reduce domestic emissions in an ETS sector. The climate benefit of such overlapping policies depends on their design, location and timing. Perino et al. (2020) developed a framework to identify whether there are interactions and if so to distinguish when policies leverage additional climate benefits elsewhere in the system, or when they backfire by raising aggregate emissions. It is important to account for these interactions, and the quantitative analysis reported here is set up to acknowledge emission implications of such overlapping regulations.

Greenhouse gas emissions: sector contributions

In Austria, the industry and energy sectors are responsible for 43.4% of GHG emissions (reference year 2018) (M. Anderl et al., 2020), resulting in the stringent need for deep decarbonization options to achieve EU climate targets. Thereof, the energy sector contributes 12.6% to the overall GHG emissions and includes public electricity and heat production (without waste incineration) (7.5% of the Austrian total), refineries (3.6%), the extraction and transportation of fossil fuels as well as diffuse emissions from energy production and distribution. The industry sector accounts for 30.7% of Austria's GHG emissions. Within the industry sector the iron and steel industry (14.2%) is among the largest single contributors considering both combustion and process emissions. Remaining combustion emissions across industry account for 11.7% of the Austrian total; all other emissions are process emissions, i.e. arising from chemical processes that can only be avoided by technological shifts (or carbon capture). These amount to 4.8% of the Austrian total, of which the non-metallic mineral industry (including cement) contributes the largest share (3.7% of the Austrian total) (Umweltbundesamt, 2020). The present study – in terms of industrial sectors – thus focuses in more

detail on the iron and steel industry, the chemical industry and the cement industry, all of them also facing high process emissions. This results in more detailed decarbonization strategies depicted for these industry branches, including a shift to new low-emission processes, (renewable) hydrogen, electrification and carbon management in a circular economy (e.g. carbon capture and use, CCU). The remaining industry branches include food and beverages, electronic equipment and manufacturing, engineering, glass, leather and textiles, petrochemical, and paper and pulp industries. In addition to the strategies mentioned above, energy efficiency as well as changes in production technologies (intermediate demand) also have a crucial role to play.

Second to industry and energy, the transport sector was responsible for 30.3% of all greenhouse gas emissions in 2018 (M. Anderl et al., 2020), thus motivating its explicit and detailed consideration in this work, including both passenger and freight transport. In a country characterized by significant urban sprawl, cars dominate passenger transport and cause it to account for two thirds of GHG emissions from transport (with rising emissions over the last years). Freight transport is a large contributor to overall emissions mainly due to the heavy focus on diesel-fueled road transport. Rail cargo, which is to a large extent electrified, accounted for only 24% of total transport volume in 2018, while on the road (74% of total transport volume), diesel engines accounted for nearly 100% (Statistik Austria, 2019a). In order to reduce emissions, lower transport levels (induced inter alia by transport-saving spatial planning and new production modes, such as 3D printing) and a significant change in modal split for the remaining transport towards environmentally benign modes (walking, biking, public transport, rail freight transport) is crucial, along with incentivizing the use of other fuels and technologies in road transport. Barring any major policy intervention, freight transport is likely to rise with increasing rapidity; while it has nearly doubled since 1990 ((Plötz et al., 2018), 13; (TRAFICO et al., 2009)), estimates find that by 2030 freight transport performance and ton-mileage may rise further (Rail Freight Forward, 2019).

The building sector via its direct operating emissions (fossil fuels for heating) accounts for 10% of Austrian GHG emissions. If the whole life cycle of buildings is considered, the share is significantly higher. If considered thusly, at the global level 39% of GHG emissions are accounted for by buildings (GABC, 2019), including the construction of the building, the materials, the building operation and end of life. It is therefore crucial to reduce both direct and indirect emissions from buildings in order to achieve ambitious climate targets. Operational emissions largely depend on the energy sources used for heating and cooling, as well as – with increasing relevance – on the electricity mix. Reductions in both energy demand and emissions can be achieved through higher standards for new buildings, as well as refurbishment of the current building stock. Ideally, refurbishments both increase energy efficiency through better insulation, and change fossil fuel-based heating systems to renewable energy. Indeed, it is crucial that both targets are addressed simultaneously, reducing energy demand and transferring it fully to a renewable basis – either in the building sector itself (independent of energy supply) or in the energy sector (if district heating or electricity are concerned). If only one is addressed this will either be insufficient or can even be counterproductive, and holds for buildings as it does for all the other sectors. E.g., in a setting with a fixed absolute cap in the European ETS, a target to just increase energy efficiency of electrical appliances (e.g. heating systems for buildings, or electric cars for the transport sector), will backfire and increase aggregate GHG emissions, as both ETS emissions will unambiguously be unchanged (i.e. the reduced heat pump or e-car electricity demand will be counterbalanced by rising emissions from elsewhere) and the reduced operation bill for the heat pump or e-car will raise expenses for other goods (rebound effect) and according emissions in sectors without an emission-cap (Jarke-Neuert and Perino, 2020). Whether recent and more sophisticated revisions of the ETS, in particular the Market Stability Reserve (MSR), can mitigate or fully avoid such a "waterbed" effect, is at least uncertain (Bruninx et al., 2019; Perino, 2019). Thus, interactions between the ETS and non-ETS sector policies need to be factored in, for the above example of additional electric-efficiency-enhancing policies an accompanying reduction in ETS allowances would only ensure actual GHG emission reduction. Conversely, only transforming the energy sector to renewable energy will likely imply aggregate energy demand beyond available renewable potentials, if efficiency is not simultaneously addressed.

Agriculture (excluding direct energy use accounting for 9.2% of Austrian GHG emissions in 2018) and Waste management (3.2%) contribute major shares of non-CO_2 GHGs (methane, nitrogen oxides). Emission reduction strategies in these sectors include comprehensive circular economy approaches, diet changes and production process innovations.

Policy framework

To provide a policy framework for the instruments needed to achieve emissions targets in line with the guiding strategy bundle inversion/integration/innovation, we adopt the *Avoid, Shift, Improve* (ASI) approach, which was initially developed by the German Corporation for International Cooperation to structure policy measures in the transport sector with the goal of reducing environmental impacts (Bakker et al., 2014). While it originally focused on reducing the impact of rapid motorization in a development context, it rapidly gained wider use and broader acceptance around the world in a multitude of contexts (Dalkmann and Brannigan, 2007; EEA, 2012). The framework has recently been proposed as a more generalizable way to think about demand-side solutions to meeting climate targets, highlighting its benefit in enabling the identification of possible cross-sectoral measures and allowing for intersectoral learning (Creutzig et al., 2018).

The three aspects of the ASI framework are (Bongardt et al., 2019; Creutzig et al., 2018):

- Avoid (or Reduce): Refers to the need to change the system or sector in such a way as to allow for reduced material use or consumption while maintaining at least the same service, such as e.g. avoidance of trips via private car due to improved spatial planning or producing higher quality goods that are used longer, and thus need to be purchased less often.
- Shift: Focuses on modification of a current behavior or consumption patterns, e.g. by changing the manner of travel from car to bike, or by changing the use of a CO_2 intensive input in production to a climate neutral variant.
- Improve: Refers to changes which allow the current sector or process to occur with higher efficiency and/or less emissions, such as the replacement of conventional cars by electric vehicles or the introduction of more energy-efficient appliances. We note, that if higher efficiency addresses an energy carrier regulated under a thereby not changed cap (such as electricity under the current European ETS), addressing efficiency only is likely to backfire and thus needs to be complemented with other measures (see subsection “Sector contributions” just above).

In the context of this report, “avoid” raises productivity of the welfare generating economic system. Inspired by the inversion strategy, the at-least-same-level functionality is supplied, yet at (possibly significantly) lower (material) input, while a shift to increased (human) capital input (smart solutions) may occur. “Shift” can follow from the integration strategy, indicating a more comprehensive employment of infrastructure and operational design. “Improve” approaches enhance productivity and efficiency in the most direct technical sense. In terms of innovation, all three classes of instruments in the above framework can be related to the strategy.

Below, for the purpose of being able to model the economic implications, we outline one exemplifying set of necessary policies to transform Austria and place it on a low-carbon trajectory to 2050, organized within the ASI framework, and identify any cross-sectoral policies or synergistic approaches that might emerge.

A summary of the main target policies included in our aggregated model packages can be found in Table 4.1 at the end of the chapter. Note that quantitative modeling of these policies is implemented for policy packages, not single policies, in order to keep result data and tables at a level of disaggregation still well comprehensible. Nevertheless, specific and detailed polices are stated in the following, as these inform the parametrization of the packages’ modeling.

Avoid

Industry

Within the industry sector, avoidance is achieved by either producing higher quality products or by demand-management strategies. In other words, the production of high-quality industrial goods balances tailor-cut consumer needs and economies of scale thus requiring less emissions and raw material but creating more added value. Demand-management strategies, however, tackle the overall consumption of products and concentrate more generally on incentivizing the reduction of material throughput (reduction of material consumption).

Chemical industry

A reduction of GHG emissions in the chemical sector, especially in the production of plastics, could be achieved with demand-management strategies. The emission reduction effect by avoiding plastic products is shown by Zheng and Suh (2019) for worldwide plastic demand. Fostered also by the growth of global population, a worldwide annual growth rate in plastics of 4% is expected and would produce a high burden of additional lifecycle GHG emission until 2050. According to Zheng and Suh (2019), a reduction of 56-81% of additional life-cycle GHG emissions (depending on the energy mix) until 2050 could be achieved if this global growth rate in plastics could be reduced to 2%.

Cement industry

Demand management strategies and a more efficient use of cement would also lead to emission reductions in the cement sector. Accordingly, one would expect a lower demand if cement could be used more efficiently, especially in the construction sector. For example, due to different cement content in concrete the statistical span of the embodied emissions of CO_2 /m^3 in current ready-mix concrete is found to vary by 30%, while in all cases meeting the required performance criteria of concrete. Similarly, the mixing processes (onsite vs. ready-mix plant) of concrete can have an impact on the amount of cement required and thus reduce the demand for cement (Habert et al., 2020). In concrete component construction itself, substantial reductions are feasible. For example, for ceiling constructions adequate formworks can reduce concrete demand by up to 60 to 70%. In order to further promote these strategies, standards requiring procurement and building codes to favor low embodied emissions components as well as technological standards that qualitatively define the mixing methods and the required cement content in the concrete mix can both ease a faster reduction in emission caps.

Transport

Avoidance of physical passenger transport is centered on infrastructure policies and the improvement of (legal) framework conditions, focusing on reducing the need for transport. Policies that work to that end first relate to spatial planning and infrastructure development. The goal is to enable basic aspects of day-to-day life (working, shopping, leisure time) to be met within short distances, thus substantially increasing the share of environmentally benign modes such as walking, biking or public transport. In suburban and rural areas, the focus will be on fostering central locations, while in urban areas the focus will be more on expanding green spaces and providing public living space for people, including the conversion of road and parking infrastructure, thus decreasing the demand for “escape travel” for leisure and on weekends.

Another key aspect of avoiding transport emissions is the possibility of teleworking. The option of videoconferences and working from home opens new possibilities of avoiding passenger transport and has gained broader acceptance on both the employee- and the employer-side during the pandemic. Policies regarding telework include the legal entitlement to conduct a certain work/time share by means of telework. However, enhancing telework by itself does not necessarily reduce transport flows; compensating effects may dominate (e.g. commuting distances increasing); therefore, adequate overall framework conditions are also crucial for this policy, if it is to contribute to a low-carbon pathway.

In terms of freight transport, there are three possible approaches to avoiding emissions. The first involves the shifting of production of industries to favor a more regional or localized structure balancing economies of scale and transport distances, either because of technological change or due to policy or preference changes. Technological change could come about via additive production such as 3-D printing which could reduce the need for transportation of intermediate goods, while policies or preferences could affect transport due to higher shipping prices (internalization of all transport costs) or enhanced consumer awareness of local goods. Similarly, policies or consumer preference shifts could lead to buying higher-quality and longer-lived goods, thus reducing transport burden for new goods. The last approach involves improving logistics and road freight operations to increase efficiency and reduce transport flow and incidence of trips without freight. Incentivizing supply chain collaboration and construction of urban distribution hubs ("Sammelzentren" – with collaborative local distribution of otherwise distinct supply service providers) is the core of this avoid policy and can potentially achieve energy savings between 20 and 50%. ((IEA, 2017), p.130-131)

Buildings

Avoiding GHG emissions in the building sector can take many forms, including constructing nearly zero energy buildings (nZEBs). to avoid operational emissions. The embodied GHG emissions in new constructions can be reduced by using construction materials with a low full life cycle related impact.

In this study, we focus on the avoidance of new operational energy demand in newly constructed buildings, i.e. by the construction of advanced nearly zero energy buildings with useful energy demand according to OIB 10 line with high-efficiency building technology including mechanical ventilation with heat recovery, and by deep renovation with passive house components. In order to reach very low heating demands, new buildings should be built with stricter requirements than the current Österreichisches Institut für Bautechnik (OIB) standard, i.e. reducing useful heating demand to 10 kWh/m2GFA. This high standard, in combination with shift measures (see next section below), will be crucial to achieving more ambitious GHG targets.

In addition to new buildings, operational energy demand needs to be reduced particularly in existing buildings. There are three types of refurbishments considered: (1) deep refurbishment of the building envelope (the external walls and roof as well as windows, including improved air tightness); (2) substitution of the heating system, or (3) both combined. The replacement of the heating system is covered in the "Shift" section, while the integration of on-site PV is accounted for in the electricity sector. The deep refurbishment of the building envelope aims to reduce the space heating demand through the insulation of the walls and roof, new windows, and improved air-tightness (ideally in combination with mechanical ventilation with heat recovery).

Currently, the rate of subsidized refurbishments of residential buildings is below 1%. However, the equivalent total refurbishment rate (including both subsidized and non-subsidized refurbishments) is approximately 1.5% for Austria (Amann et al., 2020), and is slightly unevenly spread across its provinces, e.g. it has been identified to be at 1.3% for Tyrol (Ebenbicher et al., 2018). The current refurbishment rates should therefore increase and should aim at very ambitious energy levels, if possible down to passive house levels in order to reach the emission reduction target (BMNT und BMVIT, 2018; Bundeskanzleramt Österreich, 2020) and to guarantee a substantial reduction in the energy demand of the building sector. As renewable energy carriers' availability is limited in Austria and neighboring countries also strive to achieve climate targets, a substantial increase in imports of renewable energy from neighboring countries may not be possible in the future – both on a net basis, but especially in winter. Hence, the reduction of the energy demand in all sectors is crucial.

Deep refurbishment should focus primarily on less performant or older buildings, which would require renovation anyway, to achieve the best possible reduction at low additional costs. Moderately efficient renovated buildings are not likely to be renovated again for a couple of decades, given the lifetime of building components and the financial burden on owners to recover the original renovation upfront investment. As an example, no one would agree to replace windows 10 years after their installation. Hence, moderate improvements in energy performance have a negative long-term effect, known as the "lock-in" effect. The long lifetime of building components of more than 50 years and heating, ventilation

and air-conditioning (HVAC) components of more than 20 years involves a high danger of lock-in effects in the building sector. This implies that any (private or public) investment made today needs to be compatible with net-zero emissions in 2040, i.e., either already zero-emission or relying on a centrally provided energy carrier such as electricity for which a net-zero strategy exists.

In addition to new construction, new buildings and newly refurbished buildings should implement room temperature control in order to avoid excessive temperatures and thus avoidable overheating throughout the day (referred to as rebound effect). Mechanical ventilation with heat recovery and shower drainage water heat recovery can significantly contribute to reduce energy demand while maintaining a high level of comfort and indoor air quality. Other possibilities to avoid emissions would be the reduction of net space per person or the reduction of temperature i.e. a reduction of the energy service, however, this is not likely to be acceptable to, let alone preferred by, the majority of the population and is therefore not considered as a policy here.

Shift

Industry

For industry at large, shift measures support either a fundamental change of the production process or the use of alternative energy sources and raw materials. Overall, the shift to alternative fuel such as (renewably produced) hydrogen and increased use of electricity from renewable energy requires either adjusted equipment or completely new production facilities. In order to accelerate the shift to such new production sites/processes and the use of alternative fuels and raw materials, large financial investments are required. Therefore, a national transition fund, bundling private capital with public/federal funding – and in project financing complemented by EU funding – will give a boost to the technological shift in Austria's industry sector. Given the variability of renewables' supply, the adjustment of production processes relying on electricity to become more flexible and therefore able to respond to the time- and location-specific availability of electricity would be an important contribution to integrating a higher share of renewables in the power sector. Instruments that could foster such adaptation include nodal pricing, by which electricity prices reflect not only overall scarcity but also local and time-specific scarcity, the relevance of which rises with the market share of renewables.

Iron and steel industry:

In the iron and steel industry, such a shift includes the switch to a renewable energy and hydrogen-based production route. Firstly, renewable electricity or green gas can be used as the main energy source, substituting fossil energy for providing process energy. Secondly, electrolysis for production of steel from iron ore can have higher energy efficiency and can give steel of higher quality. Thirdly, in the conventional production route coke is used as a reduction agent when processing iron ore to pig iron, leading to a high amount of CO_2 as a waste-by-product. These process emissions can be avoided by using hydrogen for the reduction process which generates water (H_20) as a by-product.

Today, the conventional route applies a blast-furnace (BF) and an ensuing basic oxygen process (BOP) fueled by fossil energy (coal) and coke as a reduction agent. In order to fully switch to a hydrogen-based steel production, two alternative processes could be applied, either direct reduction of iron ore (DRI) with further treatment in an electric arc furnace (EAF) or plasma direct steel production (PDSP). The DRI/EAF route is ready for implementation, with a transition phase using methane as an energy source and hydrogen as the reduction agent, until fully shifting to hydrogen whereas the PDSP route has only reached laboratory scale and requires further research developments (Mayer et al., 2019). For the electrolysis of iron ore for steelmaking, industrial maturity will need longer than the transition to hydrogen-based methods. Still, if other regions would succeed with electrolysis, they might be (substantially) more competitive so that extended research into electrolysis can be considered highly recommendable.

Chemical industry:

In order to achieve decarbonization in the chemical industry, the low-carbon production of base materials is central (Windsperger et al., 2018). These base materials are: (i) chlorine with caustic soda as a by-product, (ii) ammonia and urea for fertilizers and plastics, (iii) methanol for syntheses and (iv) olefins (ethylene, propylene) as central raw materials for plastics and many other products.

The shift towards low-carbon production of chemical base materials includes four decarbonization strategies (Windsperger et al., 2018; Windsperger and Windsperger, 2020), the first being the electrification of chemical processes such as steam production, mechanical steam recompression and the operation of industrial furnaces and drives. Second, for hydrogen – as an input for chemical synthesis – to switch to "green" hydrogen. In other words, conventionally generated hydrogen by gas reformation of methane needs to be substituted by a renewable process such as in particular the electrolysis of water, based on electricity from renewable energy sources. Therefore, processes such as alkaline electrolysis, proton exchange membrane (PEM) electrolysis, or steam electrolysis with ceramic membranes need to be applied. Third, the fossil feedstock for base materials such as methanol and olefins can be replaced by hydrocarbons from a circular material flow or biomass. The use of hydrocarbons means that CO and CO_2 captured within other sectors (e.g. iron and steel sector, cement and mineral production, energy sector) constitute a low-carbon alternative feedstock for further synthesizing with hydrogen into methanol and olefins. Alternatively, biomass from wood and crops are processed with a gasification technology or within a biorefinery (see also Appendix I for Material Use of Biomass). The gasification process yields a synthesis gas which can be used for the production of all basic chemicals. In the biorefinery, the biomass is fermented and bioethanol is manufactured. Fourth, intensified recycling has the potential to provide a large amount of the feedstock needed and is therefore a central pillar for the climate-neutral transformation of industries. For that purpose, different recycling methods exists – either mechanical or chemical – which are applied depending on the waste material and on the grade of purity of the produced feedstock. Chemical recycling, although producing feedstock of higher quality, is not implemented on a large scale today but will potentially diffuse in the next decades (Netherlands Institute for Sustainable Packaging, 2018). Considering also raw material constraints, a mix of all four decarbonization strategies is most likely.

Cement industry:

In the cement industry, the main shift strategy is a switch to alternative fuels. Thermal energy is required for the operation of a rotary kiln, where clinker is reduced to cement. This process requires a high amount of thermal energy, typically provided from fossil fuels such as oil, coal and gas. A shift to alternative fuels lowers combustion emissions from the kiln. Alternative fuels can be sourced from waste streams such as used tires, pretreated industrial or municipal wastes, used oils and solvents, plastics, textiles or paper wastes, sewage sludges, or waste wood. While average substitution rates are at 41% in Europe, some plants in Austria already operate at full substitution, contributing to an overall rate of alternative fuels already above 80% in Austrian cement production (Schneider, 2019).

Another way to achieve a reduction of GHG emissions is the substitution of cement constituents with alternative materials, called supplementary cementitious materials (SCMs) (Habert et al., 2020). This is especially relevant for replacing a considerable proportion of clinker, as the constituent dominating the overall GHG balance of cement (process-related emission). The most widely used SCM is fine limestone although it has a limited reactivity and therefore is primarily used as a filler and not a cementitious material. Other SCMs, which decrease the environmental impact of the cement production (especially because they are by-products from coal-fired power plants and the iron and steel industry) are fly ash and blast furnace slack. Although their contribution could be further increased, decarbonization in the energy sector and iron and steel sectors must be considered, as this leads to a phase-out of technologies producing those by-products. High potential is seen in the use of calcined clay, as clay is abundantly available worldwide and is highly reactive. Calcined clay in combination with fine limestone seems the most promising SCM for substituting clinker.

Remaining industry:

For the remaining industry sectors (except electronic equipment and engineering), the main emission source is process heat, which is currently produced from fossil fuels. In order to decarbonize the required process heat, two strategies exist. The process heat can either be generated by bioenergy (with or without combined heat and power (CHP)) or processes will be electrified and fed by electricity from renewable energies (Bataille et al., 2018; Gerres et al., 2019).

Box 4.1: The paper and pulp industry

Within the low emission industries, the pulp and paper industry is a special case, as it is very close to being an energy-intensive industry. Furthermore, there will likely be different development trends for different forms of paper in the next decades. While graphic and some specialty papers have experienced a decrease in demand, others like packaging and hygienic papers have experienced an increase in Europe in the period from 2010 to 2016 (Moya and Pavel, 2018). The use of paper for packaging in particular will become more relevant in the future if plastic packaging is substituted. However, total paper demand in Europe is expected to increase only by about 7% from 2015 to 2050, a projection based on historical data and population growth (Moya and Pavel, 2018).

While this – compared to other product groups relatively modest – increase in across the board paper demand is a positive message for the GHG emission balance, currently applied technologies still need to transform into less emission-intensive processes to achieve an emission reduction. For example, a new field in the paper and pulp industry is provided by the biorefinery concept, utilizing biomass as raw material (Moya and Pavel, 2018). The biorefinery concept integrates other technologies such as black liquor gasification, biomass gasification, lignin/hemicellulose production and synthesis gases. As a result, not only the required products for the paper and pulp industry are produced but also valuable by-products which can serve as a feedstock in the chemical sector for producing methanol and bio-based fuels. This concept allows for a circular use of materials and provides an efficient use of the biomass raw material.

Transport

For passenger transport, shift policies aim at two mutually reinforcing goals, dis-incentivizing individual motorized transport and increasing the attractiveness of active and public transport. To lessen the appeal of individual motorized mobility, both restrictive and economic policies can be employed. Restrictive measures include car-free city centers or employing more restrictive speed limits. Economic policies could include congestion charges for city centers, road pricing and a raising of parking costs, with a simultaneous reduction of ground level parking capacities within city centers.

An ecological tax reform could also support a shift in the conventional mode of mobility, but it is important that there be an equal focus on promoting alternative modes of mobility in order to enable a shift and raise public acceptance. Here the focus is on the provision of infrastructure, the spatial and temporal enhancement of the public transport system, but also on the promotion of the actual use of alternative modes of transport by awareness campaigns and mobility education in schools. Promoting alternative modes of mobility is especially important in suburban areas, where a daily commute to city-centers is common. In less densely populated areas it is further essential to focus on the last miles of mobility, with the promotion of car-pooling, shared taxis and on-call buses, to achieve an effective shift in the transportation mode.

For freight transport, two areas of focus are crucial, the first being a shift from road freight to rail, which is challenging and limited by available rail infrastructure at any point in time and its relatively high costs ((Scheucher, 2014), 42). One reason for these higher costs are the externalized environmental and social costs in the road freight transport sector. Thus, internalizing these costs by e.g. introducing a CO_2-tax would allow for a stronger shift to rail. In the currently-discussed update of EU climate policy, both transport and buildings are considered to either get their own ETS or to be integrated into the EU-ETS, which would be another form of pricing. Even without broad carbon pricing, subsidies for the rail sector can decrease the relative price of rail transport, making it more attractive and leading to a modal shift. The shift can also be encouraged via the development of semi

or fully automated loading and unloading equipment for end-point trains (an example being craneable semi-trailers ((Heinfellner et al., 2018), 53), which is shown to increase rail transport attractiveness ((Islam et al., 2016), 12). The feasibility of a shift from road to rail also depends on the capacity of rail transport, which can be increased by investments into rail-infrastructure.

Accomplishing such a shift within the timeline foreseen to reach carbon neutrality (2040) is very challenging but can be achieved with a mix of measures. Alternative fuels and technologies can be encouraged by differentiated vehicle taxes on vehicle purchase, also known as feebates (combination of fees and rebates), which tax vehicles by level of CO_2 emissions, and use the revenues to subsidize alternative fuel vehicles. Zero-emission vehicle (ZEV) mandates/credits can also be used; these mandates target vehicle producers by mandating them to sell a minimum share of low (or zero) carbon vehicles, while credits are tradable and allow for market flexibility, where the bigger the market, the higher the flexibility. This would contribute to meeting the EU- and fleet-wide CO_2 emission standards for heavy goods vehicles (Regulation (EU) 2019/1242, approved mid-2019, which will become effective in two stages from 2025 and 2030), For passenger cars and light duty vehicles, fleet-wide performance standards has already been introduced in 2012. Road pricing, based on emitted CO_2 and overall driving performance ("flächendeckende LKW-Maut"[8]), could also be employed, where total charges correlate with overall transport kilometers driven ((IEA, 2017), 131 & 132). Other regulative measures for increasing the market penetration of alternative fuels are access restrictions in urban areas based on vehicle specific CO_2-emissions characteristics (implemented for noise or other emission reasons, but effectively also encouraging low-carbon engines) or increasing the cost of access to urban areas ((IEA, 2017), 134).

In order to make these measures effective, RD&D (Research Development and Deployment) and respective support of it need to accelerate the low-cost availability of alternative fuels and technologies ((IEA, 2017), 132).

Beyond the above, a shift to alternative fuels requires massive infrastructure investments. Depending on the replacement technology (e.g. battery or hydrogen-based), appropriate filling or charging stations are required, along with the appropriate supply infrastructure for distribution of e.g. hydrogen fuel. Such a shift in only 10 years will involve either public construction or subsidized construction of required infrastructure, or alternatively provision of some form of investment incentives to that end. Additionally, in order to prevent an increase in indirect emissions in the energy sector, sufficient capacities for renewable electricity generation have to be guaranteed in parallel to the implementation of measures in the transport (and other) sector(s) ((IEA, 2017), 132 & 133).

Buildings

A large part of buildings' GHG emissions is still caused by operational energy (e.g. heating, cooling and electricity for lighting and appliances). "Shift" measures therefore address the energy sources for heating and electricity systems. To reach stricter GHG emission targets, we follow IPCC Special Report 1.5°C recommendations that all new buildings are heated by fossil-free energy carriers, and existing fossil fuel-based heating systems will be phased-out and substituted by direct renewables, renewable driven district heat, or high-efficient electricity driven systems, as electricity will again have to be produced from renewables. The change of a heating system can either happen when the lifetime of the existing system is reached, or alongside a building's envelope refurbishment.

The rapid phase out of fossil-based heating, ventilation and air-conditioning (HVAC) systems (Bundeskanzleramt Österreich, 2020) requires a significant boost in the replacement rate of heating systems. The heating demand previously covered by fossils will be covered in a major part by biomass, district heating and heat pumps and in a minor part by direct electric systems and solar thermal (in combination with biomass heating systems). Therefore a significant increase of district heating grids' extents and of the production of heat pumps should be taken into consideration.

[8] A study by the Umweltbundesamt indicates a recommendation of introducing road pricing for all trucks starting in 2025 ((Heinfellner et al., 2018), 55), if an effective emission reduction is sought.

A number of barriers have to be overcome in such a process. There are several gaps that have to be adressed in the very near future and solutions have to be developed:

- **Technical gap:** Replacing (decentralized) oil, gas and E-boilers in multi family houses with heat pumps, for which currently no solutions are available on the market.
- **Owner-user gap:** The building owner is often not the beneficiary of investment, but the tenant is
- **Social gap:** Mixed housing (tenant, owner structure) might be an unbreachable obstacle, if e.g. some parties did replace gas boilers recently, while others alternatively replaced windows.
- **Financial gap:** Renovation might be economically feasible considering life-cycle costs, but high investments are required immediately, which may surpass liquidity constraints

Furthermore, constraints such as the available potential of biomass, the possibility to expand district heating networks, or the build up time for the large scale production and installation of renewable energy solutions all require consideration.

In addition to the aforementioned measures (occurring mainly on the building level), energy carriers for the production of electricity and district heat will shift to renewable sources, thus reducing the indirect CO_2 emissions linked to the increase of district heating grids and of heat pumps electricity demand. The energy system therefore needs to be properly adapted in parallel to the building stock, in order to avoid the simple shifting of GHG emissions from the users (the buildings) to the providers (the energy producers). This topic will be more extensively addressed in Chapter 5 (Energy Sector).

Energy

History shows that human wellbeing is closely tied to the use of energy. The measures described here focus exclusively on network-bounded provision and transformation of energy in the form of electricity, heat and climate-friendly gas.[9] The most relevant shift in the provision of energy to address climate targets is from indirect solar energy stored underground in fossil fuels to a much more direct provision of energy through solar radiation. Transformation technologies like photovoltaics, wind power, heat pumps, solar thermal collectors, electric motors etc. need to replace conventional technologies like internal combustion engines, oil-based heating boilers or gas-fired power plants. A substantial part of this required shift leads to decentralization of the energy provision, with new business models ('prosumers') and/or different organizational structures arising ('energy communities'). Also, the role of utility companies shifts as they diversify, providing new ancillary services in order to manage bi-directional networks and to balance shortages and excess supply of electricity, heat and climate-friendly gas. These new services need new market instruments in order to be adequately compensated. Additionally, these new services are crucial to cope with the increasing supply variability of a renewable energy system.

The package of measures for this shift in the provision and transformation of energy includes command-and-control-like regulation, market-based instruments, and long-term strategies. The recent-past policy approach in Austria addressing the energy sector relied for the most part on EU regulation through EU ETS carbon pricing. Both further revisions in EU ETS and possibly a new ETS for transport and buildings could be introduced in 2021/2022. On the national level, there are no specific targets of RES penetration in the electricity/heating mix, but there are some additional market-based instruments such as feed-in tariffs and investment subsidies. A more recent process explores the long-term vision of turning Austria into a hydrogen-based economy ('H2 strategy'), embedding the use of hydrogen in a carbon circular economy.

[9] Measures regarding the level of energy use e.g. of industry, transport and buildings are stated in the respective sections, hence they reflect measures of "demand side management" in a broad sense.

Box 4.2: Services from batteries for electricity supply

Over the last decade, a surge in lithium-ion battery production has led to an 85% decline in prices, making electric vehicles and energy storage commercially viable for the first time in history. Most analysts see the 2020s ahead as the "battery decade", with storage to revolutionize industries and the management of our grids. In order for batteries (and other forms of flexibility) to help stabilize the grid, it is important that they receive appropriate price signals, i.e. including expected local scarcity. We here give a short survey of utility-scale batteries and the services they have started to supply.

The first battery for utility-scale operations in Hornsdale, Australia with a capacity of 129 MWh and 100 MW power, completed in 2017, demonstrated the high technological and financial value of "Big Batteries", i.e. utility-scale batteries of dozens of MWh of capacity. The Hornsdale battery provides several ancillary services for stabilization of the grid (see Table Application of Utility-Scale Batteries); has several times prevented a large-scale disruption of electricity supply when big fossil power plants failed and is so profitable that dozens of batteries of similar and much bigger size are now under construction in Australia and more in the U.S. The biggest is the 20 GWh battery for the proposed Sun Cable solar farm in the Northern Territory (Rapier, 2020). In the U.S., a utility is planning on replacing the San Juan coal-fired station's 847 MW of capacity with 650 MW of solar generation and 300 MW/1,200 MWh of accompanying energy storage (Sylvia, 2020).

Big batteries now begin to substitute gas peaker plants (Vorrath, 2020). Moreover, they allow a kind of increase of capacity of transmission lines, when the transmission line is used at times of low load to charge a battery where electricity will be needed at times of peak load. There are basically two types of „Big Batteries", physically Big Batteries and virtual Big Batteries, i.e. behind-meter batteries that can be controlled by software to provide services as a collective, like a physically big battery. The most important source of income from big batteries is purchasing of low-cost or acceptance of surplus electricity – the battery operator is paid for this service – and the selling of electricity during times of peak demand, i.e. at times of high prices. These few lines demonstrate a phenomenal success and very fast acceptance of big batteries. The company with the globally highest manufacturing of batteries at about 35 GWh per year, Tesla in its "Gigafactory", is planning to increase its production within the next several years by a factor of 100 ("Tera is the new Giga") and decrease battery costs by another 45%.

Table B4.2 Application of Utility-Scale Batteries (based on Bowen et al., 2019)

Application	Description	Duration of Service Provision
Arbitrage	Purchasing low-cost off-peak energy and selling it during periods of high prices	Hours
Firm Capacity	Provide reliable capacity to meet peak system demand.	4+ hours
Operating Reserves		
• Primary Frequency Response	• Very fast response to unpredictable variations in demand and generation.	Seconds
• Regulation	• Fast response to random, unpredictable variations in demand and generation.	15 minutes to 1 hour
• Contingency Spinning	• Fast response to a contingency such as a generator failure.	30 minutes to 2 hours
• Replacement/ Supplemental	• Units brought online to replace spinning units.	Hours
• Ramping/Load Following	• Follow longer-term (hourly) changes in electricity demand.	30 minutes to hours
Transmission and Distribution Support	Reduce loading on Transmission & Distribution during peak times	Hours
Black Start	Units brought online to start system after a system-wide failure (blackout)	Hours

Improve

Industry

In industry, improve strategies are understood as measures which either increase the energy and process efficiency of existing processes or apply end-of pipe technologies. In order to increase energy and process efficiency, performance standards can be implemented, and the installation of best available technologies (BAT) can be required. As we discuss below this is particularly relevant for the non-ETS industry. Note, that for industries in EU ETS, efficiency improvements could backfire in terms of GHG emissions, as indicated in section "Sector contributions", if not adequately complemented. End-of-pipe technologies are often solutions of last resort only, however, in some instances they could act as valuable sources of input materials for other industries. For example, carbon capture in the cement industry could deliver CO_2 as a valuable input material for production of methane if combined with green hydrogen. In such cases originally end-of-pipe technologies could become core elements of circular economy solutions, here as carbon capture and use (CCU) in the context of carbon management. Depending on the process, different configurations of carbon capture and use are applicable (Gerres et al., 2019).

The implementation of energy (electric and thermal) and process efficiency measures need to be implemented across all industry sectors. However, efficiency measures are particularly important for low emission industries such as in engineering, transport equipment, and small and medium sized enterprises of emission-intensive industries.

Carbon capture technologies have potential in the iron and steel industry, the (petro-)chemical industry, the cement industry as well as the paper and pulp industry. The most prominent application, however, is in the cement industry, in which two thirds of the emissions are process emissions and one third are combustion emissions (Gardarsdottir et al., 2019; Hills et al., 2016; Schneider, 2019). For a reduction of process emissions, the use of SCMs (as described above) potentially lowers emissions, but otherwise no low-emission process technology is available for the cement industry – making carbon capture and use (CCU) a relevant technology. Today, different CCU technologies are under consideration including the absorption with amine-based solvents or ammonia, with membranes, calcium looping or the oxyfuel technology (Gardarsdottir et al., 2019). However, high learning rates are expected for absorption with ammonia, the reason being that ammonia is synthesized from hydrogen, which will be available in larger amounts in the future. Hence, learning rates for ammonia production are assumed to be similar to those of hydrogen production. Finally, it must be noted, that carbon capture – while being accounted for as an end-of-pipe technology - has its potential for the circular use of materials. Captured carbon represents an important raw material for the low-carbon production of plastics and fuels.

Transport

Where motorized transport cannot be avoided, the focus should be on technological solutions. While the shift to alternative fuels (within individual transport) and to public transport and other modes was already covered under "Shift", we here consider the technological improvement within, i.e. improved electric vehicles, and promoting further electrification of public transport. To achieve a fast and successful transition towards a more carbon neutral passenger transport system, restrictive measures supporting the phasing out of fossil-fueled cars need to be employed. These can take the form of restricting the admission and use of fossil-fueled cars or stopping their admission and banning usage altogether.[10]

[10] While in the EU each car supplier under current regulation has to meet an average overall emission target for its fleet, and thus single Member States implementing e.g. admission bans on fossil fuelled cars would as an immediate implication only shift those car sales to other Member States, a series of countries discusses or has implemented phase-outs of internal combustion engines in order to adhere to their climate targets, suggesting an expected accommodating adjustment also at the EU regulation level. For example, Norway is targeting 2025, Sweden 2030, and France has legally implemented for 2040. See Appendix H for details.

While avoiding freight transport and shifting from high to low emission-intensity technologies are seen as most effective for emission reduction, decreasing emissions and energy demand via improvements in vehicle efficiency and systemic changes in logistics and operation will also be required. Previous policies to encourage vehicle efficiency, such as fuel economy standards (EURO VI, in place since 2013) are already in force, but will need to be increased gradually, encouraging improvements such as improved aerodynamics, lower rolling resistance tires, light weighting/material substitution, transmission and drivetrain improvements, reducing idling and hybridization. Vehicle standards might be the right instrument to achieve such improvements ((Teter, 2018), 16). Further measures concerning the improvement of vehicles are the introduction of high-capacity vehicles (HCVs) which can improve fuel efficiency per kilogram of freight transported, thus reducing energy use and CO_2 emissions. However, substantial detrimental consequences in other dimensions may arise, namely significantly more wear and tear on infrastructure.

Buildings

The building sector in this study does not consider any "improve" measures except a constant technological improvement of appliances (i.e. A+++) and lighting (i.e. LED), policies that can be effective even in overlap with EU ETS (Perino and Pioch, 2017). Energy efficiency measures are carried out on larger scale as refurbishments of older buildings and covered in the section "avoid". Furthermore, small efficiency increases, e.g. in the efficiency of heating systems, are not explicitly considered here but implicitly accomplished with the exchange of the heating system. If a heating system is changed or updated, it also includes a shift from fossil to renewable energies and is therefore covered in section "shift".

Energy

A stronger integration across regions/countries ('energy union') offers potential for substantial efficiency improvements through trade itself but also by using new transmission technologies like high-voltage direct current lines. A stronger integration across sectors ('sector coupling', see Jarke-Neuert and Perino (2019)) increases not only energy conservation (e.g. storage by batteries, pumped hydro, electrolysis-based hydrogen, heating/cooling in buildings) but also value added by absorbing otherwise unused by-products ('circular economy'). Another relevant 'improve' measure for the energy sector, yet of lower impact in terms of absolute emission reductions, pertains to incremental improvements in energy efficiencies such as deploying combined heat and power (CHP) production. In none of the mentioned aspects, the current and official stance of Austrian policy goes beyond strategy discussions.

Box 4.3: Projecting electricity costs from Photovoltaics in an integrated system

Many players provide average costs of electricity from Photovoltaics (PV) over the last three years. PV had a learning rate of more than 20 percent per year over the last 20 years, implying that such average costs over the last three years are usually 40% higher than present costs; with the past three year average thus a misleading cost number for appraisal of future projects. As research in PV is strong and highly productive, cost decline is expected to continue unabatedly for at least several more years. Beyond the cost of mere PV modules, also Balance of System (BOS) costs are rapidly decreasing to date, although BOS is a complex composite of power electronics (e.g. inverters), installation, administrative costs and more. BOS can make up about half of the costs of a solar installation. For an outlook on electricity costs, instead of averages of the recent past we use costs of *present* (very recent) Power Purchase Agreements (PPAs) as a PPA includes all costs; i.e. the sum of costs of PV, BOS, O&M (operation and maintenance), capital costs and depreciation. Additionally, we use costs for a very large-scale solar plant where work has begun to have an outlook how costs for electricity in Europe may develop, taking into account the obvious necessity for large-scale imports of electricity from other world regions.

A recent tender in Abu Dhabi for a PV farm of 1.5 GW located in Sweihan gave a bid for PPA of $0.0135/kWh (Bellini 2020). In Sweihan the 20-year average of insolation is 2050 kWh/kWp (20-year average on the flat plane in a cell of 1°x1° at 24°N, 54°E, 100 km west of Sweihan; data from NASA Solar Sizer). If this PV plant could be constructed in location "A" in southern Europe at comparable costs, it would give electricity at costs of $0.0135 x (insolation in Sweihan/ insolation in "A"), for example at $0.0163 in large parts of southern Spain.

The by far most ambitious PV projects is the Sun Cable project in Australia. It will combine the globally currently planned largest solar farm of 10 GW with the globally largest battery with 22 GWh of capacity and its electricity will be transmitted to Singapore through an undersea HVCD cable with 3,770 km of length; the globally longest cable. This project is most interesting for us as the managers who are implementing it see it as the beginning of a global effort for exporting electricity from Australia throughout all of Asia. Most likely this will be the beginning of a global grid. It will be located in the Northern Territory of Australia (Newcastle Waters Station at 17.4°S, 133.40°E) and will be installed by robots from pre-manufactured solar panel arrays giving very low installation costs. It is planned to be operational in 2025 or earlier. Electricity costs in Singapore will be ¢3.4/ kWh (Rapier 2020) – our cross check calculation (see below) results in ¢3.62/kWh. Insolation at the location is 2211 kWh/kWp (data from NASA Solar Sizer for a cell of 1°x1° at 18°W, 133°E). This insolation is 10% higher than in the solar park Sweihan in the UAE, that we have the PPA for.

The entrepreneurs that implement this project have a proven track-record; the software billionaire Cannon-Brookes was a driving force behind the Hornsdale battery which was the by far largest battery of the world at the time of its installation. Cannon-Brookes says that this project is a "lighthouse project" for the world (Mazengarb 2019). The project is managed by Sun Cable Pte Ltd. located in Singapore and has received early stage funding. The Australian federal government is fast-tracking it as "the world's biggest solar and storage project" (Maisch 2020). In May 2020, Sun Cable awarded its cable route survey contract to Perth-based Guardian Geomatics. Sun Cable CEO David Griffin said 'This project is helping to grow a new industry, utilising intercontinental HVDC submarine transmission systems, to supply renewable electricity to major load centres in the Indo-Pacific and support the region's low-emissions goals', and 'Ultimately we are looking at a network that extends from India to New Zealand,' (Smyth 2020).

Electricity costs of ¢3.62/kWh, as derived in the subsection below, would be cost for firm electricity (securely supplied 24/7, already having adjusted for renewable variability). We have shown in Grossmann et al., 2013 and 2014 how, using large grids, electricity costs can be further decreased for a highly reliable electricity supply that fully meets the complex European load pattern. Thus, these costs from the Sun Cable project indicate the enormous potential also for supply of renewable electricity to Europe, in particular also from the southern hemisphere, and thus overcome the expected shortage of electricity supply on the northern hemisphere in winter. This project demonstrates what is becoming feasible in technological terms and what the costs of firm electricity will be if this route is selected.

Details of electricity cost calculation

At an insolation of 2211 kWh/kWp, 10 GWp of PV could generate 22.1 TWh per year or firm energy of 2.5 GW in combination with the battery of 22 GWh. The cable will transmit 3 GW to Singapore (Rapier ,2020). Insolation in the solar park could be higher by about 10% than 2211 kWh/kWp because the insolation number given above is the average over a cell of 1°x1°, i.e. an area of 111 km x 105 km; average values for large areas are usually lower than values for the best locations in such an area. The transmission line with a full length of 4,500 km would imply an overall power loss of 14.6% (Rapier, 2020). Hence, 3 GW may be the peak value for the cable, respectively the solar park will have about 30% more PV capacity than 10 GW. Costs of PV installations, i.e. PV plus BOS, can be derived from the PPA indicated above. The installation in Sweihan would generate 2050 kWh/y for 1 kWp of PV which gives revenues of $27.67 per kWp per year. With capital costs of 4%/y and initial annuity of 1%, i.e. 5% total[1], the amount of $27.67 could pay for an investment of $553.5 minus about 5% for O&M, i.e. about $526 per kWp of PV. 10 GW of PV capacity would thus cost about $5.26 B. Battery costs at the pack level in 2019 was at $156/kWh (IEA 2020) and will decrease by 44% according to Tesla's projection from its battery day in 2020 (Tesla, 2020) Battery packs need power electronics so that they can cooperate with grids. We increase present battery pack costs by 40% which gives battery costs of $214/kWh which is still considerably lower than costs of the Hornsdale battery installed in 2017. The battery with 22 GWh would thus cost $4.8 B. The transmission line would then cost $16B minus costs for PV and battery, i.e. $5.94B. At total costs of $16B for 2.5 GW, and at 5% costs for capital and annuity, electricity costs would be capital costs per year of $800M divided by electricity generation of 22.1 TWh/year, resulting in $800M/22.1e6= ¢3.62/kWh of electricity.

Overarching Measures

Carbon pricing

Carbon pricing is a climate policy instrument of central importance affecting all three broad categories of avoid-shift-improve. The underlying mechanism substantiates seven arguments in its favor (Baranzini et al., 2017): First, the carbon price signal reflects the socio-ecologic consequences of emitting carbon, hence the relevant information is explicitly included in decision making by market actors. However, current EU ETS allowance prices do not yet fully reflect the social costs of carbon. Second, carbon pricing acknowledges the heterogeneity of emitters, thereby minimizing total abatement costs. Third, there is a permanent incentive for research, development and deployment of climate-friendly technologies ('dynamic efficiency'). Fourth and fifth, *global* carbon pricing is most effective to address rebound and cross-border leakage. Sixth, the information requirement is decentralized – the necessary information for policy makers is minimal. Seventh, consumption decisions are much more affected by prices than attitudes of environmental protection. Finally, carbon pricing also has its limits, especially in situations without relevant substitution possibilities. Its effectiveness, thus, strongly depends on whether additional measures are able to allow for shifting away from (socially) undesired activities. Particularly in the EU ETS sectors, focus of policies should be to provide options for switching rather than mandating the switch itself. Otherwise, the cost minimization property is lost.

A sometimes-ignored topic of carbon pricing refers to revenue use (Klenert et al., 2018). However, its discussion is of high strategic relevance. As carbon pricing can have unintended consequences, e.g. regressive income distributional effects, the revenues of carbon pricing could be directly used to mitigate them ('climate dividend/eco-bonus per capita' or reduction of electricity surcharges). Further strategic emphasis could be placed by directing revenues from carbon pricing towards research, as well as development and deployment of climate-friendly technologies. Lowering other existing taxes would be another option of revenue use. In Austria, carbon pricing exists through the EU ETS, covering network-bound electricity and heat provision as well as industrial energy-intensive sectors. Currently, ETS revenues raised often finance climate mitigation measures in member state countries but its volume (and thus strategic power) could be further raised by a more comprehensive auctioning of allowances and stricter emission caps (Wiese et al., 2020). For the remaining non-ETS sectors in Austria, there is no explicit (and significant) element of carbon pricing yet, but the current policy debate screens respective options (i.e. a tax or allowance market) and the associated refunding of additional public revenues, also dependent to adjust to the eventual results of EU-level discussion with regard to either creating a new ETS for transport and buildings or even integrating them into the existing EU ETS, both possibly effective from 2025 onwards.

Innovation policies

Decarbonization requires the large-scale deployment of low-carbon technologies across emission sectors, so innovation policy instruments also play an overarching role in the policy framework. The process of technological change in general, and environmental innovation in particular, is characterized by possible market failures related to knowledge (when innovation gains cannot be fully reaped by the innovator) and environmental externalities (when polluting remains without cost for the polluter), as well as by path dependencies related to market size and price effects. Therefore, if left to the market, innovation in a range of low-carbon technologies tends to be too low (Acemoglu et al., 2012; Aghion et al., 2016). Without government intervention to direct technological change towards carbon neutrality, our current lock-in into fossil-fuel technologies will continue to hinder decarbonization (Steininger et al., 2020b). However, government policy can also hinder innovation, e.g. if market entry barriers are employed to block the expansion of renewables in order to protect static benefits of publicly owned utilities.

Although adequate government measures to stimulate the development of low-carbon technologies can be costly, they can also bring significant long-term benefits. A strong innovation performance

creates new market opportunities for domestic companies, thus enhancing international competitiveness and ultimately generating economic growth (Aghion and Howitt, 2009). In times of economic crisis therefore, focusing scarce public investment on promising areas of future technological development – which decarbonization has arguably become (Stern, 2015) – can contribute to addressing both economic and climate crises cost-efficiently. Importantly, countries' current areas of innovative strength and weakness can both be targeted with tailor-made policy instruments in order to optimize their contribution to competitiveness and decarbonization (Vollebergh et al., submitted).

In principle, governments have a range of instruments at their disposal to stimulate the development of low-carbon technologies. On the one hand, *technology policy instruments* include R&D subsidies, which address the invention phase of technological development; start-up funding and export support, which help turn inventions into successful innovations; and adoption subsidies and technology standards, which support the diffusion phase. Note that if ETS sectors are concerned, complementary policies may be crucial (see section "Sector contributions" above). On the other hand, *environmental policy instruments* include economic instruments, such as emission pricing (carbon taxes or tradable emission permits) as well as command and control instruments, such as emission standards and internationally binding climate targets. Appropriately pricing carbon emissions addresses the environmental externality and fosters emissions-reducing innovations in general by providing a price incentive to both inventors and consumers of a technology. R&D subsidies address knowledge externalities and provide a stimulus to innovation in low-carbon technology areas where currently not enough innovation is taking place. Finally, adoption subsidies and technology standards increase the size of the market for low-carbon technologies and support the diffusion of existing innovations in areas where a country performs well but emissions are still high.

All of these instrument types can be oriented towards low-carbon technologies, where this is not yet the case. For R&D subsidies such as the Austrian R&D tax credit (Forschungsprämie) – currently a generic instrument without a specific technological focus – funding schemes could be introduced that explicitly focus on decarbonization, similar to the investment subsidy introduced in 2020 (Investitionsprämie). Existing R&D funding instruments that already have an explicit climate-relevant focus could be expanded, as they tend to be heavily oversubscribed (Schneider et al., 2020). Finally, technology standards and adoption subsidies should be updated regularly to ensure they always support the latest low-carbon technologies.

Table 4.1. Overview of core policy package elements to achieve carbon neutrality for macroeconomic simulation, organized by the Avoid-Shift-Improve framework.

Sector	Avoid	Shift	Improve
Industry	• Standards for high-quality products with reduced raw material input (all sectors)	• Change manufacturing processes to low-carbon variants • Switch to alternative / renewable fuels in processes • Electrification of industrial processes	• Energy and process efficiency measures • Carbon Capture and Use
Transport	• Infrastructure improvement (walking, biking) • Encouraging tele-working • Spatial planning	• Road pricing • Restrictions for freight service to urban areas • Zero-emission vehicle mandates • Differentiated vehicle taxes • Management and reduction of urban parking areas • Subsidizing rail freight transport / infrastructure • Infrastructure development (overhead catenary, hydrogen filling station, electricity charging) • Vehicle technology standards	• Stricter speed limits • Investing into RD&D and subsidizing efficiency improvements particularly for logistics firms • Increasing shares of bio-fuels and e-fuels (especially in freight transport market segments)
Buildings	• Nearly zero-energy building standard (or at least passive house standard) for new buildings • Room Temperature Control • Deep refurbishment • Mechanical Ventilation with Heat Recovery (MVHR) and shower drain water recovery	• Replacement of existing fossil fuel-based heating systems with renewable energy • Phase-out of new installed fossil fuel-based heating systems	• Energy-efficient appliances and lighting
Energy		• Increasing penetration of renewables e.g. solar • Decentralization of energy provision	• Stronger integration ('energy union') • Improving transmission technologies • Improved combined heat and power production
Overarching pricing	• Carbon pricing with revenue recycling to avoid regressive income distributional effects		
Innovation policy	• Introduction of a decarbonization focus into existing R&D tax credit (Forschungsprämie), e.g. through funding scheme targeting low-carbon technologies		

5 Modelling of Economic Implications: Overview

Stepping up the European 2030 climate target and seeking to achieve climate neutrality by 2040 for Non-ETS sectors (Bundeskanzleramt Österreich, 2020) and by at least 2050 for sectors regulated at the European level (European Commission, 2020b) involves a transition which implies a multitude of effects on the Austrian economy.

A range of them tend to be positive, i.e. activity (and welfare) enhancing:

- Such a transition requires a substantial amount of directed additional investments. If such investment does not fully crowd out other investment – especially in a post-Covid situation of strongly underutilized capacity, crowding out will be very low, if existent at all – it will create additional value added and employment (and respective household income).
- The (quicker) switch to a renewable resource base reduces the currently substantial amount of fossil imports (currently about EUR 8 billion/anno, (Steininger et al., 2020a) and shifts expenses for energy services to additional domestic value added.
- The transition fosters a modernization and digitalization of the economy, enhancing both productivity and international competitiveness.

While another range of effects tends towards negative impacts, reducing domestic activity (and possibly immediate welfare):

- At the firm level, enhanced investment expenditures and possibly rising unit costs for energy may result in the short term in reduced international competitiveness and thus challenge exports beyond the EU. An adequate policy framework can mitigate these losses, especially competition with foreign (not climate friendly) supply to markets within the EU, e.g. by appropriate EU-level border carbon adjustment policies.
- At the household level higher low-carbon investment (e.g. higher expenses for renovation of buildings) increases credit expenditures and in that respect reduces consumption temporarily. Possible energy poverty or otherwise regressive policy implications can be avoided, e.g. by adequate transition/bonus funds or refund schemes.
- The rebuilding of the electricity sector might lead to a higher electricity price that could reduce household consumption and firm competitiveness in the short term. Adequate market regulation (e.g. low-priced base demand) can avoid unintended distributional consequences.

These various economic implications and effects all work simultaneously, and partially in opposite directions, and have different influence at the firm, sector, household, national and global level, as well as differently in time. Most notably we expect positive effects to unfold sustainably in the long term, whereas negative economic effects are likely to be merely relevant in the short term. This could imply a trade-off of consumption possibilities across generations. Both inter- and intra-generational consumption discrepancies could be moderated by adequate policies.

For the analysis of such implications, a range of approaches is available. One may consider a quantification too uncertain, especially for such long-time horizons and restrict the analysis to a qualitative one. If quantitative assessment is desired, one may be interested in the near-term development only, say over the next five years. In that case an econometric approach (i.e. prognostic tools) could be the adequate one, exploring how the Corona recession could be overcome by the mid-2020s and what specific role climate targets could have in these years. The research question of the call that this present study is addressing had a different interest. The concern was on the long term, asking for an analysis of long-term (2050) macroeconomic effects of achieving a stricter EU climate target in 2030 (assuming different burden sharing within the EU) relative to a baseline scenario with a weaker climate target of 40% in 2030. There are at least three elements in this question: an interest in (a) a quantitative indication of growth and employment implications, (b) a comparison of two developments (old versus new EU climate targets) and (c) a long-term development (both the situation by 2030 but also up to 2050). For this combination of interests the most adequate method

to date is a scenario comparison by means of dynamic, multi-region, multi-sector computable general equilibrium (CGE) modelling, which we also apply in this study. There are multiple reasons, with three core ones. First, uncertainties in the long-term abound, with one of the major uncertainties relating to the baseline development itself, while conclusions on the deviations of a stricter climate policy to any such baseline can be more reliably deferred. The here applied CGE approach is thus one that builds upon a baseline (a single one, or for sensitivity analysis a set of them) and focuses on the deviations from this baseline due to a specific policy, in our case stricter climate policy. Second, in the long-term it is structural changes that are the relevant ones, dominating over business cycle issues. The approach we here discuss focuses on these structural changes, and has the long-term perspective. Third, in the long-term micro- and macroeconomic balances are relevant, such as budget balances, long run market supply and demand, as well as between production costs and revenues at the firm or sector level (including a relevant profit share), but also foreign trade balances. In the short run significant deviations may occur ('market sentiments'), but in the long run (10 years and more) there are forces active that work against deviations ('fundamentals'). The here applied approach is based on integrating these long-run forces but is not restricted to them, given that the global economy is currently situated in an unprecedented recessionary phase.

More specifically, a multisector-multiregional dynamic macroeconomic modeling approach is applied to shed light on the respective quantitative relevance of each of the above-mentioned economic impact chains and the resulting net overall implications, when advancing a climate-oriented transformation, following different climate stringency targets. In the following we present the overall macroeconomic model approach fulfilling these requirements, developed and employed in the current study, as well as the sub-models for individual sectors it draws upon.

For an economy as foreign trade oriented as the Austrian one, the degree of (potential) divergency between EU climate policy and that of its trading partners is crucial. While both scientific evidence (IPCC, 2018) and international agreements (UNFCCC, 2015) clearly show that ultimately the global community needs to shift to climate-neutrality if it wants to avoid catastrophic damages, different speeds in achieving this transition may occur. Thus, at least for some time, divergence in stringency levels between the EU and its trading partners are likely to be relevant. The most extreme ends in this regard would be either only Europe engaging in climate policy, and European products for the transition period being characterized by a stronger competitive disadvantage (while in the long term climate neutral technologies are usually found to be more competitive), or conversely, that the rest of the world shifts to a climate neutrality transformation much faster than Europe, and that foreign demand for – in this case too-carbon-intensive – European products significantly drops, hurting the European economy for *not* being climate ambitious. Considering these extreme cases as unlikely, the main scenario in this report follows a middle path. We assume climate policy-relevant foreign trade measures to avoid strong competitive disadvantage for those time periods where EU climate policy stringency diverges from that of its trading partners or equivalent preferences in its trading partner countries.

Whether policy-induced new investment implies crowding out (and if so at what degree) is dependent on the aspects of (a) financing new facilities and (b) the degree of utilization in physical production of goods with existing facilities. Crowding out means that policy induced investment does not come as an additional output in the economy. This is either because overall financing resources are limited, and thus financing the new investment means a (up to equivalent) reduction of financing for other investment, or – and this constraint works at the physical production side – because the economy was already operating at full capacity, and any additional final demand (investment) thus can only be met in substituting for other (investment or consumption) demand. In the current situation and for the type of investment that we are concerned with, however, both aspects seem to be irrelevant. On the financing side, investors are seeking sustainable projects ("green investments") much beyond their current supply. On the physical production side, due to Covid-19 there is a large degree of underutilization of the current capital stock and labor force, many investments goods sectors are idle, and new investment demand just fills this demand gap, and does not replace other production. A study published in 2018 on climate paths for Germany (and drawing upon an extensive industry manager survey, commissioned by the German Federation of Industries) even for the situation before Covid-19

did not identify any capacity constraints for climate transition investments, but found industrial capacity utilization (trend) in Germany to be 75 to 85% (Gerbert et al., 2018).

Any modeling approach aims at reducing complexity, thus has its strengths, but also its potential shortcomings. Especially the shortcomings have to be cross-checked for their relevance with respect to the specific interest analyzed, and the approach has to be adjusted accordingly to avoid them materializing. Before going into the details of the model specifications as implemented for the present study, we here first report the potential shortcomings of our approach in this context, and how it was adapted. First, strong reliance on market price mechanisms is often considered a kind of "black box", possibly neglecting technological details. We thus here specify – for each of the main emitting sectors – detailed technological pathways that are implemented exogenously, not relying for their implementation on the price mechanism (in the literature this is known as "Leontief" production technology modeling). To that end we link up the macroeconomic model to either detailed subsector models (such as for the buildings sector), where such pathways are modelled in technological detail, or link up to the relevant literature and sector experts for specification of such pathways (such as for the iron and steel sector). In many cases this is done based on longer term collaborations in earlier research projects, that have focused in full detail on the relevant sectors (transport, industry, energy). Second, the financial market is not explicitly integrated in such an approach but the chosen modelling settings allow for an implicit representation of it, which allows for a context-dependent change in the availability of funds for both investment and consumption. Third, full employment of factors – as in the textbook models of this type – obviously does not correspond to reality and thus in any applied research applications is adapted to depict unemployment adequately. In our case not only in the labor market, but also in the capital market, to reflect the situation as indicated in the previous paragraph. Finally, supply side constraints in the availability of production factors are not always striking – in the post-Corona phase and for climate policy they may be relevant only for very few special factors, such as currently for skilled labor for buildings renovation, but definitely not in general. Thus, such supply side constraints are set to be inactive in the post-Corona phase, with the demand side governing economic activity in this recessionary period.

The following subsections present a series of short, conceptual overviews of the models used in this assessment; for a further, more detailed explanation of model frameworks and processes, see the relevant Appendices.

Non-technical description of the economy-wide model WEGDYN

For the assessment of the economy-wide – or macroeconomic – implications of climate policy measures, we use the WEGDYN model, a global, multi-sectoral, multi-regional, computable general equilibrium (CGE) model (Mayer et al., 2019).

CGE models are based on national accounts and describe the economy as monetary flows across all production sectors and final demand agents (i.e. representative public and private households), on an annual basis (see e.g. Lofgren et al. (2002) for a comprehensive description). Each economic sector receives inputs from other sectors and production factors (e.g. labor, capital, and natural resources) from final demand agents in order to produce output, which is delivered to other sectors or final demand agents. These agents generate income from their supplying production factors, which is then spent on consumption or is saved (to finance investments). Thus, all economic sectors/agents are interlinked. In the case of multi-regional models, trade with other regions is explicitly accounted for and thus cross-border effects are also included.

The main idea behind CGE models is that market forces drive the economy towards a "general equilibrium" state where supply equals demand on all markets and from which there is no incentive to deviate. After having calibrated the CGE model to a benchmark equilibrium, it can be "shocked" to assess effects of exogenous interventions in the economic system. Such shocks occur by e.g. enabling sectors to apply a different production technology, or by changing final demand patterns, which in turn triggers sectors and agents to adjust their demands and supplies (based on changes of relative prices) until a new equilibrium emerges. From the comparison of new and old (i.e. benchmark) equilibria we can draw conclusions as to how the economy would look different due to a system

intervention. In a recursive dynamic CGE model (such as WEGDYN) annual equilibria are connected via investment and capital accumulation, where investment of one period determines the capital stock of the next period. Using a recursive dynamic approach, we can thus draw pathways of the economy-wide developments and compare different pathways with each other.

Typical model results are relative changes in macroeconomic indicators such as GDP, welfare (consumption possibilities), unemployment or tax income, but also sectoral indicators such as prices, output, sectoral value added, trade patterns etc.

WEGDYN is based on the static version of (Schinko et al., 2014) and has already been applied in numerous ways in the field of economics of climate change mitigation (Bachner et al., 2019, 2018; Mayer et al., 2019). The model is calibrated to the GTAP9 database (Aguiar et al., 2016) and has been refined and further developed for the purpose of this analysis. The main characteristics are briefly summarized in the remainder of this sub-section; for details, please see Appendix C.

In the variant of WEGDYN applied here, the world is structured into seven regions/countries: Austria (AUT) and its closest trading partners Germany (DEU) and Italy (ITA) as well as China (CHN) are modeled as individual countries. The rest of the world is represented by regional aggregates: the rest of Europe (REU), North America (NAM) and the rest of the world (RST). There are 22 separate economic sectors, with special emphasis placed on the electricity sector, which is further divided into 12 sub-sectors. Regarding CO_2 emissions, WEGDYN includes both combustion-based CO_2 emissions as well as CO_2 emissions arising from industrial processes, like from iron and steel or cement production. WEGDYN works in a recursive dynamic fashion that explicitly models the pathway of economic development in 5-year time steps from 2015 to 2050. The general development of the economy is calibrated to the Shared Socioeconomic Pathway 2, a middle-of-the-road narrative of global socio-economic development (SSP2; see O'Neill et al. (2017) for details on the narrative).

In this variant of WEGDYN, special emphasis is placed on the treatment of investments and "crowding-out" (see also introductory text of this section). In the post-Covid period we assume that the economy is in a phase of recession, in which capacities (mainly the production factors of capital and labor) are idle. This means that production factors are not fully employed and can be activated by policy intervention. In terms of CGE modelling this implies that capital which was unproductive in the recession becomes productive (or "available") due to exogenous stimulation, without having to carry out investments to build up a capital stock beforehand. It is rather that the existing capital stock is used more productively, and thus no crowding-out of other final demand (other investment or consumption) needs to take place. In addition, new financing for green investment can easily be obtained from the financial market, providing as well additional capital to the real economy.

To summarize, by using the WEGDYN model, we are able to quantify economy-wide and sectoral effects of specified system interventions ("shocks") in Austria. These interventions are in our case a multitude of climate change mitigations measures and policies. As WEGDYN is a multi-regional model, cross-border effects are also accounted for, i.e. issues of international competitiveness (with other EU member states and beyond EU borders) are included.

Quantification, implementation and macroeconomic evaluation of climate policy measures

Scenario framework

In order to evaluate the macroeconomic effects of increasing the stringency of climate mitigation targets in the EU and especially in Austria, we make use of a scenario approach. Scenarios are plausible and internally consistent descriptions of future developments. Note that scenarios are different to predictions or forecasts, as they do not claim to become a reality, but rather show what *could* happen in the future, given certain framework conditions and parameter settings. By comparing different scenarios to each other, one can isolate effects of system interventions under a *ceteris paribus* assumption.

Given the main objective to compare the earlier EU climate target of 40% GHG emission reduction by 2030 (relative to 1990) with the revised target of 55% GHG emission reduction, in this study we make use of two scenarios:

1. The "EU40" Baseline scenario: This scenario describes the evolution of the economy under existing measures and trends. It includes generic socio-economic parameters such as population growth, trends in fossil fuel prices, autonomous energy efficiency improvements etc. (see Appendix C for a full list and respective parameter settings). Note that the EU40 Baseline scenario is different from a Business-as-Usual scenario, as it also includes major changes in the socio-economic system and climate policy; most notably the EU 2030 target of reaching greenhouse gas emission reductions of -40%, relative to 1990 as well as (domestic) climate neutrality by 2040. These targets are reached by policy measures (e.g. CO_2-pricing) and technological changes (e.g. a shift to climate neutral steel production or the adoption of electric vehicles at relatively large shares). Also, the EU40 Baseline scenario accounts for the Corona crisis in 2020 and its medium- to long-term consequences with respect to declines in value added (GDP) and respective economy-wide income. For details on the Baseline calibration, please see Appendix C.
2. The "EU55" Enhanced scenario: This scenario builds upon the EU40 Baseline in terms of generic socio-economic parameters but adds a multitude of additional climate change mitigation measures and strengthens existing policies in order to achieve earlier GHG emission reduction, i.e. a stricter target by 2030, while equivalently with EU40 reaching (domestic) climate neutrality by 2040. We further differentiate the EU55 Enhanced scenario in the following way:
    a. EU55-seq: In this setup policy measures in response to the Corona crisis and to the climate crisis are implemented **seq**uentially; i.e. starting with *generic* economic stimulation measures and only some years later specific climate change mitigation measures are being implemented.
    b. EU55-sim: In this setup policy measures in response to the Corona crisis are at the same time climate change mitigation measures (earmarking) or are added at the same time on top of generic measures; i.e. measures are implemented **sim**ultaneously. This setup describes the strategy to channel the now available large amounts of (public) funds into climate neutral investments, rather than into sole and conventional economic stimulus.

Thus, by comparing the EU55 Enhanced scenario to the EU40 Baseline, we can draw conclusions on what the economy-wide effects of an increase in the stringency of emission reduction targets by 2030 would look like. By further differentiating between sequential (seq.) order and simultaneous (sim.) implementation we can draw conclusions on the effects, advantages or disadvantages of delaying climate change mitigation measures. We are especially interested in the risks of creating lock-ins and path dependencies, when following a potentially too weak medium-term 2030 target (or delaying climate change mitigation), which is not compatible with long-term 2040/2050 targets (i.e. being fully climate neutral).

Industry

Iron and Steel

We analyze a climate policy package for the energy-intensive industrial sector, which incorporates a technology standard for primary iron and steel production. The iron and steel sector accounts for about half of Austrian industrial-related GHG emissions and around 5% of domestic sectoral output, numbers underlining the relevance for its consideration. This technology standard leads to a *Shift* away from conventional and emission-intensive steel production reflected by the blast-furnace route to innovative new processes, which are based on electrolysis-derived hydrogen and are thus almost emission-free (in terms of production-based accounting; for the overall impact on emissions of this process, the prevailing electricity mix is key). The relevant framework conditions and parameterization of this technological pathway are comprehensively analyzed and discussed

elsewhere (Bachner et al., 2020; Mayer et al., 2019). We here specify how the enhanced EU-wide emission reduction target (the EU55 scenario) translates into increased ambition compared to the expiring target (the EU40 scenario) regarding the contribution of the iron and steel sector.

The **EU40 Baseline** scenario is characterized as follows (Table 5.1): Industry representatives envision a technological restructuring starting by the end of this decade (we assume 2030), which in a step-wise linear manner phases-out the conventional (blast-furnace) technology to be replaced by hydrogen-based steel making. We assume for a central case that this transition takes place in all EU member states and does so a bit earlier than in the rest of the world (ROW, which starts in 2032). Since the European steel industry starts its transition only in 2030, the contribution of this sector to the EU40 Baseline reduction target is rather small in 2030 (the market share of hydrogen-based steel making is only 10%) and other industries covered by EU ETS regulation would need to step-in.

In the **EU55 Enhanced** scenario, an increasing political ambition necessitates a stronger contribution of the European iron and steel sector and, therefore, an earlier start of the sectoral transition compared to the EU40 Baseline. We define the two Enhanced scenarios as follows. In the EU55-simultaneous scenario, the iron and steel transition itself is already a substantial part of implemented recovery measures and thus starts even earlier; i.e. in 2027, with a market share for hydrogen-based steel making of 40% in 2030. In the EU55-sequential scenario, the starting year of the transition in Europe only follows the implementation of generic policy packages in response to the Covid-19 pandemic, i.e. in 2028. As the market share of hydrogen-based steel is also 40% in 2030, the sequential scenario requires a faster scaling up of climate neutral production facilities for achieving the same sector contribution to the enhanced target. However, both enhanced scenarios involve an earlier completion of the transition (compared to EU40) and a stronger contribution of emission reductions in 2030. For ROW, no further measures (as those specified in the EU40 Baseline) are assumed. To avoid a loss of competitiveness for the transition period (while EU iron and steel is assumed to have transformed by 2037, ROW is assumed to have fully transformed by 2042 only), an internationally-uniform greenhouse gas price would provide sufficient legal and planning security. As long as this is not realized, we suppose implementation of combinations of measures to address the issue, both at the EU and national levels. At the EU level, measures such as carbon pricing at the EU's external border relating to production outside of EU borders (administratively easiest might be free carbon allowances within the EU, but relating to declining certificate quantities and implied rising costs a thus accommodated supplementary Carbon Border Adjustment Mechanism), as well as market access rules for products and related international agreements could be supplemented at the national level, such as by creation of markets for green products, export or investment promotion or differential compensation for energy costs. For energy- and/or emission-intensive industries, the availability of renewable energies and compatible substitute fuels needs to be ensured – both at the EU level (internal energy market) and at the national level through corresponding strategy implementations, infrastructure investments and international agreements. Full details are given in Chapter 7. These requirements are also relevant for competitiveness concerns under EU40, but increase in relevance for stricter EU climate targets.

Two further variants of overall targets (EU50 and EU60) are connected with lower and higher market shares of hydrogen-based steel making, respectively, when compared to the EU55 target (Table 5.1).

Table 5.1: Iron and steel - main scenario assumptions.

	Iron and steel								
	Shift: Phasing out BF-BOF & phasing in hydrogen-based steel making								
	Transition start		Transition duration (years)		Market share H2-based steel			Learning factor*	
	EU27+	ROW	EU27+	ROW	EU27+ 2030	ROW 2030	Global 2050	EU27+ 2050	ROW 2050
EU40	2030	2032	10	10	10%	0%	100%	1.22	1.20
EU50	2027	2032	12	10	35%	0%	100%	1.26	1.20
EU55seq	2028	2032	9	10	40%	0%	100%	1.24	1.20
EU55sim	2027	2032	10	10	40%	0%	100%	1.26	1.20
EU60	2027	2032	9	10	45%	0%	100%	1.26	1.20

Notes: *Learning rate 1% p.a. gets active at year of transition start.

If not otherwise stated, we use the 'high-cost' technology representing the hydrogen-based direct reducing of iron ore followed by electric arc furnace steelmaking for establishing our scenarios. From a unit-cost perspective[11], i.e. looking at required EUR per ton of the primary iron and steel mix produced, taking into account evolving shares of conventional and emission-free new technologies, the EU55 target is costlier (relative to EU40) in the short term, up until around 2035 (excluding learning effects and carbon pricing).[12] From then on, new facilities are already (financially) depreciated due to the earlier transition start, and thus the cost disadvantage of the new technology starts to fall (relative to the steel mix that would be produced in the EU40 Baseline at that point in time). This effect of falling relative unit costs occurs until the point in time where the investments of the EU40 Baseline would also be (financially) written off (i.e. in 2044).[13] Note, that this is a relative comparison between EU40 (when some of the climate-benign investment occurs only later) and the EU55 pathway. The depreciation period applied is 15 years; during that period capital expenses are written off. With an advancement of climate-benign investment these costs both show up and disappear earlier. The unit-cost disadvantage up until 2035 can be lower and a break-even achieved even earlier with the cheaper 'low-cost' hydrogen-based technology (based on plasma processing; not shown). It is also evident that EU ETS carbon pricing[14] can support the uptake of emission-free new steel processes by reducing the cost disadvantage relative to blast furnaces. Again, it is the difference between EU40 and EU55, with a higher carbon price in the latter scenario comparatively reducing the unit cost difference. These factors highlight relevant technological and political dimensions of the available 'policy option space'.

[11] Table E.1 in Appendix E summarizes the main technological and cost parameters for our model-based evaluation.

[12] Note that the macroeconomic model (WEGDYN) solves in 5-year steps. Therefore, we translate yearly parameters (cost, market shares and investment levels) using 5-year moving average values.

[13] Note that we only assume a single investment cycle. Hence, unit-cost of the EU55 scenarios compared to the EU40 baseline converge in the long run (when the penetration of new technologies is completed) and only operating expenditures determine cost competitiveness.

[14] EU ETS carbon price assumptions for the shown unit-cost comparison: 30 / 120 / 180 EUR/tCO2 in 2020 / 2030 / 2040 remaining at that level thereafter.

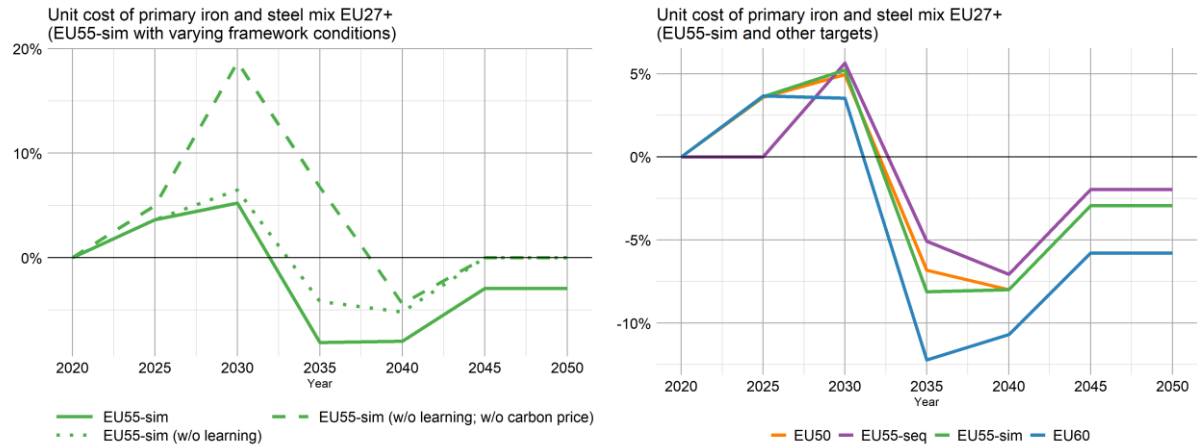


Figure 5.1: Percentage difference of the unit cost level of the primary iron and steel mix in EU27+ compared to the respective level in the EU40 baseline. Left: EU55-simultaneous excl./incl. carbon pricing and/or learning. Right: Different EU targets.

Another dimension of the 'policy option space' is timing. Implementing a new technological process triggers local learning effects, which (partly also protected through intellectual property rights) accrue only to applicants. Additionally, early movers can reap comparative advantages not only by learning itself but also by setting industrial standards through patenting activities shaping a new technological regime. Factoring in such aspects, we assume a moderate "local" learning rate of 1% per year, which means that productivity of technologies starts to rise annually at the time when applicants implement the new technological process. Consequentially, learning improves cost competitiveness further – as shown by the solid green line (including learning and carbon pricing) in the left panel of Figure 5.1 – and long-run operating expenditures in the EU55 scenarios are and stay below the EU40 baseline. Comparing different emission reduction targets (right panel of Figure 5.1), the unit-cost of primary iron and steel from 2030 onwards is lowest in the EU60 scenario, due to earlier investments and the connected earlier learning effects. This shift in iron and steel production requires additional investments as shown for Austria (left panel) and the EU27+ (right panel) in Figure 5.2 for a capacity of around 7 and 113 million tons of primary iron and steel production, respectively. It is clearly visible that stricter targets correspond to earlier investments.

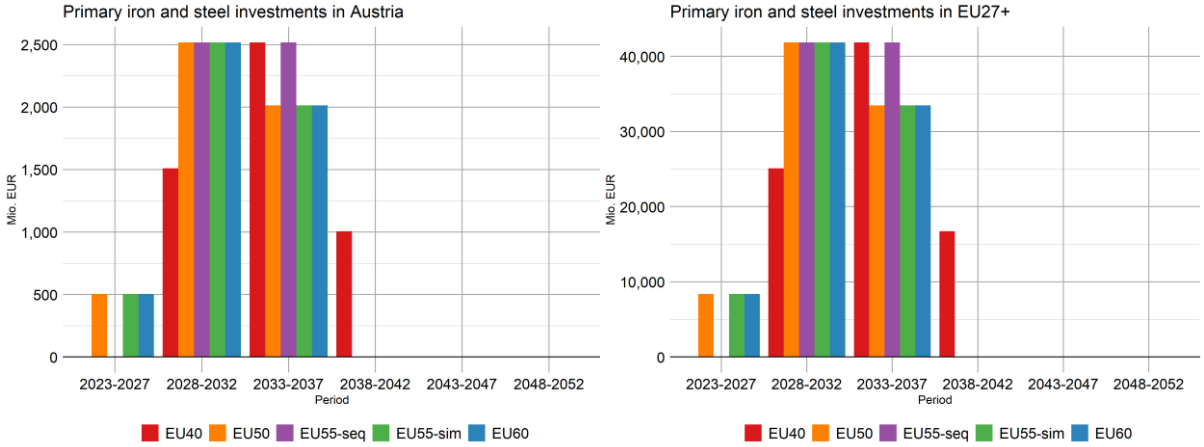


Figure 5.2: Investment requirements of iron and steel transition across EU emission reduction targets. Left: Austria. Right: EU27+.

Cement

The modelled policy package for cement production incorporates, first, a standard necessitating a retrofit of cement facilities with carbon capture (CC) appliances. Although some European-level projects endorse underground storage of captured emissions, Austrian industry envisions another option, which is, second, cross-sectoral mitigation in energy-intensive industry connecting renewable electricity, hydrogen and captured carbon emissions from cement production with the refinery and chemical industry (C2PAT[15]). The exact link and respective techno-economic constellation is not yet fully resolved in all quantitative details. However, to allow for such an industrial circular approach in the macroeconomic model we not only account for the retrofitting of cement plants with CC but also for the valorization of (hydro)carbon, which would (almost) close the carbon circle in these industries. Implicitly, we thus assume a carbon contract-for-difference regime, which ensures profitability of carbon capture (and use) even for the period when the carbon price has not yet risen sufficiently (currently carbon prices of around 130 to 150 €/t of CO_2 are considered to grant profitability). A carbon-contract-for-difference is one instrument to enable investment decisions in industry, potentially differentiated by technologies, allowing for higher rates for technologies with higher learning potential. As support rates decline with rising carbon prices, and potentially also with observed learning, market distortions are only temporary, and intentionally to foster targeted innovation.

We take the following approach. The EU40 baseline is taken to require 40% of cement plants in Austria (and on average for all EU27+ countries) to apply the carbon capture technology (to be on the worse end we use the rather high-cost end, but otherwise niche-technology of the "chilled ammonia process (CAP)") by 2030 (starting in 2027). Referring to the example of CAP being already a technology with a readiness level of around 6-7 (Gardarsdottir et al., 2019), we assume that in the EU55-simultaneous scenario, retrofitting starts even earlier, in 2025, and all plants capture their carbon emissions by 2030. Note, that the latter is an extremely ambitious scenario, considering that after an eventual pilot phase for ~2 years, a similar duration for planning of the upscaling is not unlikely, before construction can be completed for operation at that scale. As has been stated earlier and will be reiterated in Chapter 7, there is a range of prerequisites that have to be implemented before such a pathway is possible. These include the implementation of both the energy and material infrastructure, as well as creation of markets for the respective (green) product, but also all related legal aspects (such as approval and environmental impact assessment, R&D support, or investment tax breaks). The retrofitting scenarios are summarized in Table 5.2.

Table 5.2: Cement - main scenario assumptions.

	EU40	EU50	EU55seq	EU55sim	EU60
Starting year	2027	2027	2027	2025	2025
Retrofitting period length [y]	10	4.5	4	5	4.5
Share of carbon capture in operation in 2030	40%	89%	100%	100%	100%

[15] https://www.zement.at/7-news-teaser/602-c2pat-auf-dem-weg-zu-klimaneutralitaet-und-co2-kreislauf

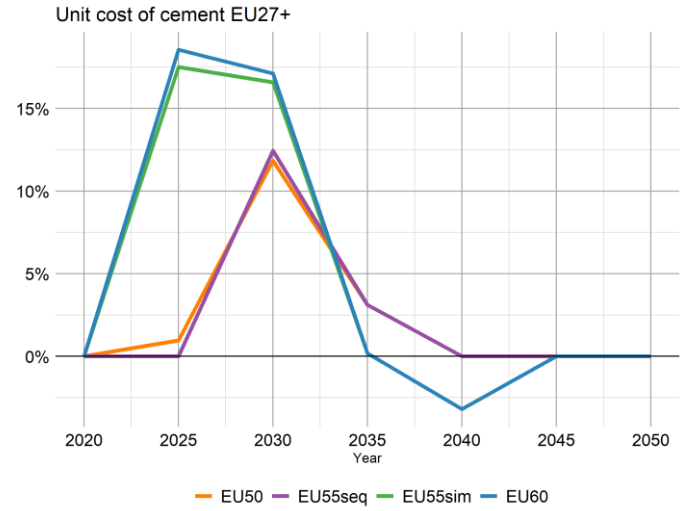


Figure 5.3: Percentage difference of the unit-cost (net of taxes) of cement production in EU27+ compared to the respective level in the EU40 baseline.

In our scenarios, cement production in EU27+ including CC evolves such that stricter targets (and thus earlier retrofitting) lead to higher unit-cost (EUR per ton of cement) until around 2035 (Figure 5.3). The cost assumptions of retrofitting with CC are summarized in Table F.1 of Appendix F. After 2035, they are temporarily lower for the EU55-simultaneous and EU60 targets because the retrofitting is already completed there but not yet in the EU40 baseline. Needless to say that relying on end-of-the-pipe abatement only is costly. The corresponding investment requirements for these retrofitting measures are shown in Figure 5.4, assuming capacities of 4.5 (180) million tons of cement in Austria (EU27+).

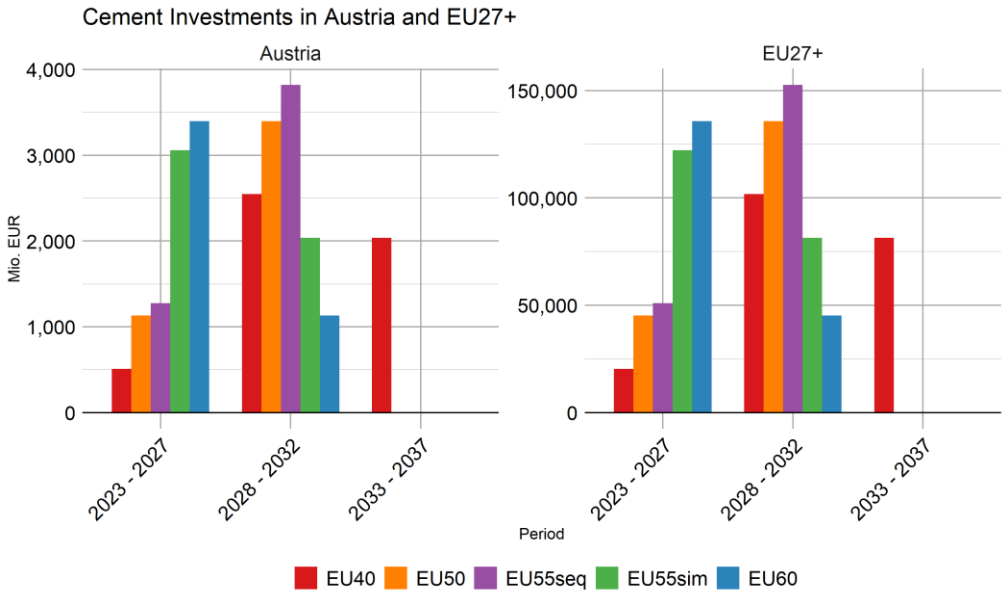


Figure 5.4: Investment requirements of cement retrofitting across EU emission reduction targets. Left: Austria. Right: EU27+.

To account for the value of the captured by-product, we introduce hydrocarbon as a second commodity of cement production in the macro-model (joint product "P_C"; cf. model sectors in Table C.2), which then can be used for other economic purposes (e.g. in the chemical industry). Our assumption is that the cost of CC reflects the minimum willingness to pay of hydrocarbon consumers (or strike price, which is fully passing on the cost of abatement) such that this circular industrial approach avoids rising marginal cost of the cement industry. Put differently, the costs of implementing CC are assumed at a level at which they are fully covered by the price that the

hydrocarbon sells for. One setting to implement such coverage for transition periods when carbon taxes or permits have lower prices could be the establishment of carbon contracts-for-difference. Without both, such a setting and high enough carbon prices, the following prevails: On the one hand, this clearly neglects an explicit modeling of the step of producing hydrogen and the processing of hydrocarbon, hence this assumption in such a setting tends to *under*estimate the cost of abatement. On the other hand, refraining from this carbon-to-product approach tends to *over*estimate the cost of abatement and the "true" cost will be likely in between.

Transport

To achieve climate neutrality in the Austrian transport sector by 2040, the target stated in the current government's program, a comprehensive policy package, necessarily combining a broad range of different elements is required, which are spelled out in detail e.g. in Thaller et al. (2020). These policy elements broadly cover all three types classified in Chapter 4, i.e. aiming at avoidance (as fostered by transport saving spatial planning or through new organizational designs, such as home office or 3-D printing), at shifting to environmentally benign modes (such as public transport, biking or walking) and at environmental improvement in current modes (such as electrified buses and rail). Many of these policies clearly imply an immediate overall economic productivity gain and enhanced welfare (mainly due to less resources devoted to mobility while at least the same level of access is maintained). But a few of them clearly involve economic challenges, be it substantial up-front investment or the requirement of sufficient supply of additional renewable energy (electricity to be more specific). These latter are the ones we model, in order to analyze the quantitative relevance of economic challenges involved, including in a post-Covid situation. Our transport analysis thus again is focusing on the upper end of costs, as with the sectors covered before.

Passenger transport

From the passenger transport climate policy package it is two elements that we evaluate with the macroeconomic model. The first resembles emission performance standards for motorized individual transport (MIT) issued by EU regulation 2019/631 (European Commission, 2019a), which fosters the electrification of car travel ('improve'). Secondly, carbon pricing of transport-related greenhouse gas emissions (non-ETS) is used as overarching instrument, inducing e.g. a shift to public transport and other environmentally benign modes such as biking or walking. Electrification is connected to investment for e-vehicle purchases and their required infrastructure, which we account for by using an investment cycle module differentiating car vintages, purchase costs, the share of electric cars in the total fleet as well as the overall modal split of (person-kilometer) travel-demand. For the EU40 baseline, we assume a moderate penetration of e-cars in 2030 of 40% in the total share of MIT. The stricter targets assume stronger penetration of e-cars by 2030 with shares of 50%, 55% and 60% for the EU50, EU55 and EU60 scenarios, respectively. In all scenarios, e-car penetration reaches 100% by 2040 fully phasing out conventional cars. In Figure 5.5, we compare the unit-cost of the MIT mix – composed of conventional and electrified cars – relative to the EU40 baseline. Although capital expenditures of e-cars are higher than for conventional cars, their much lower operating expenditures dominate the overall comparison and the unit-costs of driving (or total cost of ownership in EUR per person-km) are lower for all stricter targets compared to the EU40 baseline. Note that imposing a stricter target but postponing e-car uptake and going for a conventional economic recovery first leads to stranded investments in conventional cars, as shown for the EU55-sequential scenario ("sunk costs"). The visible spike in unit costs for this scenario shows that car owners then would be confronted with capital costs for both, a (stranded) conventional vehicle and a new electric vehicle at the same time. Details on techno-economic assumptions can be found in Appendix H.

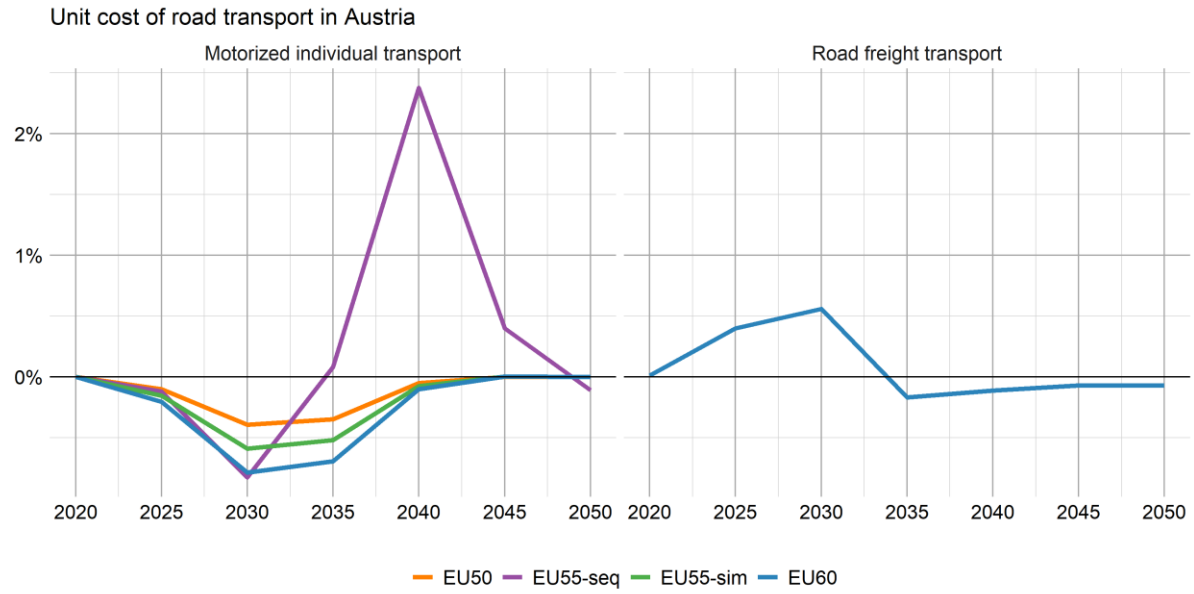


Figure 5.5: Percentage difference of the unit-cost (net of taxes) of road transportation in Austria compared to the respective level in the EU40 baseline. Left: Passenger transport (mix of conventional and electrified vehicles). Right: Freight transport (mix of conventional and alternative technology/fuel vehicles).

Freight transport

The climate policy package for freight transport that is modelled includes technology standards for vehicles on the road as well as development of infrastructure for alternative technologies and a national carbon price (non-ETS). Here, the focus is put on road freight transport as it accounts for a relatively large share of total transport CO_2 emissions and is expected to increase in terms of ton-kilometers (see Chapter 4). Thus, a shift from combustion engine diesel (CE-D) technology to combustion engine hydrogen (CE-H2) vehicles, battery electric vehicles (BEV), overhead catenary electric vehicles (OC-EV) and fuel-cell electric vehicles (FCEV) in the long-term and combustion engine gas (CE-G) as a bridging-technology is applied in modelling (differentiated by range and use case). Moreover, an increase of biofuel share in CE-D and biogas share in CE-G is considered, along with implementation of power to liquid (PtL) and power to gas (PtG) technologies, which are considered as substitutes for diesel fuel and compressed/liquid natural gas (CNG/LNG). Further details on the used technologies in this work and the exact market penetration of each technology are shown in Appendix H, where the relevant cost parameters implemented in the model can be found, as well as details on the timing of the transition for alternative technologies and fuels. As the discussion on new technologies in the road freight transport sector has only recently emerged and as the road transport sector is quite diverse in its use cases, more than one technology needs to be considered in modelling.

In terms of existing relevant policies, European regulation 2019/1242 (European Commission, 2019b) states that a 30% decrease of CO_2 emissions of newly registered vehicles in 2030 compared to 2020 is mandatory. This policy measure, however, is not sufficient to strongly decrease the emissions of the freight transport sector; not even to meet the Baseline EU40 target (-36% compared to 2005). Therefore, to achieve an overall reduction in line with our scenarios, more measures need to be implemented. In the EU40 baseline, we assume penetration of alternative impulsion technologies and fossil-free propellants in order to achieve non-ETS emission reductions of around -36% by 2030 relative to 2005. In 2040, fossil-fuel-based trucks are fully phased-out, based on the recent government agreement regarding a climate-neutral Austria by this time. The same 2040 zero-emission requirement applies for the stricter EU55 target, but the market share of alternative technologies and propellants in 2030 are such as to achieve a 43% reduction of carbon emissions by 2030. Parallel to the performance standard set by EU legislation, a national carbon

price is also modelled; the respective assumptions are given in the section on cross-cutting measures below. The changes in the unit-cost of road freight transportation (including infrastructure investments) is shown in Figure 5.5. Since we isolate the difference between stricter emission reduction targets relative to the EU40, additional costs are moderately higher until 2030 and almost equal thereafter. Note that for road freight transportation we assume the same development of the EU55-simultaneous scenario also for the other variants of a stricter target (EU55-sequential, EU50 and EU60). Further details on techno-economic assumptions can be found in Appendix H.

Road transport investments

The modelled transport policy packages for motorized individual transport and road freight transport are connected to large investment demands. We here focus on the comparison of total vehicle (comprising both passenger and freight vehicles) and infrastructure investments in the different scenarios. The new transport system has a very different character compared to the current system and annual investment requirements range in between 1.5 and 2.5 billion EUR, regardless of the emission reduction target (Figure 5.6). Although stricter targets require earlier investments, the annual difference to the EU40 baseline is not significantly pronounced because upfront cost are high for all reduction targets and necessary to incentivize uptake of non-fossil transportation. A substantial share of the infrastructure (e.g. charging stations) is used by passenger and freight vehicles. Hence, stricter targets with higher penetration of alternative technologies and fuels are connected to a more efficient use of infrastructure.

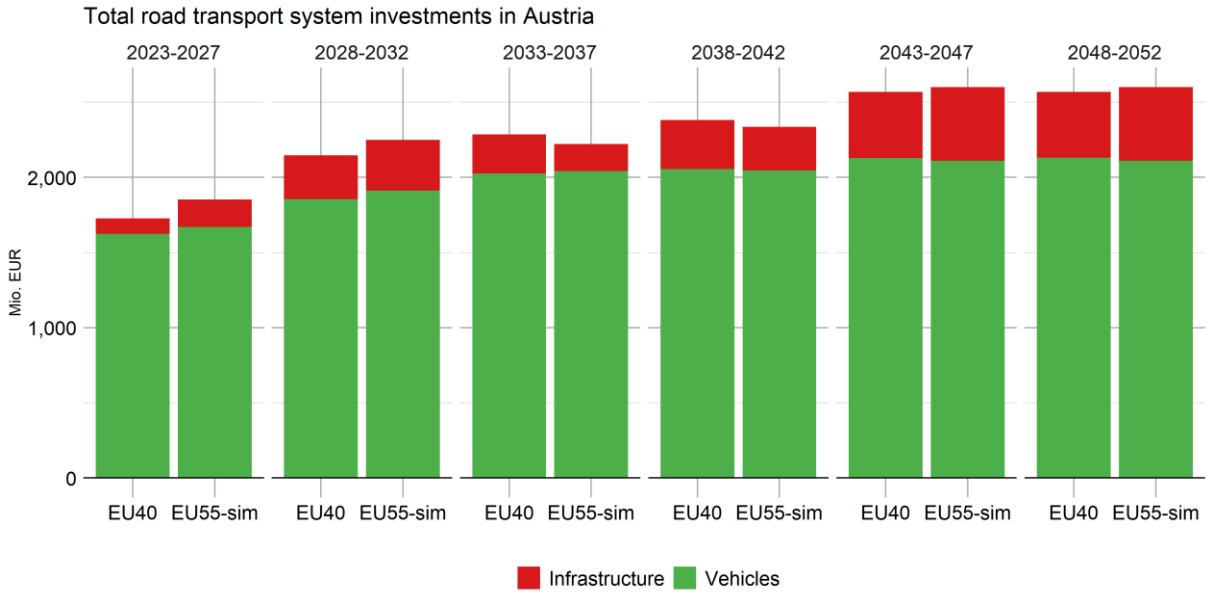


Figure 5.6: Investment requirements of road transport decarbonization in Austria distinguished by vehicle stock and infrastructure. (Note that in national accounting some of these investments (those by private households) are categorized as (durable) consumption.)

Buildings

For the building sector we make use of a sequential bottom-up approach. We first use a building stock and renovation tool, specifying the quality and quantity of new building construction and renovation activities and corresponding energy demand of buildings by energy carrier (Dobler, 2016). Furthermore, in a scenario-cost analysis activities of new building construction and renovation are translated into cost categories of construction materials and services with respect to the required building and renovation quality. Finally, the additional construction activities are represented in the macroeconomic model by an increased investment demand for construction activities with its

derived input structure together with induced change in building energy demands for households and service sectors.

The building stock and renovation tool consists of two main parts: (1) a building stock scenario model and (2) a renovation measures package database. A detailed description of the assumptions of these two tools can be found in Appendix D. The output of this tool is dependent on the chosen scenario with respect to renovation rate, deepness and package, the total energy consumption starting from year 2021 and the development until a target year (i.e., 2030).

As input the scenario model uses the extension of the building stock and the respective final energy consumption in the base year, available from national statistics. We use Statistik Austria "Nutzenergieanalyse" data (Statistik Austria, 2019b), which provides the total final energy consumption per energy carrier for the period 1993-2018. Considering 2018 as base year, an extrapolation is required for the period 2018-2020: with sufficiently good approximation, a constant energy consumption in the building sector can be assumed in these years (i.e., a business-as-usual (BAU) development with same energy carriers as 2018 and unchanged building stock).

The building stock is further disaggregated into residential and non-residential buildings. For residential buildings a more detailed distinction is provided (single family houses, small and large multi-family houses) in order to account for the different available solutions in terms of HVAC size and typology and of envelope conditions. The building stock and renovation tool is consistently calibrated to future population increase (Kc and Lutz, 2017) and accounts for the developments regarding the demolishment rate of existing buildings and the extension of the building stock.

Assumptions regarding the possible paths to meet the target of CO_2 emission reduction concern the energy demand of renovated and new buildings, the refurbishment rate of existing buildings and the heating system exchange rate. The resulting scenarios for the buildings sector are listed in Table 5.3, structured into the main scenarios BAU, A, B and C. In scenario B and C, the HVAC exchange rate is increased to achieve the complete phase out of fossil-based HVAC systems by 2040. The buildings scenarios are then allocated to correspond to the overall EU scenarios with varying emission reduction targets (last row in Table 5.3).

Table 5.3. Resulting scenarios from the building stock scenario model. A more detailed description of the renovation quality taken into consideration is presented in Appendix D

Buildings scenario	**BAU**	**A**		**B**		**C**	
Renovation quality	BAU	deep	best	deep	best	deep	best
Renovation rate	1.5%	1.5%		1.5%		2.5%	
HVAC-only change rate	1.5%	2.0%		2.0% % (+fossil HVAC selective reduction)		2.0% % (+fossil HVAC selective reduction)	
2040 fossil phase out	w./o.	w./o.	w./o.	w.	w.	w.	w.
EU scenario		**Reference**	-	**EU40**	**EU50**	**EU55**	**EU60**

An additional input is the share of the energy carriers adopted in the buildings. A different energy mix is adopted according to the building type, year of construction (renovated or new) and intended use (space heating or domestic hot water preparation).

One final output of the building stock scenario and renovation tool represents the final energy required by the different building types over the simulated period. It is therefore possible to follow the trend of the energy carrier demands with the defined assumptions. The share of different energy carriers (fossil (gas, oil, coal), biomass, district heating, electricity) used in the building sector (see Figure 6.8) can then be converted into respective GHG emissions (see Figure 6.9) using appropriate conversion factors (as in Table 5.4). Further calibration inputs for the scenario set-up are provided in Appendix D. It should be noted that electricity produced by photovoltaic systems on buildings will be considered as input to the national electricity system rather than as directly balanced within the building. With this assumption the total produced electricity can be used and is available in the national energy system. However, the installation of PV should be always combined with deep renovation in order to enable cost-effective solutions.

Table 5.4. CO_2 equivalent emission factors for the non-ETS energy carriers.

	f_{co_2} / [g CO_2eq/kWh]			
	Oil	**Gas**	**Coal**	**Wood**
Direct emissions	271	200	334	6
Total emissions	337	270	381	23

A renovation package database is defined to consider the possible measures on the existing prototypical buildings. Such prototype buildings are defined for several building periods using the online database "Tabula" ("TABULA WebTool," 2020) and calibrated against the baseline values using the PHPP tool (Passive House Institute, 2020) and recalculated to the OIB method. These are then used to represent the building stock condition in the base year. Possible renovation packages are then studied to evaluate the possible renovation measures (e.g. additional insulation, windows change, air tightness, heating system and heat emission system improvement) required to meet the energy consumption targets fixed in the scenario model.

The cost estimates performed within this study serve to analyze the cost deviation of different scenarios for new buildings and refurbishments in order to derive selected input parameters for the macroeconomic modelling of the buildings sector.

The results of the cost estimates are based on the structure of ÖNORM B1801-1 (ASI, 2009) and include selected costs for building finishings and technical equipment (HVAC and MVHR) as part of the cost category "construction costs".

Since these are rough cost estimates in order to identify the possible trends of different refurbishment scenarios until 2050, no detailed sensitivity or uncertainty analyses have been conducted in this study. Therefore, the cost estimates may vary depending on the underlying assumptions. In the following we list the assumptions made for the cost estimates, first for "new buildings", thereafter for "refurbishments".

New buildings

Based on a top-down approach, cost estimates for newly built passive houses were performed for the year 2021. The cost benchmarks from the literature (BKI, 2018a) used for this initial cost estimate refer to the net floor area (NFA) of the buildings. Where the relevant literature only provided cost benchmarks related to gross floor area (GFA), they were converted to NFA using a conversion factor of 1.25. This assumption was applied to all building types considered (single-family houses, small and large multi-family houses, and non-residential buildings). It should be noted that this is a simplified assumption and the conversion factor can vary for the different building types in practice (Kolbitsch et al., 2008). The assumed cost benchmarks were adjusted to the base year 2021. For the verification of the cost estimates, a bottom-up approach based on a previously-conducted research project was additionally applied (Sölkner et al., 2014). The cost benchmarks (€/m2 NFA) were extrapolated with the simulated building stock, i.e. by the use of the reference area (m2 NFA) and the number of newly constructed buildings of the considered building types (see Figure D.4 and Table D.1).

Refurbishments

For the developed refurbishment packages (for details, see Table D.14 to Table D.25), in a first step, a bottom-up approach was applied for the refurbishment cost estimates. In a second step, the estimated costs were compared with benchmarks from the literature using a top-down approach. Costs have been estimated based on developed renovation packages including renovation activities such as the additional equivalent insulation thickness of walls, floors and roof, by the necessity of changing the windows and eventually installing the MVHR. For each renovation depth (2011, BAU, Deep and Best as in Table D.11) three different renovation packages are defined, one for each pre-renovation boundary condition (V1, V2 and V3 as in Table D.11). As input parameters for the cost estimates, the three pre-renovation scenarios for each building period were combined into one pre-

renovation scenario. This input parameter thus represents a simplified average value of the assumed renovation activities.

For the cost estimation, the same input parameters of large multi-family houses were used for non-residential buildings in a highly simplified assumption. The cost benchmarks gathered from the renovation packages were extrapolated using the simulated building stock, i.e., by using the number of renovated buildings and the number of HVAC/MVHR systems installed.

Several scenarios are then defined using different renovation rates, HVAC exchange rates and renovation qualities; all these activities are assumed to start in 2021. In accordance with the targets proposed in "mission2030" (BMNT und BMVIT, 2018), it is assumed that no fossil-based HVAC systems are installed after 2020; heat pumps, district heating and biomass will therefore play the major role in the next years. The efficiency of the heating system is then taken into account in the evaluation of the final energy demand of the evaluated scenarios from the useful energy.

Technical approaches for insulation thicknesses depend on energy calculations; a practical implementation plan must be verified by building physics and building services calculations as well as by a technical feasibility analysis. Legal aspects (e.g. agreement of all owner) for specific refurbishments should also be considered.

Due to insufficient cost data for buildings installation within refurbishment in relevant literature, assumed prices for HVAC/MVHR systems in practice may differ significantly from the assumptions made in this study. Therefore, detailed HVAC/MVHR calculations depending on the specific framework conditions at site are indispensable. Analogously, this applies to the assumptions for the replacement of windows. Moreover, technical feasibility of renovation activities for buildings at early building periods are highly limited in quantification (e.g., limitations regarding the requirements on heritage protection).

Due to these constraints in this study, average literature values (Amtmann et al., 2011; BINE Informationsdienst, 2017; BKI, 2018b; Österreichisches Institut für Wirtschaftsforschung, 2008; VFF and BF, 2011) were used for the cost estimation. The ranges include all considered building types and building periods. Figure 5.7 shows the range of cost benchmarks for insulation material (floor, wall and roof) and the range of cost benchmarks for the replacement of windows (depending on the underlying Uw-value) in €/m2 building component.

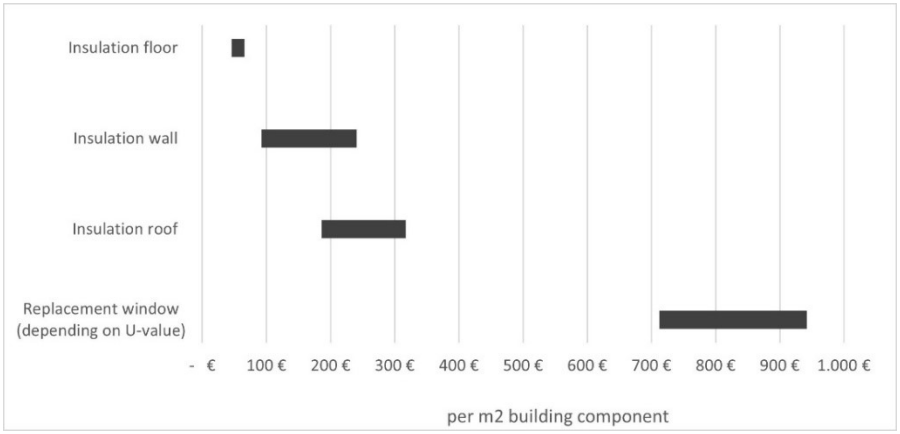


Figure 5.7. Ranges of cost benchmarks for insulation material and replacement of windows.

Figure 5.8 shows the range of cost benchmarks for HVAC change within a thermal renovation (central and decentral), the HVAC change only, the HVAC change only for additional phase out without a thermal renovation and the range of the cost benchmarks for the installation and change of the mechanical ventilation heat recovery (MVHR) system in €/flat.

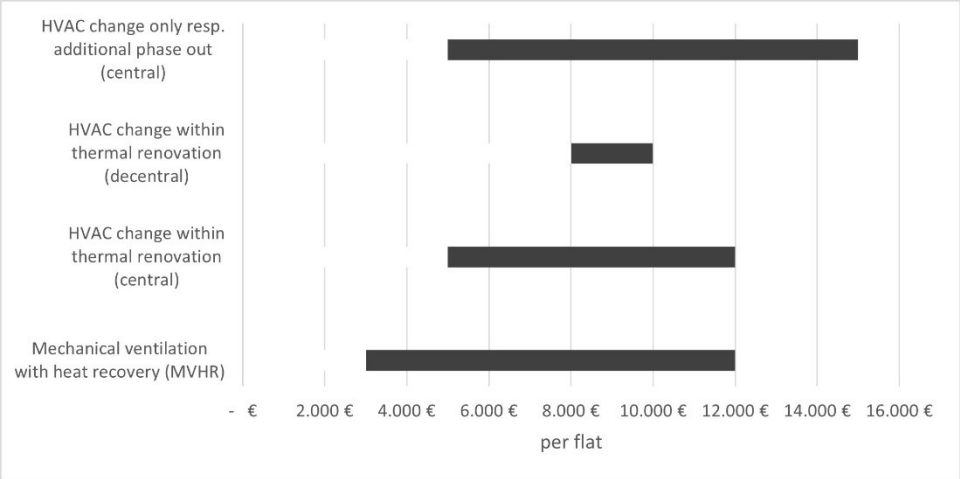


Figure 5.8. Ranges of cost benchmarks for HVAC change and MVHR.

In the cost estimates for single-family houses, it is assumed that there are no decentralized HVAC system changes; replacements of decentralized HVAC systems only take place within thermal renovations at small and large multi-family houses and non-residential buildings. Within these building types, HVAC installations in terms of deep/best renovation scenarios are assumed to be installed 50% decentral and 50% central. HVAC changes without simultaneous thermal insulation have been assumed as 100% central. The cost estimates for the renovations of building installation (HVAC and MVHR) are based on existing literature (Amtmann et al., 2011; BINE Informationsdienst, 2017; BKI, 2018b; Holzer, 2020; Lenz et al., 2010; Ochs et al., 2020; Sölkner et al., 2014).

Building installations which are replaced within a thermal renovation can be dimensioned with a lower performance due to the optimized heating demand of the building. The costs for these building installations are therefore lower than for the building installations in those buildings which are not thermally renovated. The costs are further lowered by the additional performance requirement reduction of HVAC systems due to the installation of a mechanical ventilation heat recovery (MVHR) system.

Due to lower insulation quality on the one hand and missing MVHR systems on the other, costs of HVAC change without a thermal renovation are higher than in deep and best renovation scenarios. Further relative cost saving potentials due to the size of the renovated buildings have been taken into account.

Finally, it should be noted that additional costs for e.g., sound insulation, specific space requirements on sites, longer distribution lines within the buildings, or services within building installations are not considered within this study.

Estimated costs

Figure 5.9 shows the relative deviation of the overall cost estimates between the reference scenario (A-deep) compared to the examined scenarios A, B, C for new built and renovated buildings. The results conducted by the rough cost estimates (scenario A, B, C) represent the building sector's cost input parameters for the macroeconomic modelling for the base year 2021.

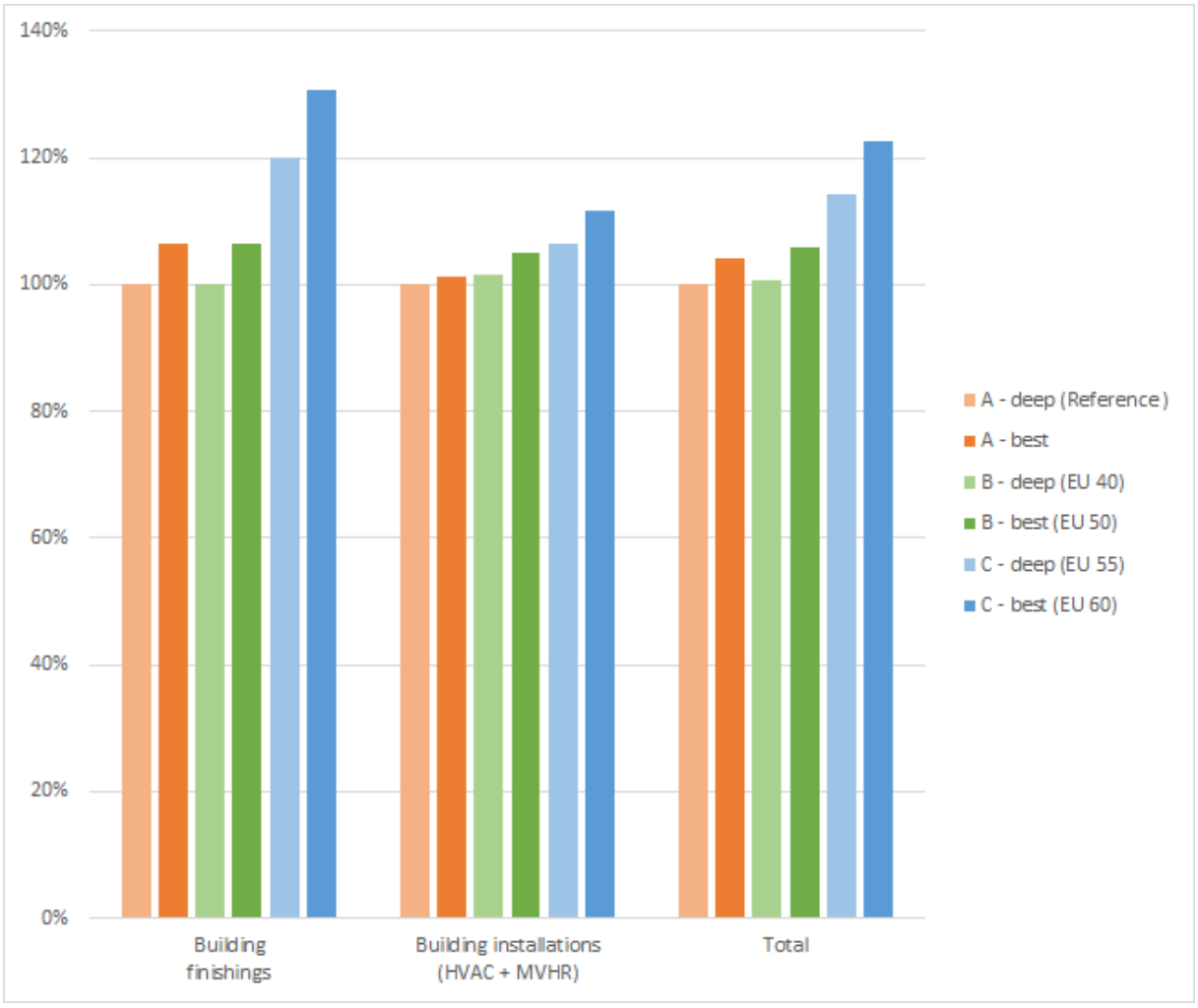


Figure 5.9. Relative cost deviation (new buildings and refurbishments) of examined scenarios for base year 2021; renovation quality A-deep is used as reference (100%)

For the macroeconomic evaluation, we use outputs from the building stock and renovation tool, in terms of energy cost reductions for heating, as well as from the scenario-cost analysis, in terms of additional upfront investment for different building components.

The necessary investment for building finishing and installations is higher with a stronger emission target. Figure 5.10 (top) shows the sectoral allocation of total investment into upstream construction inputs. As improvements in the buildings stock occur earlier in the EU55 scenario, additional investments decrease over time until 2050. As in the EU40 and the EU55 scenario, a phase-out of fossil heating systems is accomplished by 2040, corresponding investments occur earlier in the EU55 scenario and even turn negative in the two decades before 2050 (accounted for in building installation (OME)). Energy cost savings manly occur for electricity and biomass because of increased thermal building standards (Figure 5.10 (bottom)). For fossil energy demand, only minor reductions occur for gas until 2030, as fossil heating systems are phased-out by 2040 in all scenarios.

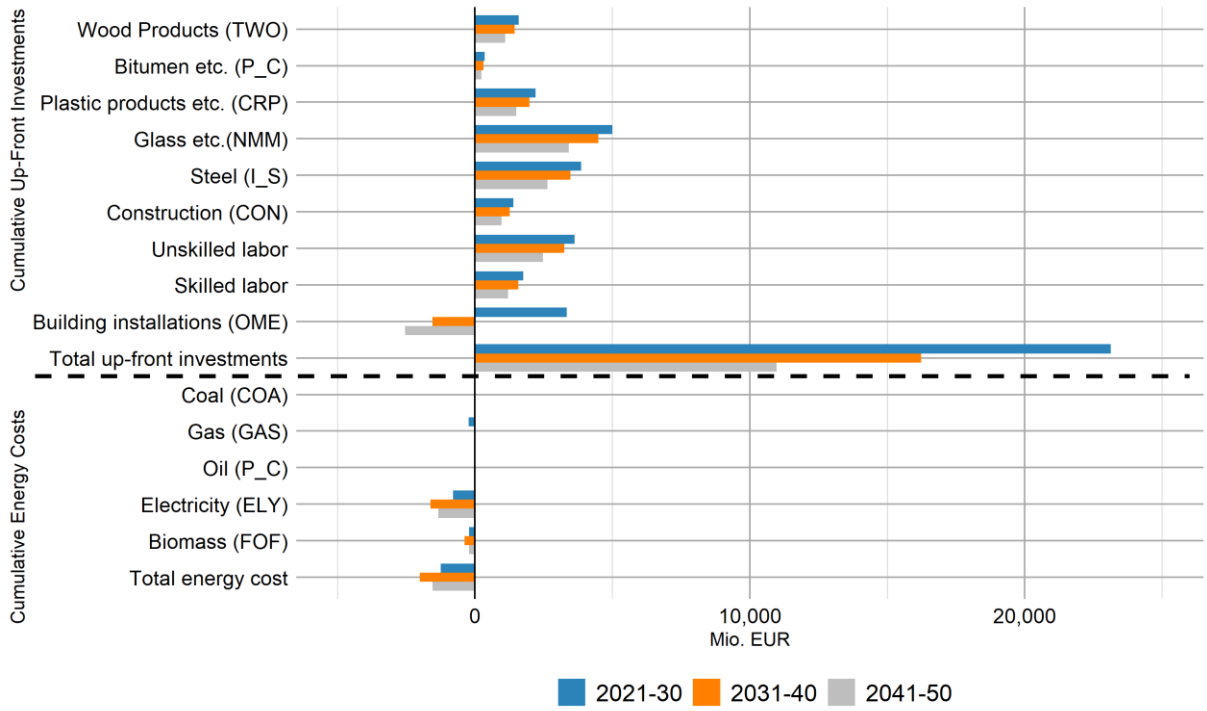


Figure 5.10. Cumulative upfront investments (top) and cumulative energy costs (bottom) over the periods 2021-30, 2031-40 and 2040-50 (in Mio EUR difference to EU40) for the EU55 target

Overall upfront investments outweigh the energy cost saving by a factor of ten. However, with the additional investment in the buildings stock quality, an increase in property value is expected to accompany renovations.

In the macroeconomic evaluation, upfront investments and energy savings are implemented for private households in terms of residential buildings as well as for buildings of the private and public service sectors (SER, OSG). Private households are assumed to bear the annualized additional building investment costs in terms of additional spending on rents (or imputed rents) and reduce spending on other commodities correspondingly. Similarly, additional investment in service buildings is reflected by higher capital expenditures in these sectors. The higher property value from the improved building stock is reflected by a higher output value, corresponding to the additional capital expenditures, and therefore not changing the productivity of service sectors.

Energy

Boundary conditions

For both EU40 and 55 targets, assumptions on the maximum potential of each technology in the energy mix and their (renewable) basis are required, reflecting the demands for both generation of energy (including electricity and heat) and material use in industry (including paper and chemical). On the latter, see Appendix I (Material Use of Biomass). For energy use we establish these upper bounds based on a review of the relevant literature, in terms of both the technologically- and economically-feasible generation potential. Figure 5.11 shows the range of possible values for eight major energy generation technologies in terms of both technological and economic feasibility. As seen in the figure, the technological potential varies widely for all generation sources, with the majority of estimates ranging by at least 10-15 TWh, and with even more variability when including values outside the 1st and 3rd quartiles. Biomass for heat and electricity generation is especially variable; estimates in the literature range between 30 TWh in 2050 to just over 125 TWh.

Conversely, the economic potential generation of each technology shows much less dispersion up to the year 2050, despite these estimates being based on a number of additional assumptions and incorporating additional layers of uncertainty with regard to the modeling approach used,

macroeconomic assumptions (e.g. growth, fuel costs etc.), technological costs, and policy assumptions. As the potentials displayed are derived from various assessments undertaken in the past, they also model the potential energy mix under different decarbonization targets, ranging between 40% to 55% reductions. Even so, there is relatively broad agreement in the near-term (e.g. 2030) for all technologies besides biomass, however 2050 projections see higher dispersion in terms of estimated PV and wind generation. These variations may be due to a number of reasons; (Gass et al., 2013) highlights in an assessment of the economic potential of wind in Austria that discount rates play a large role in modelled capacity, with an increase of only 1% reducing installed capacity by 50%. Other factors, such as social barriers, are less easily modelled and may also have marked effects. (Höltinger et al., 2016) highlight that social barriers could drastically reduce the potential for wind power in Austria, from 93 to 3.9 TWh; excluding forested areas as potential wind sites lowers the country's maximum potential by 45%. Thus, some variation in both technological and far-term economic potential is to be expected.

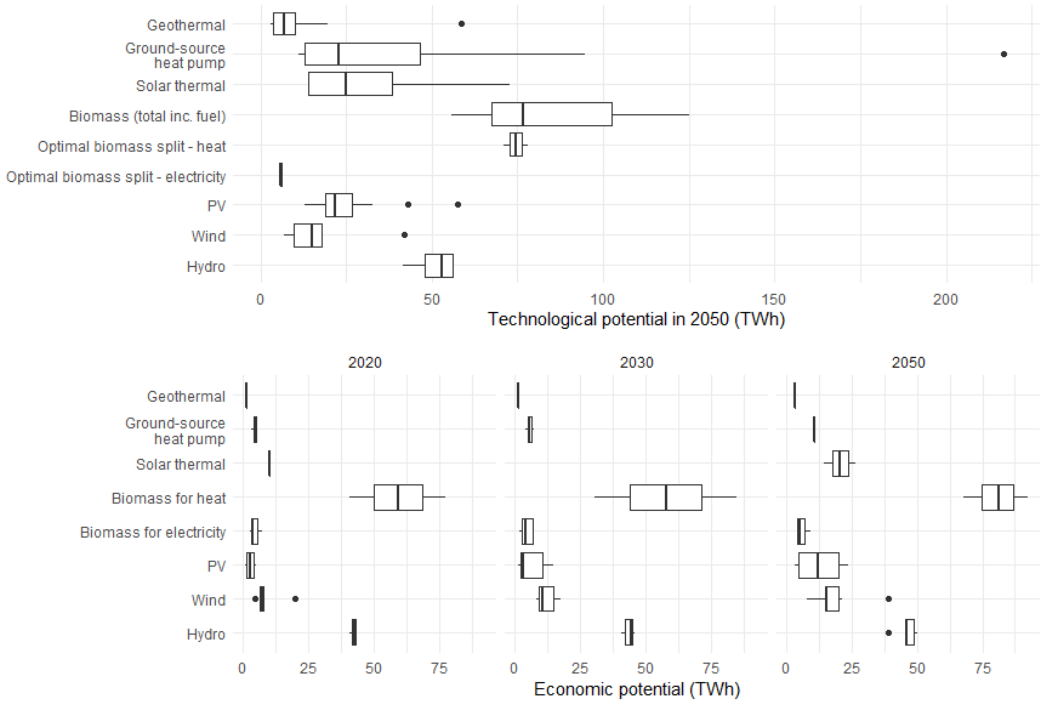


Figure 5.11. Summary of technological[16] and economic[17] generation potential for electricity and heat-generating technologies, based on literature review. The upper panel illustrates technical potential in 2050, and the lower panels show the modelled potential estimates from a mix of economic analyses for the years 2020 (left) 2030 (middle) and 2050 (right). The boxes indicate the interquartile range (the 25th to 75th percentile estimates) – the solid vertical lines in the boxes show median values – with horizontal lines indicating values up to two standard deviations from the mean, and points indicating outliers. We note that enhanced cascadic use of biomass may initially reduce biomass heat potential, while enhanced integrated PV will expand the respective potential relative to what is indicated by some of the sources cited.

Based on the results of our literature review, we determine the maximum available long-term (2050) generation capacity for each technology, as shown in Table 5.5.

[16] Sources of technical potential estimates: (Bliem et al., 2011; Haas et al., 2014; Haas and Redl, 2009; Kaltschmitt and Streicher, 2009; Moser et al., 2018; Österreichischer Biomasseverband, n.d.; Simoes et al., 2017; Streicher et al., 2010)

[17] Sources of economic potential estimates: (Bliem et al., 2011; Capros et al., 2016, 2013; Haas et al., 2017; Kalt et al., 2016; Krutzler et al., 2015; Nijs et al., 2018; Paardekooper et al., 2018)

Table 5.5. Parameterization of maximum possible renewable generation capacity in Austria (long-term, 2050) for each technology in the WEGDYN model.

	Hydro	Wind	PV	Biomass for			Solar Thermal	Heat Pump (ground-source)	Geo-thermal
				Fuels	Electricity	Heat			
Maximum generation (TWhr)	50	20	25	1.3	6.2	77.9	10	10	5

Scenarios

Based on the boundary conditions, we calibrate the macroeconomic model to a domestic generation of electricity in Austria of 85 and 105 TWh in 2030 and 2050 respectively (interpolating linearly). In 2019 renewable electricity production was at 57 TWh, with an above average hydropower contribution. Due to fluctuating hydropower, we use an annual average production of existing facilities of renewables at 55.5 TWh. The EU40 baseline assumes an increase in renewables-based production mostly driven by increased photovoltaics capacity and some wind power and other technologies, in 2030 complemented by 18 TWh of fossil source to achieve 85 TWh of domestic generation. By contrast, the stricter EU targets require stronger RES penetration and Austria almost decarbonizes its electricity mix by 2030. The specific contributions by RES technology reflect the targets given in the recent "Erneuerbare-Ausbau-Gesetz"[18], with additional 5 TWh of hydro power, additional 10 TWh of wind power, additional 11 TWh of PV and one additional TWh of other RES sources. While climate neutral from a net balance perspective, domestic production has a share of 2.5 TWh of fossil generation in 2030, and 82.5 TWh renewable. By 2050 renewables generation has risen to 102 TWh. This *Shift* in the structure of the electricity mix for stricter than EU40 targets is accompanied by additional measures: (i) demand side related improvements in the energy efficiency (*Avoiding* consumption by commercial and private appliances) by up to 1.3% p.a. (for the EU60 target compared to 1% p.a. for the EU40 baseline; next to last column in Table 5.6) and (ii) stronger regional integration of Austria within a renewable energy union allowing for *Improved* trade in electricity through e.g. common pricing zones and/or building required transmission infrastructure (last column in Table 5.6).

Table 5.6: Electricity transition in Austria – main scenario assumptions.

		Electricity system in Austria								
			Avoid Shift Improve							
		2019	**2030**	**2050**	**Add. TWh 2030 rel. to 2019**				**Energy efficiency°**	**RES union#**
Generation [TWh]		72	*85*	105	Hydro	Wind	PV	Other*	p.a.	multiplier
EU40	**RES share**	78%	*79%*	98%	0.0	1.4	10.9	0.9	1.00%	1.00
EU50		78%	*97%*	98%	5.0	10.0	11.0	1.0	1.15%	1.20
EU55seq		78%	*97%*	98%	5.0	10.0	11.0	1.0	1.23%	1.30
EU55sim		78%	*97%*	98%	5.0	10.0	11.0	1.0	1.23%	1.30
EU60		78%	*97%*	98%	5.0	10.0	11.0	1.0	1.30%	1.40

Notes: *Biomass, geothermal, waste (all elec.); °demand side energy efficiency improvements via product design standards; #Multiplier is applied on default trade elasticity of 2.8 (Beckman et al., 2011), corresponding transmission cost assumptions are shown in Figure 5.14.

[18] Erneuerbaren-Ausbau-Gesetz – EAG; Erneuerbaren-Ausbau-Gesetzespaket – EAG-Paket. Retrieved from: www.parlament.gv.at

Acknowledging potential indirect emissions through electricity imports, the electricity mix in the EU27+ also needs scrutiny. We base our scenarios for the electricity mix in EU27+ countries (without Austria) on the optimized system presented in (Pleßmann and Blechinger, 2017), which is shown in Figure 5.12. A pronounced *Shift* away from Nuclear and fossil-fueled generation towards wind power and PV is pursued with stricter targets. These EU-wide adjustments of the electricity system prevent carbon leakage due to stronger cross-border consumption. By 2050, the electricity mix is (almost) decarbonized in the EU27+.

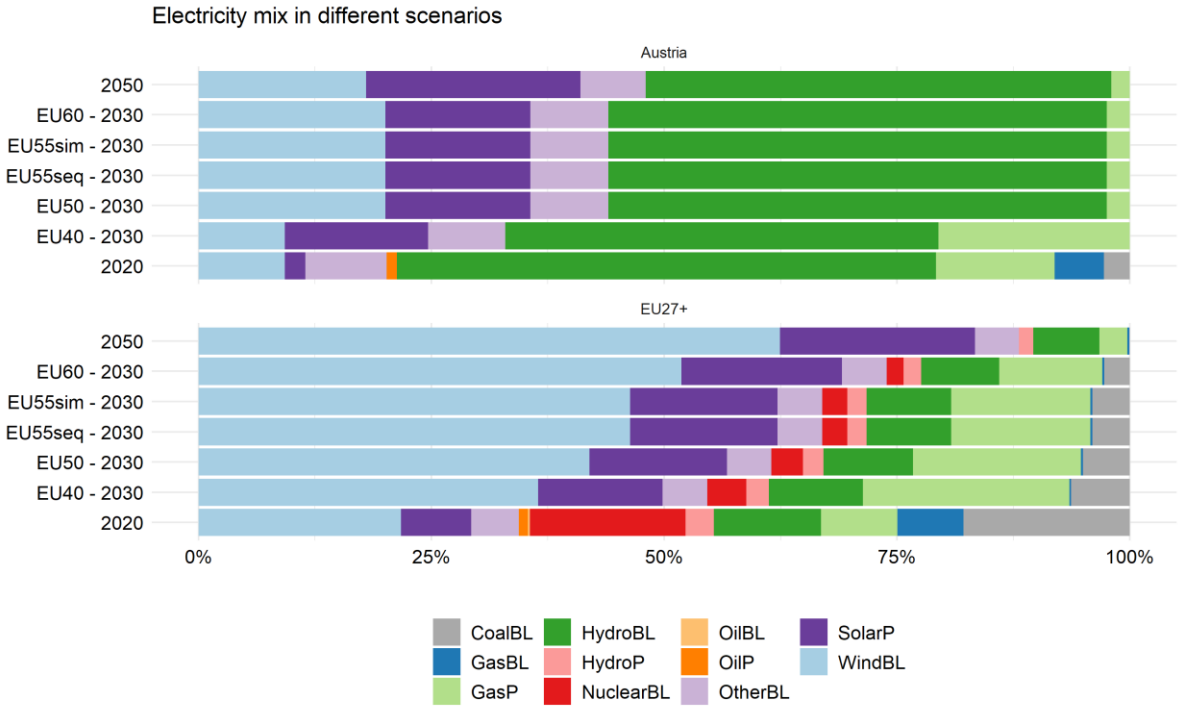


Figure 5.12: Electricity mix for 2020, in 2030 across different EU targets and for 2050. Top: Austria. Bottom: EU27+. BL = Baseload, P = Peak.

To allow for such a decarbonization, (Pleßmann and Blechinger, 2017) also take into account increased storage and transmission requirements in order to address the fluctuating nature of a high share of wind power and PV in the electricity mix. In Figure 5.13, the unit-cost difference of EU55-simultaneous scenario compared to the EU40 baseline is shown with and without storage and transmission costs (annuitized expenditures). The main cost assumptions per electricity technology are summarized in Table G.1 of Appendix G. Over time, the generation mix is less costly, with stricter EU targets benefitting from substantial cost digression in PV and wind power generation. However, the unit-cost of electricity supply (including investments in the mentioned auxiliary services) are temporarily higher, especially in Austria (left panel). It is also evident, that the greater RES potential outside Austria (which already has a high RES share in the status quo) offers larger cost savings (right panel), one of the issues that render autarky a questionable policy target. The corresponding investments in generation capacities, storage and transmission are shown in the left panels of Figure 5.14 and Figure 5.15. Total investments across EU emission reduction targets are shown in the respective right panels, which reveals that stricter EU targets come with earlier investments.

For cases when the difference between electricity demand and annual average domestic supply exceeds current levels, we assume an increase in domestic renewable (summer) production to balance (winter) imports such as to maintain the trade balance in electricity itself at current levels.

From a pure macroeconomic perspective results would be similar if higher electricity imports are matched with higher exports of other goods or services.

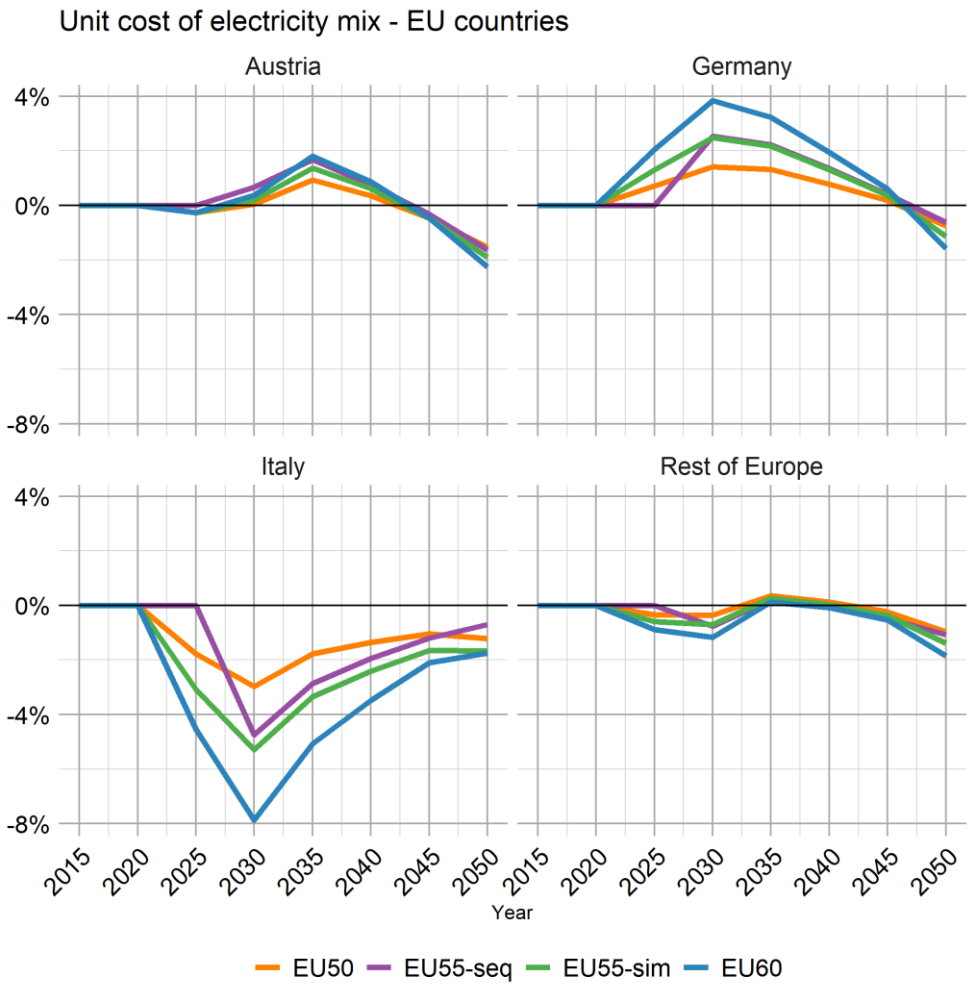


Figure 5.13. Percentage difference of the unit-cost (net of taxes) of the electricity mix in Austria (top left), Germany (top right), Italy (bottom left) and Rest of EU27+ (bottom right) across EU targets.

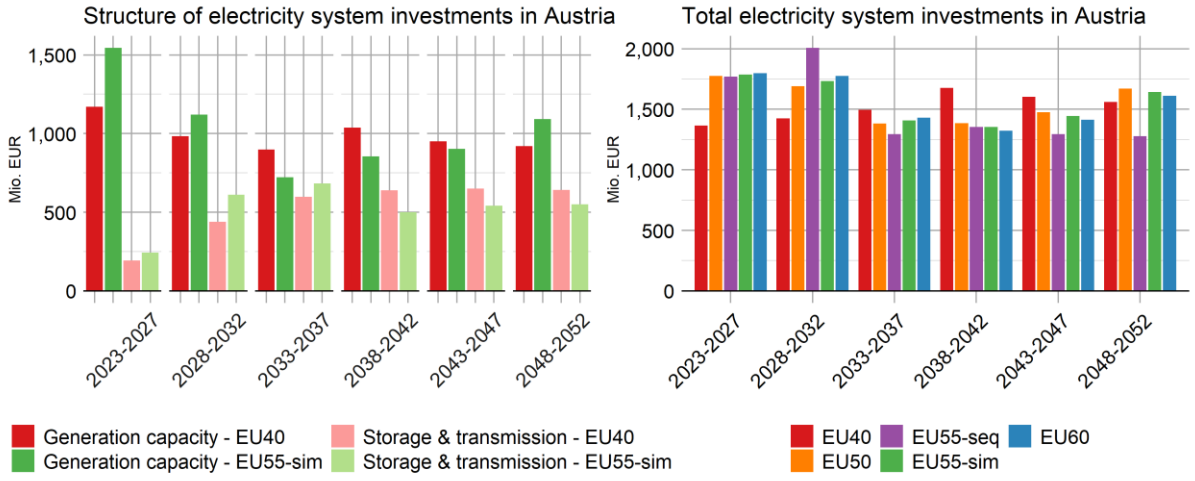


Figure 5.14: Austrian structure of electricity system investments for the EU40 and EU55-sim target (left) and total investments across EU targets (right).

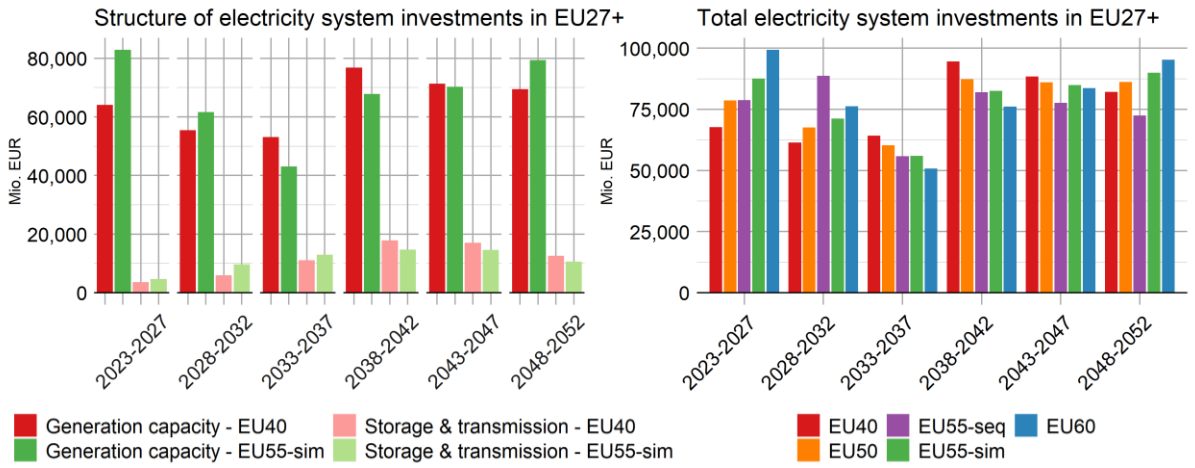


Figure 5.15: EU27+ structure of electricity system investments for the EU40 and EU55-sim target (left) and total investments across EU targets (right).

Cross-cutting measures

The following data and scenario assumptions are used for carbon pricing. For EU27+, we implement target-specific carbon emission caps for sectors covered by ETS regulation. This is based on (Steininger et al., 2020b), who break down overall EU targets to emission caps for sectors covered by the EU ETS and effort sharing emission caps per member state for non-ETS sectors for stricter 2030 EU climate targets (for different target levels of reduction). With this approach, we ensure that targeted emission levels in the EU ETS are achieved in the macroeconomic model; the development of the cap is shown in the left panel of Figure 5.16. The corresponding endogenous carbon price represents the portfolio of measures tackling emission reduction, which in the actual real world policy settings is composed of a range of different types of measures, including standards and technology shifts in addition to actual pricing. For non-ETS sectors, we assume a fixed carbon price development in Austria and all other EU member states, as shown in the right panel of Figure 5.16. This mechanism again only represents the broad range of instruments applied in reality since most member states have not (yet) implemented explicit carbon pricing either via permit trading or via taxation.

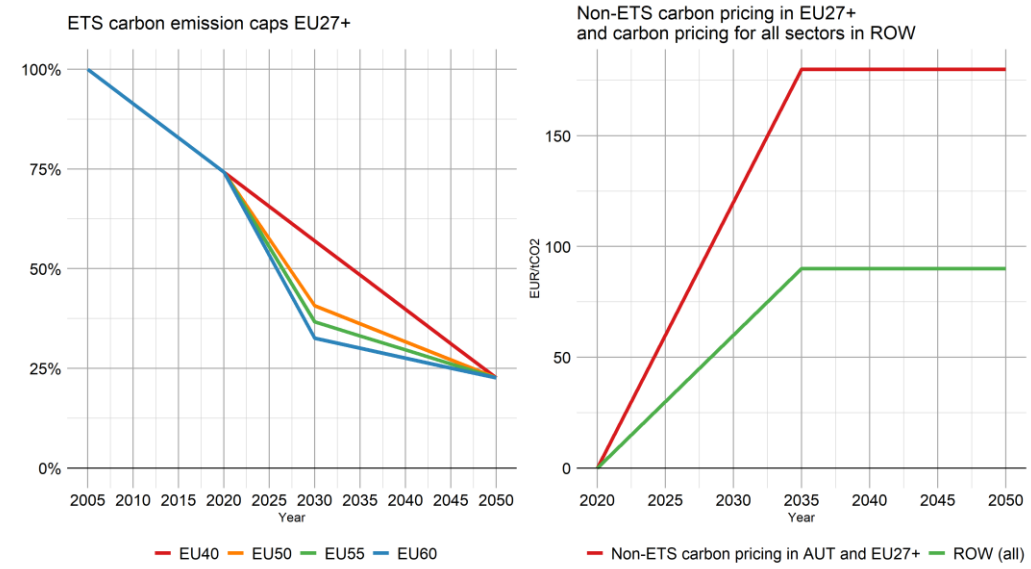


Figure 5.16: ETS carbon emissions cap in EU27+ (left); representative (i.e. explicit and implicit) non-ETS carbon price in Austria, EU27+ and for all sectors in ROW (right).

Note that we opt for a substantially lower and fixed development of implicit carbon prices in the rest of the world with a specified level of 15, 30, 60 and 90 EUR/tCO_2 by the years 2022, 2025, 2030 and 2035, and remaining at that level thereafter (right panel of Figure 5.16). This is a lower bound of to-be-expected carbon pricing outside Europe, because the number of countries and covered emissions rises every year (World Bank, 2020). For all model regions, all public revenues from carbon pricing are assumed by default to finance transfers to private households. These lump-sum transfers are a modeling device to ensure that the evaluation is neutral in the policy impact from the revenue use side. For that fraction of climate policy that actually applies pricing, actual revenue use options are much broader, including bonus schemes for both industry (innovation) and households (fostering energy or mobility related green investments).

Investment stimulus in recessionary times

The low-carbon transition requires substantial investments in climate-friendly capital. For sector-specific policies, the corresponding investment requirements have already been discussed. Here, we investigate total investments (aggregating across sector-specific measures) and lay out how these investments affect the working of economic activities during different contextual economic situations, particularly post-Covid-19. Figure 5.17 shows total investment needs of the investigated ETS and non-ETS sectors in Austria across scenarios, highlighting that stricter targets require earlier and larger investments.

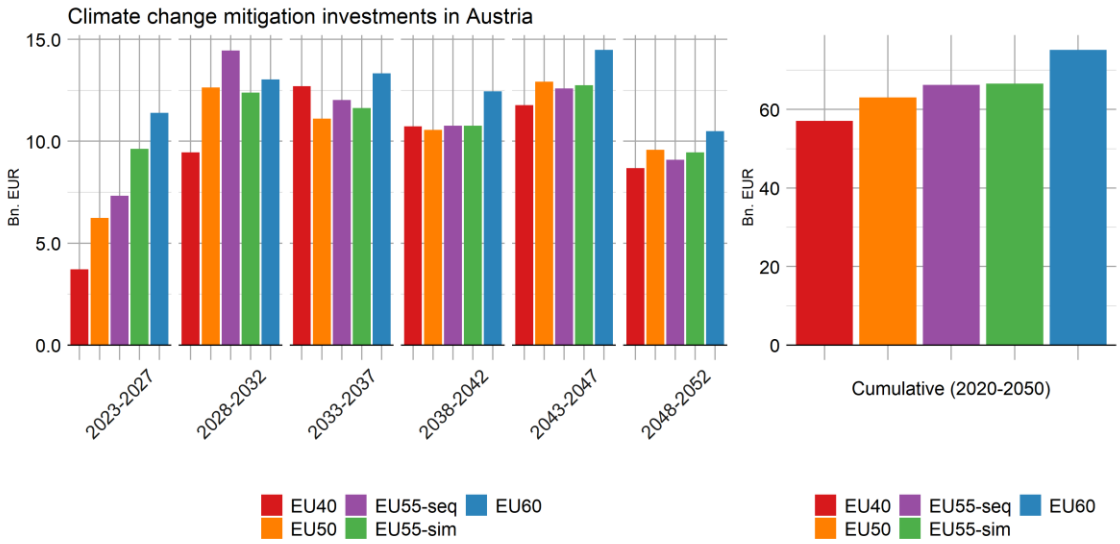


Figure 5.17. Climate Change mitigation investments in Austria across EU emission reduction targets. (Note that in national accounting some of these investments (those by private households) are categorized as (durable) consumption.)

The consideration of business cycles can have very different implications in terms of the size and direction of macroeconomic impacts associated with climate policy (Bachner et al., 2020). Currently, the tremendous economic downturn as consequence of the Covid-19 pandemic offers two crucial aspects that could make early and high climate-friendly investments socially much cheaper and more acceptable than postponing them. First, automatic economic stabilizers (e.g. unemployment benefits, ad valorem tax rates, etc.) lack comprehensiveness and profoundness to address the socio-economic challenges attached to the measures taken during the Covid-19 pandemic. Hence, governments step in, in order to bolster effective demand and ameliorate the worst effects of unprecedented lock-down measures. Thus, channeling the high private and public investments to areas with climate change mitigation potential and away from fossil energy could respond to both crises at the same time – the climate and economic crises – thereby preventing technological and behavioral lock-ins and stranded assets.

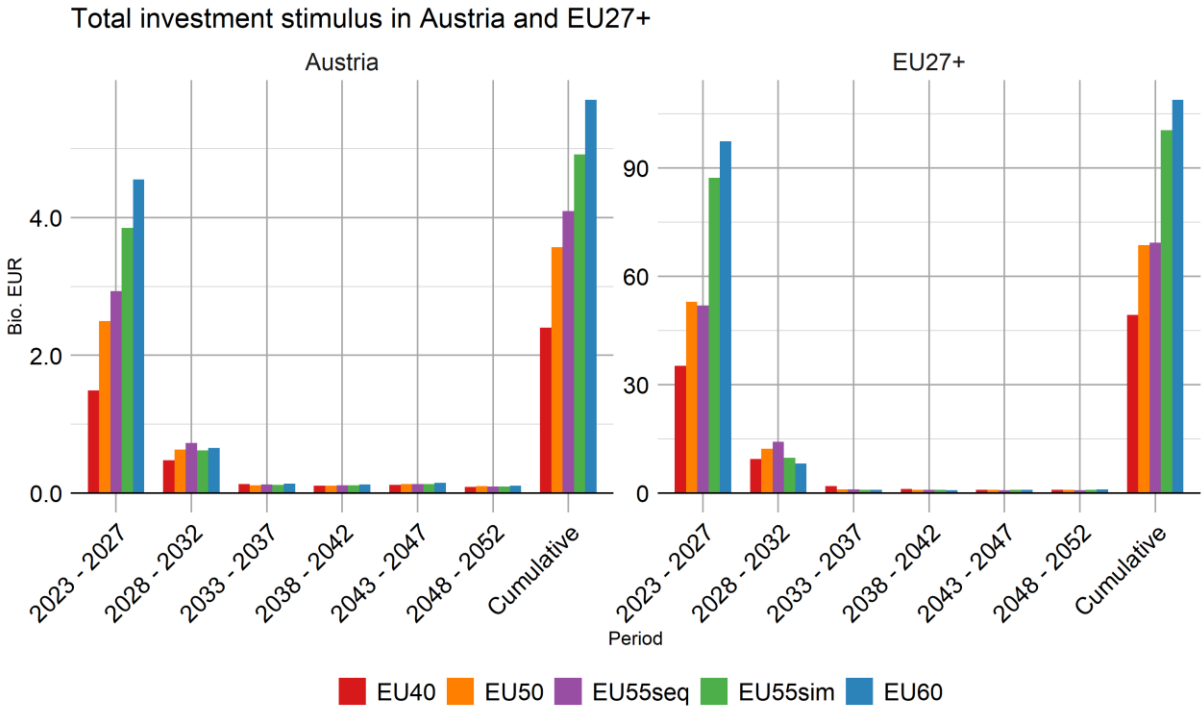


Figure 5.18: Investment stimulus across EU targets for Austria (left) and EU27+ (right) in recession phases. Volumes depicted are that fractions of investments that are not crowding out other investment but are effectively additional investment ("investment stimulus").

In economic boom phases, a high degree of capacity utilization restricts further demand-led growth; additional investment demand crowds out to a large part other investment because scarce factors of production would lead to inflationary tendencies. Hence, the second pro-argument for early climate policy action, particularly in the current situation, concerns the broad availability of idle resources, which can be stimulated in such phases of strong underutilization. Starting early (reflected by stricter emission reduction targets and corresponding investments) thus comes relatively cheaply now rather than pre-Covid-19. We translate this mechanism into our modelling by assuming that additional investments (e.g. required for the technology shift in iron and steel) only partially crowd-out other investments until capacity utilization rates have returned to "usual" levels. Figure 5.18 summarizes the aggregate investment *stimulus* from sector-specific policy measures, which is defined as the level of investments that is not crowding out other final demands in recessionary phases. It is also evident that the recovery is inversely related to non-crowding-out stimuli, which swiftly taper off over time. Looking at the cumulative stimulus, it is clear that stricter emission targets, and thus more pronounced investments at an early stage, take advantage of this temporary window of opportunity.

Insights from Austria's low-carbon innovation and export performance

Increasing the stringency of climate targets can serve as a stimulus to the development of low-carbon technologies and thus create new market niches and export opportunities for domestic companies. In order to make the best use of these opportunities, it is instructive to analyze Austria's current performance regarding low-carbon innovations and related export fields (Fankhauser et al., 2013). Areas of strength should be exploited and other areas addressed by policy to maintain and further develop Austria's international competitiveness during the transition to carbon neutrality.

To provide insights into Austria's current performance regarding low-carbon innovation in international comparison, an index of revealed technological advantage (RTA) is constructed using data on patent applications from the OECD. The RTA index can be interpreted as a measure of a country's relative technological specialization compared to all other countries (OECD, 2013). For country *i* and technology field *d*, it is written as follows:

$$\mathrm{RTA}_{d,i} = \frac{P_{d,i} \Big/ \sum_i P_{d,i}}{\sum_d P_{d,i} \Big/ \sum_{d,i} P_{d,i}}$$

where *P* refers to the number of patent applications as a measure of innovation activity. The RTA expresses country *i's* share of all countries' patent applications in technology field d relative to its share of all countries' patent applications in all technology fields.

Defining technology *d* in the numerator as a low-carbon technology, the RTA index indicates a specialization in this technology field if it takes on values greater than 1 (revealed technological advantage), no specialization if it takes the value 1, and a revealed technological disadvantage for values less than 1. The RTA index takes the value zero if the country holds no patent in technology field *d*.

The RTA index is computed for so-called climate change mitigation technologies as defined by the OECD ENV-TECH classification (OECD, 2016), relating to the emission sectors transport, buildings, industry, energy and waste (see Appendix B for details). In its environment statistics database, the OECD makes available country-level time series on patent applications for these sectoral climate change mitigation technologies as well as for all technology fields (OECD, 2020). These data are used to calculate the numerator and the denominator of the RTA index, respectively.

As a measure of Austria's current export performance related to these technologies, an index of revealed comparative advantage (RCA) is constructed based on export flow data in product groups related to each low-carbon technology d for which an RTA is calculated. The RCA index is commonly used to measure relative specialization in international trade (Balassa, 1965). For country *i* and product group *g*, it takes the following form:

$$\mathrm{RCA}_{g,i} = \frac{E_{g,i} \Big/ \sum_i E_{g,i}}{\sum_g E_{g,i} \Big/ \sum_{g,i} E_{g,i}}$$

where *E* refers to the value of exports. The RCA expresses country *i's* share of worldwide exports in product group *g* relative to the country's share of worldwide exports in all product groups. The index indicates a specialization in a product group if it takes on values greater than 1 (revealed comparative advantage), no specialization if it takes the value 1, and a revealed comparative disadvantage for values less than 1. The RCA index takes the value zero if the country has no exports in a given product group.

The RCA index is computed for product groups related to each of the OECD climate change mitigation technology fields for which an RTA is calculated. Data on the value of Austrian exports of goods to the rest of the world (excluding re-exports) are taken from the UN Comtrade database, which groups products according to the Standard International Trade Classification (Rev. 4, SITC). The RCA and RTA indices are then linked by collecting those SITC product groups that are considered most closely related to the respective low-carbon technology *d*. This is possible with a high degree of confidence for most transport and industry technologies well as for some buildings and energy technologies. For some technology fields, matching was unfortunately not possible. Appendix B contains further details on the SITC product groups matched to each OECD ENV-TECH technology.

Combining the RTA and RCA indices for climate change mitigation technologies related to different emission sectors allows identifying Austria's current areas of technological and/or export specialization: technology fields where the country registers both RTA and RCA values above 1 represent areas of strength, which the country can leverage to take advantage of new export opportunities arising from more stringent climate targets at EU level; technologies for which both RTA and RCA are below 1 represent areas of weakness, which could be strengthened using innovation and other policy instruments to better take advantage of new economic opportunities from the transition; technologies with RTA above 1 but RCA below 1 are areas of opportunity, where low-carbon innovations already exist that can be developed into an export advantage; and technology fields with RTA below 1 but RCA above 1 are areas under threat, where the current export advantage is at risk of being eroded in future because of insufficient innovation (Fankhauser et al., 2013).

6 Economic Implications of Enhanced Climate Policy

Die Zukunft soll man nicht voraussehen wollen, sondern möglich machen.
Antoine de Saint-Exupéry

A combination of indicators to shed light on overall implications

Over the last decades mankind has learned that not only labor and production capital create value added and welfare (Dasgupta, 2021), but that human welfare also crucially depends on the quality of natural services (ecosystem services, such as productive use of natural resources and amenities enjoyed), yet one main economic indicator, gross domestic product (GDP), still only reflects the former. As a consequence, if economic resources are devoted to improve or maintain environmental quality (or reduce environmental costs), as climate mitigation is, this will increase *actual* productivity (enhancing environmental services). But when measured against the only fraction depicted in – traditionally defined – GDP, it will *reduce* productivity, as then some of the additional output is not. In the following we nevertheless do utilize GDP, as one indicator, because it is strongly correlated with employment, but also because it is still used broadly in public discussion. We stress, however, to be careful in its interpretation. And we complement our analysis with a welfare indicator that seeks to more comprehensively depict wellbeing dimensions neglected by GDP.

The EU40 baseline and economic recovery from the Covid-19 crisis

The economic recovery in the EU40 baseline includes only broad stimulating policy measures, hence no enhanced climate policy mix that goes beyond the EU40 target. The recovery is modelled as "swoosh"[19], characterized by a strong decline of GDP ensued by a strong rebound that nevertheless tapers off (Figure 6.1). Consequentially, long run GDP levels are below what could have been achieved without the impact of the Covid-19 pandemic because investments in the crisis years drop, leading to lower capital formation over time. In addition, the EU40 baseline offers a temporary window of no-crowding out, during which new investments do not crowd out other investments or consumption, but rather stimulate a redirection of existing but idle factors of production facilitating structural change. Including this characteristic leads to a different EU40 baseline path, as compared to a hypothetical case with full crowding out. The different developments are given in Figure 6.1, with the red line showing the development of GDP when including a temporary window of no-crowding out and the grey line showing the development with crowding out. In order to take into account the current crisis and the availability of idle production factors (i.e. less crowding-out effects during the recovery phase), we always take the development indicated by the red line as our reference, i.e. the scenario to compare all other scenarios to (if not stated differently).

[19] https://www.nytimes.com/2020/05/29/business/economy/economy-recovery-forecast-coronavirus.html

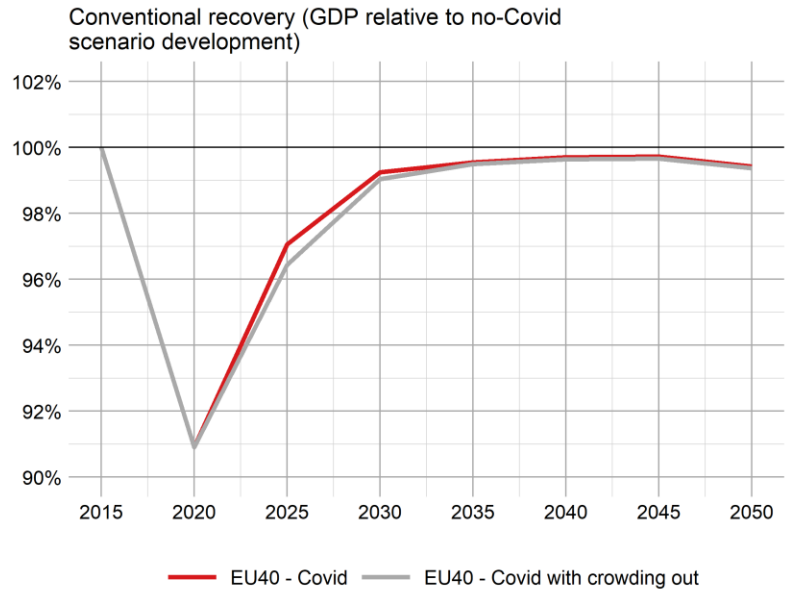


Figure 6.1: GDP development in Austria of the conventional baseline recovery as deviation to no-Covid scenario 2015-2050 (indexed to 2015).

Climate-friendly recovery – target revision and economic impacts

The effects of stepping up to the new EU55 target

As explained in the previous section, our scenario set-up and macroeconomic model allow us to explore the relevance of capital utilization, particularly in recessionary periods. The left panel in Figure 6.2 compares the development of GDP in the EU55-simultaneous scenario relative to the EU40 baseline and gives the difference as percentage deviation (EU55 relative to EU40). The solid line gives effects when assuming that the transition happens in a world with only partial crowding-out during the economic recovery, whereas the dashed line assumes a hypothetical world of full crowding-out (due to only hypothetically full capacity utilization).

We see the short run stimulating effect of the climate-friendly recovery boosts GDP up until the mid-2020s. The difference between the solid and the dashed line thus clearly shows the immediate economic opportunities that open up due to the current economic crisis, when climate policy is put in place simultaneously with recovery measures. From 2030 onwards, we see that under EU55 a fraction of climate benign investment, (which under EU40 would have only occurred in the 2030s to still achieve climate neutrality by 2040), is advanced in time and occurs earlier, thus with a lower (yet in absolute divergence still positive) GDP contribution in the 2030s. In the long-term, higher levels of GDP are sustained under the stricter EU55 scenario.

The stimulating effect of simultaneous policy action in 2025 is also visible if compared to the EU55 target designed only in a sequential manner (right panel of Figure 6.2). There, the investment stimulus is only effective later but much less pronounced, as the recovery has put the economy back to higher capacity utilization. Hence, long run GDP effects always remain below what could have been achieved with a simultaneous policy.

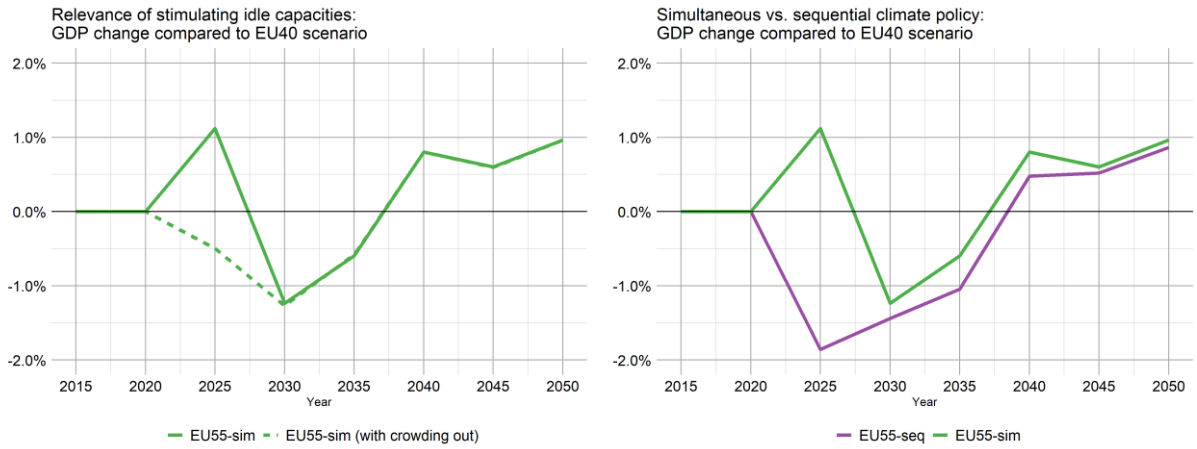


Figure 6.2: GDP impacts in Austria (%-difference to EU40 baseline) for the EU55-simultaneous target with and without full crowding out (left) and for the EU55-sequential target (right).

The core strength of the underlying macroeconomic methodology lies in the isolation of deviations ('endogenous response') from a given trend development due to specific interventions in the economic system (in our case due to earlier climate policy interventions). This means the trend is not a self-developed forecast but is based on econometric estimates reported in secondary sources (e.g. short-term forecasts for Austria by WIFO and world economic outlook by IMF).

The deviations of the EU55 pathway to EU40 depicted in Figure 6.2 thus occur in addition to economic development under EU40 itself. The latter, however, is connected to a larger set of uncertainties, not the least due to the pandemic and its aftermath. For the short-term, uncertainty of current forecasts is large due to the pandemic and the volatility of these projections very much depends on the success of fighting Covid-19. This can be illustrated by the real GDP forecast for Austria for 2021 that were available at the end of 2020. They ranged between 4.5% ("no policy change") and 2.5% ("third lock-down") – a 2-percentage-point range (Schiman, 2020). Due to a further surge of the virus, emerging new variants and corresponding policy changes, at the time of publication of this report (February 2021) current forecasts are revised downwards even below the lower end of this range (Badelt, 2021). This is still shaky and further corrections cannot be ruled out.

The macroeconomic evaluation applied in this study identifies the deviations from a baseline scenario (EU40), with results robust to a range of different possible developments. In Figure 6.3 of the many possible a rather conservative baseline is depicted in absolute terms and contrasted to EU55-sim GDP development. Table 6.1 indicates annual growth rates, i.e. the difference between EU55 over EU40, with "x_i" as an expectedly positive addend capturing a range of possible EU40 baseline scenarios (and the uncertainty around which of them will materialize). The longer-term growth rates are taken from the IIASA Socioeconomic development database (SSP2 scenario). Under current expectations of SSP2 trend growth as well as under the condition that respective climate policy measures are taken and framework conditions met, the stricter target of EU55 involves a short- and long-term boost for Austria's real GDP with some of the growth also occurring earlier than otherwise.

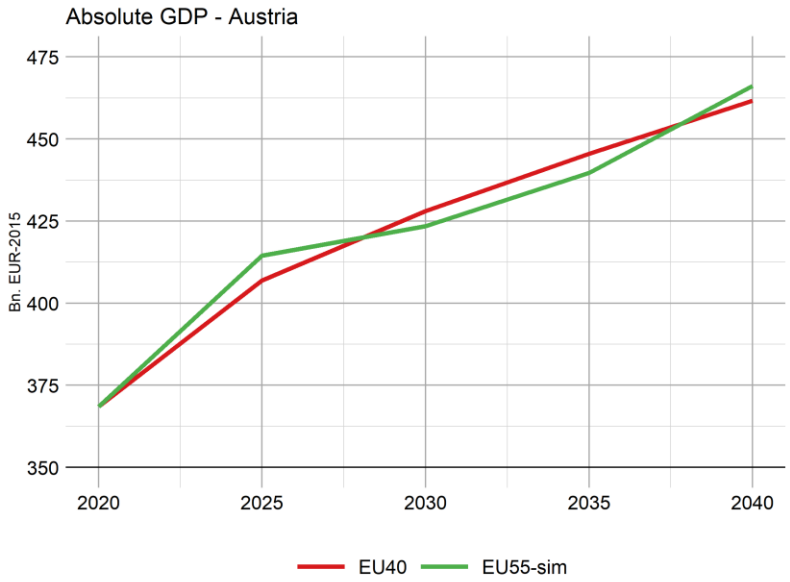


Figure 6.3 Gross domestic product – conservative baseline (EU40) development and deviation due to EU55 pathway.

Table 6.1 Average annual GDP growth rates (x_i indicates post Covid-19 and long-term baseline scenario uncertainty)

Period	EU40	EU55-sim
2021-25	$x_1 + 2.0\%$	$x_1 + 2.4\%$
2026-30	$x_2 + 1.0\%$	$x_2 + 0.4\%$
2031-35	$x_3 + 0.8\%$	$x_3 + 0.8\%$
2036-40	$x_4 + 0.7\%$	$x_4 + 1.2\%$

As we see in Figure 6.3, the effect of large parts of mitigation-relevant investments being brought forward from the period around 2030 to an earlier period is connected to a stronger stimulus earlier and a weaker one later. This weaker stimulus is visible in the temporarily slower (relative to EU40 around 2030) but still positive GDP development in the period around 2030. We test the sensitivity of model results by also implementing lower trends in real GDP growth in the EU40 baseline in order to derive a potential tipping point, where the EU55 target would lead to stagnation or even decline of Austria's GDP (in the period around 2030). We found an EU40 baseline trend growth of below 0.2% p.a. for 2026-2035 would result in the EU55 scenario's investment shift to earlier in the decade causing stagnation in the early 2030s. However, and as indicated above, potential growth even for 2021 was recently forecasted to be as high as 4.5% p.a. due to catching up in the aftermath of the global economic shock in 2020, a bandwidth crucially dependent on effects of and policy responses to the Covid-19 crisis. Summarizing, and also visible in Table 6.1, the qualitative insight gained by model simulations in terms of analyzing trend deviations is robust – from a macroeconomic viewpoint, the stricter target of EU55, under the condition that required framework conditions are set accordingly (see Chapter 4 and core demands summarized in Chapter 7), is preferable to an EU40 target.

The specific shape of GDP effects can also be informative via a more detailed view. In Figure 6.4, we thus investigate the contribution of each sector-specific policy package (left panel for ETS sector policies, right panel for non-ETS policies). Exploring the EU55-simultaneous impacts, we assume that only individual sector-specific EU55 policy packages are active and other areas stick to an EU40 pathway. In other words, we investigate the hypothetical GDP impact if measures targeting the higher EU55 objective are implemented only for one particular sector.

The left panel in Figure 6.2, focusing on ETS sector policies, reveals that the policy package for **electricity** is associated with positive GDP impacts, particularly during the recovery (orange line). The unit-cost of electricity supply in Austria slightly increases with stricter targets (including auxiliary services and net of taxes; Figure 5.13). However, four components of the policy package turn this cost disadvantage around. First, the policy package of the stricter emission reduction target is associated with slightly higher energy efficiencies at the demand side and, second, stronger regional integration of electricity supply. Third, a higher penetration of renewables in the electricity mix especially outside Austria implies lower import prices of electricity. Lastly, facing the same ETS carbon price, a more rapid structural change towards renewables renders the EU55 target cheaper. Combining all four components of the policy package leads to lower electricity prices (relative to EU40), which gives rise to productivity gains. In addition, stronger investments in early phases of the recovery are less subject to crowding-out and GDP impacts are positive.

For **iron and steel** (blue line, left panel in Figure 6.4), the unit-cost comparison shown in Figure 5.1 already identifies relevant framework conditions for a successful structural change achieving the EU55 target. At the macroeconomic level we here assume, first, that also non-EU (ROW) starts its climate ambition later, but does achieve climate neutrality in steel production by 2050 as well (see Table 5.1), second, that green steel is a market that the EU27 can serve, and third, that some type of foreign competitiveness adjustment in climate policy (e.g. EU level border carbon adjustment) prevents any substantial loss in EU27 market shares. Learning effects accumulate stronger for early movers and carbon pricing improves relative costs of hydrogen-based steel making (as the reference EU40 still incorporates larger shares of conventional steel production affected by carbon pricing). This relative productivity gain, together with the associated investment stimulus during the recovery, shows up in higher GDP levels compared to the EU40 baseline (blue line). The temporarily lower GDP growth in the period of 2030 to 2035 relates to the capital-intensive transformation costs of shifting from conventional to alternative steel making; as soon as the transformation itself is completed, substantial productivity gains increase GDP. It is crucial to note that this is an economy-wide perspective (aggregate Austrian GDP), indicating an economy-wide demand for shouldering this transition, but not indicating any specific sector contribution. It will be a range of different sectors and agents contributing to this transition, spread across the economy by investment and consumer preferences, and public policy frameworks. To name just one example: the carbon neutral transition will increase the demand for high quality steel wind rotors and rail infrastructure. Figure 6.3. does not report sectoral outputs, it reports shifts in *economy-wide* value added due to policies addressing certain sectors, both short- and long-term.

The retrofitting of **cement** facilities with carbon capture applications more rapidly than in the EU40 baseline and providing the by-product hydrocarbon to other industries generates positive contributions to the recovery (green line, left panel Figure 6.4). Without using captured carbon for other economic activities, end-of-pipe abatement would represent a productivity loss. However, since a new product augments the supply portfolio of the cement industry, which can be used elsewhere (e.g. chemical industry) and covers for the transformation costs, GDP levels are higher compared to the EU40 baseline, where this transformation happens later. Note also the strong investment stimulus from this sector post-Covid-19. Relative to the EU40 scenario, following the EU55 pathway implies that part of the positive GDP effects are advanced already to the 2020s, such that the positive effect in the 2030s is then only somewhat smaller (Figure 6.4 shows the deviations from a – in absolute terms – rising GDP development).

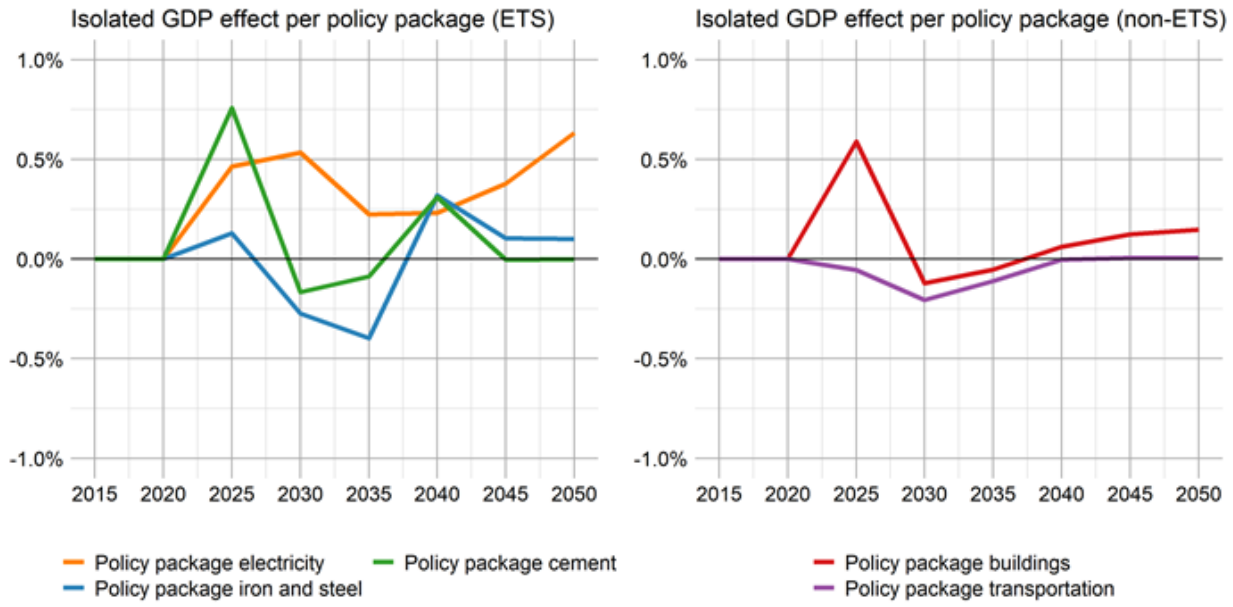


Figure 6.4: Deviation of aggregate Austrian GDP development from EU40 baseline development (traditionally defined, not reflecting environmental and non-market service productivity gains) under a solely single sector policy for the EU55-simultaneous target with policies in single sectors of ETS (left) and non-ETS sectors (right). For details and interpretation see main text.

The contribution of EU55 policy packages in non-ETS sectors is shown in the right panel of Figure 6.4. For the road **transport sector** (passenger and freight) only the high cost policy package elements of infrastructure and vehicle stock investment as well as policies depicted by (explicit and implicit) carbon pricing are modeled. With these measures implemented in isolation (and the remaining sectors keeping measures as set out in EU40), GDP effects of shifting to the EU55 scenario are negative throughout the model horizon (blue line, right panel). This effect highlights that the potential benefits from an electrification of motorized individual transport are overcompensated by costs in the road freight transport sector. Particularly, this result reveals the technological and organizational innovation gap in road freight transport. Other policy elements of the transport sector would enhance GDP, yet specific quantification of the respective dimension is more difficult to estimate.

For the **buildings sector**, GDP effects are positive post-Covid-19, with strong stimulating effects by the mid-2020s due to the large investment stimulus of the EU55 scenario relative to the EU40 baseline (orange line, right panel). Thereafter, three interacting mechanisms determine GDP impacts. Firstly, investments of the buildings policy package are labor-intensive, and even more so in the EU55 scenario compared to the EU40 baseline. This stimulates employment and affects GDP positively. Secondly, the even lower heating demand of the EU55 scenario relative to the EU40 baseline implies higher energy efficiency and additional productivity gains across the economy, also affecting GDP positively. Thirdly, the additional spending of private households on rents (and corresponding decline in other consumables) covers the additional capital expenditures related to buildings measures. This additional spending is particularly pronounced in early phases of the transformation, affecting GDP negatively. While the last mechanism clearly dominates in 2030, thereafter the other effects lead to sustained higher GDP levels compared to the EU40 baseline.

The effectiveness of varying targets

With the recent decision of the EU council to step up EU-wide ambitions to reduce greenhouse gas emissions until 2030 by 55% relative to 1990, a crucial question concerns the effectiveness of varying targets. The short-term investment stimulus post-Covid-19 is clearly stronger with increasing ambition, as higher investments then occur within a period when structural change is achievable much

cheaper than in "ordinary" situations. We again note that the transition to a stricter target requires that necessary framework conditions are set, key being (i) the availability of renewable energy at sufficient levels and competitive prices, (ii) fair market access or border adjustment rules as long as no globally uniform CO_2 price is guaranteed and (iii) a range of national framework conditions for transition as given in full detail in Chapter 7. If these framework conditions are set in due time, and given the post-Covid-19 underutilization, the immediate effects of the recent target revision are found to be beneficial (green line in Figure 6.5) and exploit this temporary opportunity. A less ambitious target revision (EU50; orange line) would have missed this chance in the short run. With policy packages achieving the EU60 target (blue line) – again presupposing that the necessary framework conditions have been set, which is even more challenging for a stricter target – we see that an even larger fraction of climate-benign investment is shifted to occur earlier, from the 2030s to the 2020s, with the implemented measures targeting emission reductions earlier generating higher GDP across the whole period, thus ranked best among the investigated scenarios in that respect.

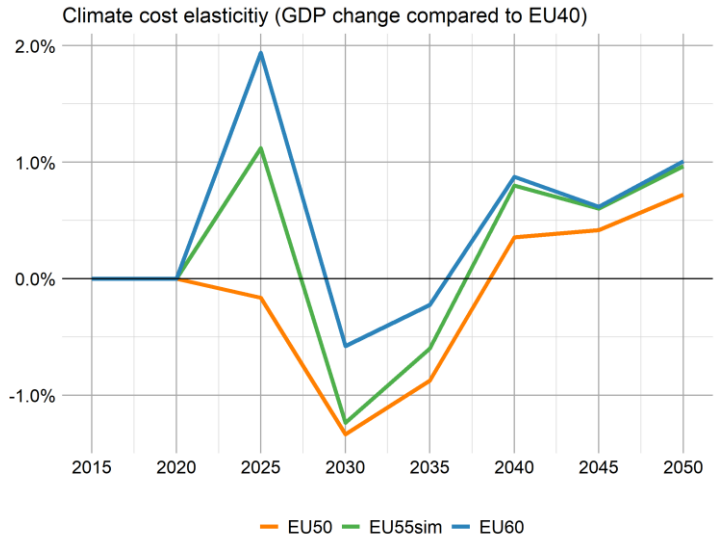


Figure 6.5: Climate cost elasticity – GDP impacts in Austria (%-difference to EU40 baseline development) for the EU50, EU55 and EU60 target.

This is also shown in Table 6.2, which gives the cumulative GDP effects over the period between 2020 and 2050 (as %-difference to EU40). With the EU55 target, the annual Austrian GDP is on average +0.2% higher until 2050 (compared to the former EU40 target). While the EU50 target generates annual GDP losses (on average -0.1% until 2050), the EU60 target performs best with an average annual GDP gain of +0.5% until 2050. Hence, the term climate mitigation *cost* elasticity that has been used in the past seems to have become misleading, because it misses out the plenitude of *beneficial* mitigation options. We also emphasize that pursuing a stricter target with climate policy implemented only after a "conventional recovery" (EU55seq) is the worst option. From a sectoral perspective, the investigated measures in the sectors electricity but also cement and buildings contribute the most to a beneficial climate-friendly recovery (top row in Table 6.3 indicating first/only simulations). The ranking of this finding is robust in terms of the sequence of activating individual policy measures (bottom row in Table 6.3).

Table 6.2: Effectiveness – cumulative Austrian GDP effects of varying targets (relative to EU40 development).

Cumulative GDP (period 2020-2050) %-difference of targets compared to EU40	
EU50	-0.1%
EU55seq	-0.3%
EU55sim	0.2%
EU60	0.5%

Table 6.3: Effectiveness – cumulative Austrian GDP effects of sector-specific policies (relative to EU40 development).

Cumulative GDP (period 2020-2050) %-difference of EU55sim compared to EU40
(with all sector policies active for EU55, the cumulative GDP change is +0.21%)

		Electricity	**Iron and steel**	**Cement**	**Transport**	**Buildings**
Sequence of activating sector policy measures	First & only	0.31%	0.00%	0.10%	-0.04%	0.09%
	Last	0.33%	0.04%	0.13%	-0.05%	0.09%

Going beyond GDP

Gross domestic product is a widely used proxy for societal wellbeing but – as indicated at the beginning of this chapter – is subject to a variety of blind spots. To account for some of them, we here provide additional model results, starting with employment, which indicates one dimension of distributional effects regarding societal groups relying more on labor income relative to capital owners. The investment stimulus around 2025 increases effective demand, leading to higher demand for labor, which increases wages and incentivizes higher employment. The employment rate for (un)skilled labor in the EU55 scenario rises by around 2.5 percentage points relative to the rate of employment in the EU40 baseline (Figure 6.6). Due to some of the investment otherwise occurring only in the early 2030s (but under EU55 advanced to already the 2020s), employment in that period of the 2030s is lower than under EU40, yet with employment by 2040 and thereafter are again above the EU40 baseline. Note, that climate policy in EU40 (also achieving climate neutrality) already increases employment, on average by 1.9% over the period 2020-2050. This higher employment level is the one the deviation under EU55 applies to.

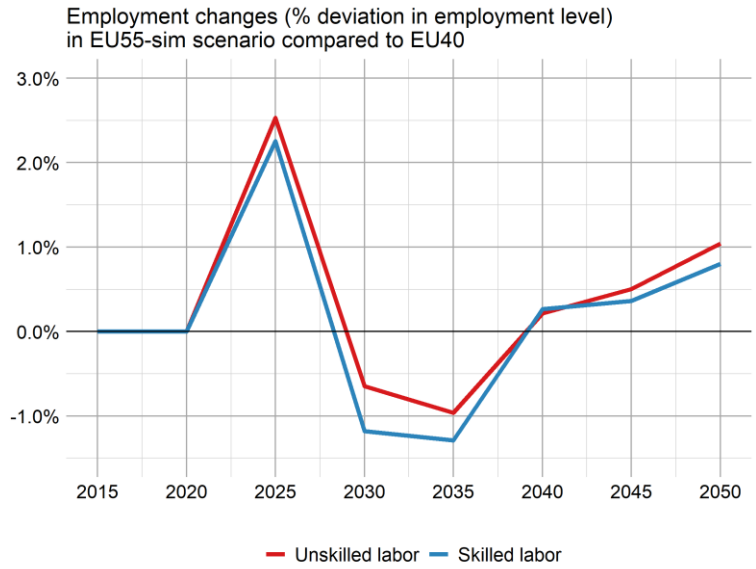


Figure 6.6: Employment impacts (reverse %-point-difference to rate of unemployment in the EU40 baseline) in Austria for the EU55-simultaneous target [positive changes indicate relative employment increase]. Note that only relative changes to EU40 are given, with climate policy already in EU40 inducing significant net employment gains (about 2% higher employment on average 2020-2050).

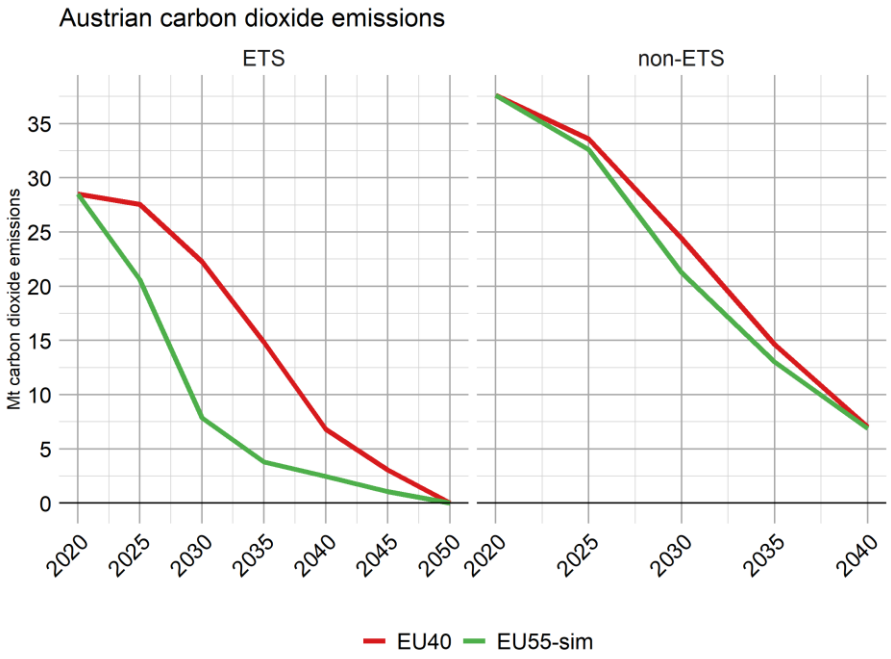


Figure 6.7: Austrian ETS (left) and non-ETS carbon emissions (right) for the EU40 baseline and the EU55-simultaneous target. As in this study among Non-ETS sectors detailed modelling addresses climate neutrality in buildings and transport only, while in non-ETS industry, agriculture and waste only partial decarbonization is achieved, carbon emissions remain in the latter sectors, implying model results to depict climate neutrality by 2040 only for the buildings and transport sector, but not for the remaining non-ETS sectors.

The Austrian cost of climate inaction, i.e. the economic impacts if emissions are not largely reduced, are substantial, their evaluation and implications are presented in (Steininger et al., 2020a). Hence, a core benefit not reflected in GDP is the substantial cut in carbon emissions achieved by the

investigated policy packages. In Figure 6.7, we depict the modelled pathway towards climate-neutrality, distinguishing emissions of ETS and non-ETS sectors. Note that, as the focus of this report are different reduction targets by 2030 (we here show EU40 and EU55), the long run emissions by 2040 and thereafter are still below Austria's necessary contribution to achieve climate-neutrality. Addressing these targets would need further measures not accounted for in this analysis (e.g. policies for aviation, waste and agriculture), but also non-ETS industry has not been modelled in full technological detail as to ensure complete climate neutrality.[20] However, climate neutrality is achieved in the main Non-ETS sectors buildings and transport, as well as in ETS.

The distinction of emissions by ETS and non-ETS sectors is a useful perspective. However, for some sectors, like the buildings sector, the interaction of ETS and non-ETS emission reductions is much more relevant. Figure 6.8 shows the EU40, EU50, EU55 and EU60 scenarios in the buildings sector. The adoption of a higher renovation quality (EU50, and EU60 respectively) allows for achievement of higher savings in terms of final energy, with respect to scenarios with the same renovation rate (EU40, and EU55 respectively).

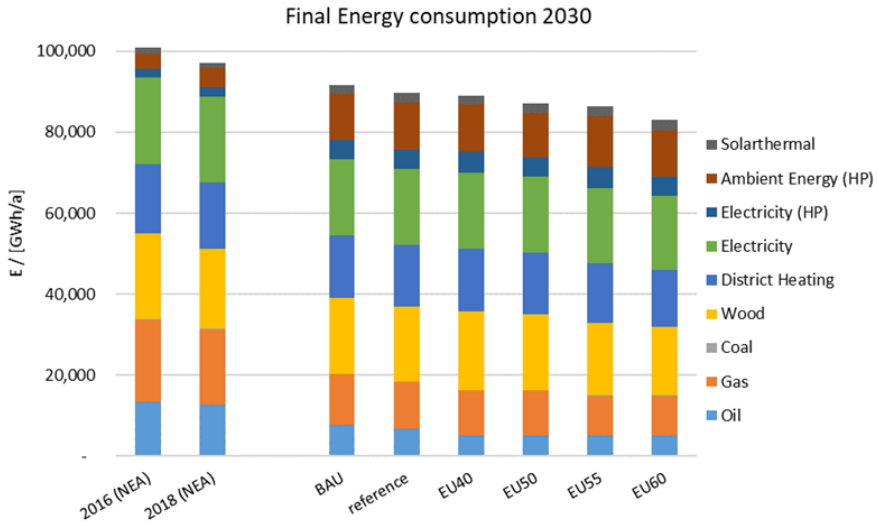
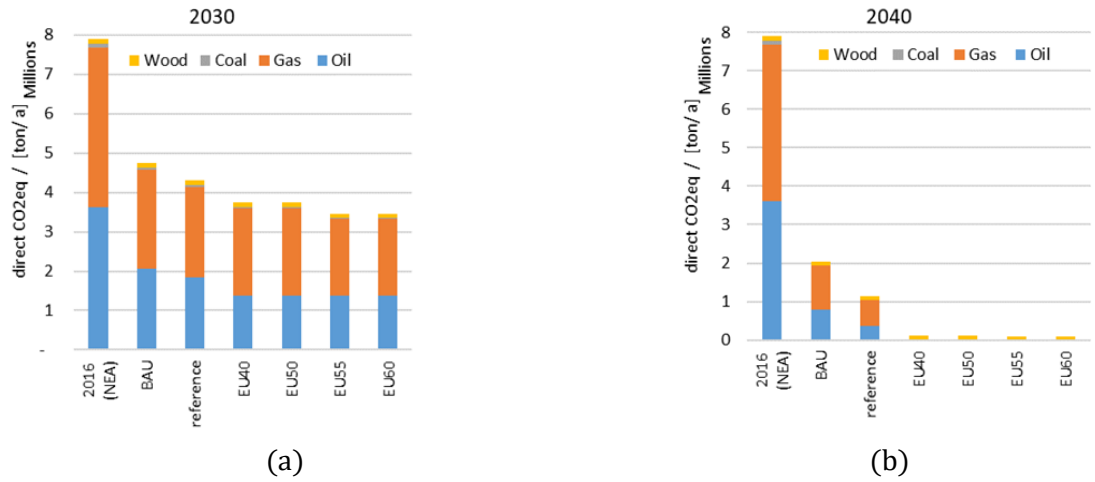


Figure 6.8: Results for the 2030 final energy demand of the building sector in the analyzed scenarios.

Electricity and district heating demand implies ETS emissions as long as fossil sources in their generation are not fully phased out. For non-ETS emissions the impact is clear as well. Figure 6.9 shows that ambitious refurbishment and heating system exchange rates, together with halting installation of fossil fuel-based heating systems from 2021, allows for fossil-free energy demand in the building sector by 2040. However, this requires an extensive application of heat pumps in order to substitute fossil-fuel-based systems. All heating, ventilation and air conditioning (HVAC) installations must operate with high efficiency (high quality of installation), otherwise an increase of the electricity demand should be expected.

[20] The EU wide implicit ETS allowance price (derived from the certificates market in the macro model) rises to 180 EUR/tCO_2 by 2030 in the EU40 baseline and to 300 EUR/tCO_2 in the EU55 simultaneous scenario. Only a fraction of that will concern actual ETS pricing. As mentioned earlier, the development of the carbon price for non-ETS sector emissions is fixed along a given pathway. Our modelling only takes up selected sector measures (those with a large emissions share); the level of the resulting ETS carbon price in the model thus is only indicative for the necessary ambition by other measures, that in reality will cover a much broader range than pricing only. This needs to be considered when interpreting these numbers. If actually charged, the revenues of carbon pricing are nevertheless crucial funds to finance transition capital or (as is modelled here) finance the public budget, including transfers to vulnerable societal groups.



(a) (b)

Figure 6.9: Results for non ETS CO_2emissions in the building sector (from the final energy consumption) in the analyzed scenarios in year 2030 (a) and 2040 (b).

From the building stock scenario model, it results that a renovation rate of 1.5%, even if coupled with an HVAC-only change rate of 2.0%, as in the reference scenario, is not sufficient to achieve a complete phase out of fossil-based HVAC systems by 2040. A selective gradual removal of fossil systems is required to reach this target, but in parallel a thermal renovation of the building stock is necessary. The installation of new generation heating systems (i.e., heat pumps) in buildings with non-renovated envelopes is not always feasible, since it would not only have no impact in the reduction of the final energy demand of the building, but it would also result in a poor performance of the technology itself.

While carbon emissions are the overall focus of this report, the investigated scenarios also generate reductions in other external environmental effects.

Co-benefits

When evaluating mitigation policies, the focus is mainly on the implementation costs, while positive spillover effects resulting from the transitions to low carbon options, so-called co-benefits, are often overlooked. This also represents a blind spot of GDP: a range of welfare enhancing implications are not visible – by its very construction – in GDP. For example, enhanced comfort in renovated buildings is not reflected, rather on the contrary, a lower energy bill will reduce the indicator GDP. While many of these benefits can clearly be listed but are difficult to quantify, in the following we shed light on one dimension for which at least comparatively robust quantifications are available: external costs of reduced air quality, respectively their reduction as a co-benefit of climate policy.

Transport sector

With the transition of the modal split in the transport sector towards increased levels of public and active transport as well as other less carbon intensive forms of mobility, various co-benefits arise. Increased levels of activity resulting from the transition towards more active mobility by bike and foot creates positive health benefits (Maier et al., 2020; Wolkinger et al., 2018). Further health benefits arise from better air quality due to the lowered levels of emissions, as the reduced exposure to air pollution reduces the risk of respiratory and cardiovascular diseases (Maier et al., 2020; van Essen et al., 2019; Wolkinger et al., 2018). For the economic quantification of such health benefits elements associated with the costs of health care, productivity losses due to morbidity and mortality as well as those reflecting the loss of life are used (Amann et al., 2017; Maier et al., 2020; Wolkinger et al., 2018). Wolkinger et al. (2018) in an analysis of health co-benefits of climate policy in the transportation sector for the cities of Vienna, Graz and Linz find that these co-benefits amount to EUR 11.7 million per year, relative to a 2010 baseline (with EUR 7.42 million from the changes in air quality and EUR 4.35 million resulting from increased activity). These results assume that the

political targets for the modal split for 2020/2025 are almost achieved, resulting in a reduction of about 290,000 t CO_2equ relative to the baseline of 1,200,000 t in 2010. When a change beyond current policy targets with an associated decrease in emissions of almost 530,000 t CO_2equ is assumed, the co-benefits amount to EUR 17.92 million per year, or EUR 18.92 million per year when complete electrification of the transport sector is achieved, resulting in the reduction of 1,000,000 t CO_2equ (Wolkinger et al., 2018). Lower levels of air pollution further create non-health co-benefits such as the reduction of crop losses, material and building damage and biodiversity loss. Material and building damage are mainly connected to pollution or corrosion of surfaces through particles whereas air quality affects biodiversity through acidification of soil, precipitation, water and the eutrophication of ecosystems (Maier et al., 2020; van Essen et al., 2019). The transition from fossil fueled individual mobility towards more public as well as active transport further creates positive spillovers concerning noise disturbance and congestion, however no studies show a comprehensively estimated scope of these co-benefits that would lend itself to a numerical estimate for Austria (de Bruyn et al., 2018; Maier et al., 2020; van Essen et al., 2019).

Energy sector

The transition from fossil-based energy production towards renewable energies and the associated reduction in emissions also results in co-benefits connected to the better quality of air (Karlsson et al., 2020; Ministry for the Environment, 2018). While the scope of such co-benefits has not been estimated for Austria, it is expected that their scale is smaller than that of the transport sector. This is due to first the simple fact that transport sector GHG emissions are higher in absolute amount than those of the energy sector (Ritchie and Roser, 2020), but, second, and more specifically, the effects of emissions arising from the transport sector have a larger impact on human health as they are emitted at lower heights and therefore affect receptors more strongly (Matthey and Bünger, 2019). This is especially relevant for particulate matter, while the effects of other air pollutants show less variation over differing release height and location (Matthey and Bünger, 2019). It can be concluded that the negative effects and hence the scope of co-benefits associated with air pollution stemming from the energy sector are smaller compared to the same emissions in the transport sector for health-related areas but comparable concerning other areas. The German environmental agency estimates a possible reduction in the environmental costs for different energy sources from approximately 20 €-$Cent_{2016}/kWh_{el}$ for lignite, coal and oil or 9 €-$Cent_{2016}/kWh_{el}$ for natural gas down to 0.3 €-$Cent_{2016}/kWh_{el}$ for hydropower and wind power, 1.7 €-$Cent_{2016}/kWh_{el}$ for photovoltaic and 8 €-$Cent_{2016}/kWh_{el}$ for biomass power plants (Matthey and Bünger, 2019). Included in these environmental costs are health effects, biodiversity losses, crop failures as well as material damages. An increased share of renewable energies further lowers dependencies on fossil based imports and hence creates co-benefits associated with the resilience of the energy system, which are not included in the aforementioned estimates (Karlsson et al., 2020; Ministry for the Environment, 2018).

Buildings sector

The transition towards less carbon-intensive forms of heating resulting in lower levels of emissions again creates co-benefits in health as well as non-health areas connected to increased air quality. Analogous to the conclusions drawn for the energy sector, the scale of co-benefits is expected to be smaller than those arising within the transport sector. The German environmental agency estimates the environmental prices for fossil based sources with approximately 12 €-$Cent_{2016}/kWh_{el}$ for lignite (briquettes) and electric heating with grid losses, 7 €-$Cent_{2016}/kWh_{el}$ for heating oil and district heating with grid losses and 5 €-$Cent_{2016}/kWh_{el}$ for natural gas. The prices calculated for the renewable sources are 4 €-$Cent_{2016}/kWh_{el}$ for shallow geothermal energy, 3 €-$Cent_{2016}/kWh_{el}$ for biomass and below 0.5 €-$Cent_{2016}/kWh_{el}$ for solar thermal or deep geothermal energy (Matthey and Bünger, 2019). The reduction of environmental costs when moving from non-renewable to renewable heating sources illustrates the scope of co-benefits arising from the transition.

The values calculated by the German Environmental Agency can serve as a second reference for the extent of the co-benefits that can be expected from emission reductions in the sectors. In our model

calculation of the co-benefits are based on several generalizing assumptions and should hence be seen as an approximation rather than a precise assessment. First, we assume that the percentage composition of the pollutants arising from the various sectors remains unchanged throughout the study period, with the pollutant composition from 2018 as analyzed by (Michael Anderl et al., 2020) taken as a basis. We further assume very simply that all pollutants are reduced or increased by the same percentage change as the CO_2 emissions change as quantified in our analysis. The monetization of the co-benefits is then done by taking estimates of the environmental costs of various pollutants for different sources from the German environmental agency (Matthey and Bünger, 2019). As the evaluation of co-benefits only uses the CO_2 reduction resulting from measures taken within the sectors as calculated in the main macro model as input, issues of double counting do not arise.

An approximation for the co-benefits is calculated for the energy, heating and transport sectors, as sufficiently accurate data is available here. While the data for the transport sector includes flight transport, which is not included in our quantitative analysis, only domestic flights, i.e. those with take-off and landing in Austria are included in the emission data. As the contributions of domestic flights to the overall pollutant emissions are only minor (0.1% or 0.04 million tons of CO_2 equivalent in 2017) their inclusion in the data has negligible effect, while still allowing for satisfactory accuracy in the results (Anderl et al., 2019). The industry sector is not included in the co-benefits approximations, as only specific sectors within it are modeled; data on emissions, however, is available only for the industry sector as a whole, hence the accuracy of such results would be too low to be of value.

Figure 6.10 summarizes the evaluated co-benefits, which we recognize as occurring alongside the market-based effects of climate policy as discussed previously. Air quality health co-benefits amount to at least annually EUR 0.8 bn. (1 bn.) by 2030 for EU40 (EU55) policy, and rise to EUR 2 bn. by 2050.

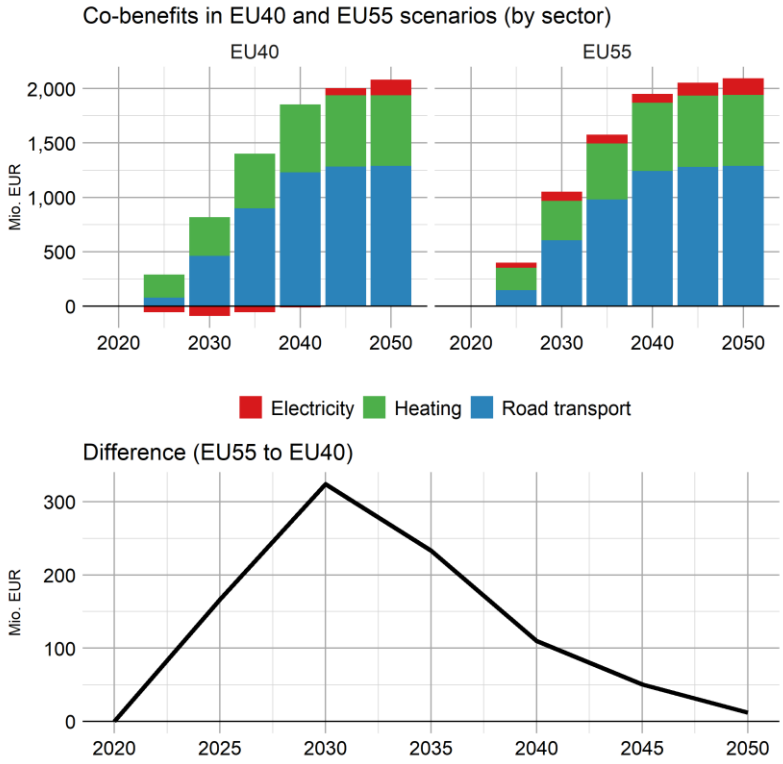


Figure 6.10: Air quality health co-benefits of EU40 and EU55. Top panel: absolute by sector. Bottom: absolute difference EU55 relative to EU40.

The economic relevance of competitive electricity cost and the new geopolitics of renewable energy

European industry, in particular the iron and steel industry and industry collaborations to employ carbon capture and use (e.g. with cement production), can only become green if it has access to green electricity (or hydrogen produced thereof). In our macroeconomic simulations, the EU40 baseline (with 10% emission reductions of Austrian iron and steel making) would already raise the steel sector's annual electricity demand by 2.6 TWh in 2030 (hypothetical, only if reductions would be fully achieved via hydrogen-based options, otherwise the increase is correspondingly lower). The increase by 2030 would be 6.8 TWh with the EU55 scenario (40% market share of H2-based steel making, with the same qualification applying). Hence, it is clear that for a complete transformation, the European steel sector can only survive the intense global competition in the sector if the needed electricity is both abundant and available at competitive prices, i.e. affordable for industrial use. The same applies to industry collaborations for carbon capture and use. For example, for the carbon captured in the cement industry to be processed with hydrogen to methane (or other feedstock) for the chemical industry (or other products) hydrogen will be required in significant amounts (Mauschitz, 2020). If hydrogen demand originating from all industrial uses is all produced from domestic electrolysis, the demand by 2030 would rise by another 17.4 TWh (or more, under EU55). The substantial hydrogen demand for CCU, however, clearly makes evident that CCU will not be the only (global) strategy to reduce GHG emissions in industry branches where relevant (see Chapter 4 for the full set of options).

During the climate neutrality transition, many areas of the Austrian economy are going electric (mobility, heating, electrolysis-based hydrogen for industrial use, etc.). Our analysis shows that by 2030 electricity demand in Austria in the scenario EU40 (EU55) will rise by 17.5 TWh (20 TWh) over demand in 2019, plus the demand for producing hydrogen domestically (in industry up to an extra 13.2 TWh in the EU40 and 17.4 TWh or higher in the EU55 scenario). While for the EU40 scenario by 2030 this demand may – just principally – be still within domestic generation potential (yet note that expansion at this speed of generation and transmission for these maximum amounts represents more than an enormous challenge, it also exceeds all expansion scenarios available for that time scale), demand for affordable (industry competitive) renewable electricity will clearly exceed domestic supply in a fully transformed economy, and most likely for policy in accordance with the EU 55% emission reduction (or higher) by 2030. Various scenarios for industrial electricity demand by a fully transformed industry on a renewable basis are available for Austria (with a time horizon of 2050). Starting from a current industrial electricity demand at 30 TWh (2017, (Geyer et al., 2019)) they range from rising to 32 TWh (Geyer et al., 2019: scenario "efficiency") to 68 TWh (Geyer et al. 2019: scenario "upheaval/Umbruch", and equivalently WKO et al. (2019): scenario high). In this study we use an overall long term (2050) domestic renewable electricity potential of 102 TWh (see Chapter 5, section energy, Figure 5.11 and Table 5.5) for the references this is based upon, a few studies give slightly higher potentials (e.g. WKO et al., 2019, at 119 TWh, due to higher values used for wind, PV and biogas). But irrespective of the exact potential for renewable electricity among those discussed for Austria, the electricity demand in a society on a fully renewable basis is highly likely to exceed this domestic potential.

The very same overall excess demand for energy has been prevalent in the past and Austria has focused on and benefited from its comparative advantages, for instance, by importing cheap fossil energy and exporting high-quality steel products in turn. Similarly, the benefits of trade are capable more than compensating the outlined domestic shortages of RES energy. The choices still have to be taken in what form renewable energy is imported, directly as electricity, bound in energy carriers (such as green hydrogen), or bound in intermediate products (such as iron pellets), and the respective shares of each of these elements. This will complement any strategy to reduce – globally and in Austria – the material quantity demand for respective products and (further) shift the output to the higher value added end in respective sectors, such as significant reduction of concrete in ceilings by lucid shuttering formwork, yet still offering activated building components for energy storage functionalities. Of the choices on (implicit) energy trade, it is likely – and promising – that some share will be renewable electricity imports, as we argue in the following.

Recently, solar photovoltaics (PV) has become the cheapest source of green electricity, with costs below 2 c/kWh, but these low costs are only possible in locations with abundant insolation, i.e., in the belt between about 30° North and 30° South. However, PV is not suitable, even if located in this belt, to supply electricity reliably day and night through all seasons because it is affected by the daily and seasonal rhythms and insolation often gets dimmed by clouds.

Increasingly, new PV parks are combined with batteries that store electricity during the day for up to 8 hours of supply after sunset. This has become possible due to the very rapid technological and economic development of batteries with lifetimes of most likely above 20 years. The costs of electricity from such installations can be below 3 c/kWh in the belt between 30°N and 30°S. At these electricity costs, the European iron and steel industry, and many other European industries, could prosper. However, Europe suffers from low insolation during winter, with solar insolation of about just 10% of insolation in summer. Storing electricity from summer for winter would need energy storage for about 100 days, which is 300 times more than the 8 hours of storage that have recently become economically feasible.

Dramatic technological breakthroughs in long-distance transmission of electricity will now be used to generate green electricity in the world's largest solar farm of 10 GW in the region of Pilbara in the northwest of Australia and then transmit this electricity over 3,800 km through a high voltage direct current (HVDC) subsea cable to Singapore (Mazengarb, 2019). This solar farm will also host a battery with 22 GWh of capacity. Electricity costs in Singapore are expected to be $0.03/kWh (OLD, 2020). Insolation in this Australian region is as high as in regions with electricity costs of $0.02/kWh in recent power purchase agreements from solar farms. Thus, the costs for the battery and the cable are about $ 0.01/kWh. One of the two initiators of this "Sun Cable" project, the Australian software billionaire (company Atlassian) Cannon-Brookes, says this $20bn solar project will be a "lighthouse" to the world and foresees the installation of hundreds of such cables not only in northern but also in eastern and western directions, i.e. over even longer distances.

Connecting both global hemispheres through cables can completely overcome the seasonal limitation of sunlight (Grossmann et al., 2015). An optimal configuration of PV installations on all continents could supply firm electricity for Europe, i.e. meet the European load pattern uninterruptedly over 20 years with their varying insolation, at electricity costs of $0.0254/kWh (plus transmission cost). The numbers given above show that costs of cables would increase electricity costs by less than 1%.

The trend of building up a global electricity grid is also followed by the Chinese government; a project that is pushed relentlessly by the Chinese prime minister (Fairley, 2019; Kynge and Hornby, 2018). China has already bought electricity distribution companies in several European countries. Another initiative in this field of electricity supply is done by the company Tesla. Here, distributed PV installations are connected with behind-the-meter batteries, controlled by sophisticated software that allows for their use as virtual batteries for buying and selling electricity and for supplying grid services like grid stabilization, frequency control and even black start. The famous "Big Battery" (129 MWh capacity) in Hornsdale, Australia, is also controlled by this software and is so highly profitable that in Australia alone about 20 more such batteries are under construction, some of them multiple times the size of the battery in Hornsdale, which two years ago was still the biggest battery on earth and was before its installation thought by experts to be impossible. Now for example PG&E has signed contracts with Tesla for construction of batteries of 10 times the size of the Hornsdale battery with 1.1 GWh of capacity.

These signals are quite clear and Europe could miss the chance of participating in this global project if it does not act quickly. Global powers, notably China, are about to dominate the global electricity market through new technologies and sophisticated software. As this electricity will be affordable, highly reliably, due to the new capabilities of batteries and direct current transmission lines, and supplied in a climate neutral manner, customers all over the world will demand this energy, also in Europe. This is a signal for Europe to speed up its activities in the field of green electricity as much as it can, i.e. pursue the most highly ambitious goals for climate mitigation to give a strong push to its industries, such as pursuing the goal of 55% reduction of GHGs, and embedding this in a strong program for digitalization. It goes without saying that an electricity grid that connects billions of

prosumers also poses a strong challenge for development of new software, which might open big opportunities for a highly developed country such as Austria. To give just one example from our own research, we found that the usual optimization of nonlinear systems with the square norm does not give an appealing fit between electricity generation and load pattern, but a change of the underlying mathematics enables much better results. These mathematics can then be embedded in cellular automatons and in AI systems, allowing new possibilities also here.

Ambitious projects in the field of renewable electricity will also constitute a lifeline for a green European industry.

Austria's low-carbon innovation and export performance

Figure 6.11 shows the average index of revealed technological advantage (RTA) over the period 2010 to 2016, computed as described in section 5, by emission sectors for Austria, the Netherlands and Germany. The index illustrates these countries' relative technological specialization in climate change mitigation technologies compared to the rest of the world. For all emission sectors considered together (top bar), Austria registers an RTA of 0.95, indicating a small technological disadvantage in low-carbon technologies. Regarding the individual emission sectors (lighter bars below), it is apparent that Austria's main area of strength lies in climate change mitigation technologies related to the waste sector, where the RTA value of 1.7 indicates a relative technological specialization. In all other emission sectors, Austria's RTA lies below 1 on aggregate, although sub-fields with RTA values above 1 exist in each sector. These are investigated next.

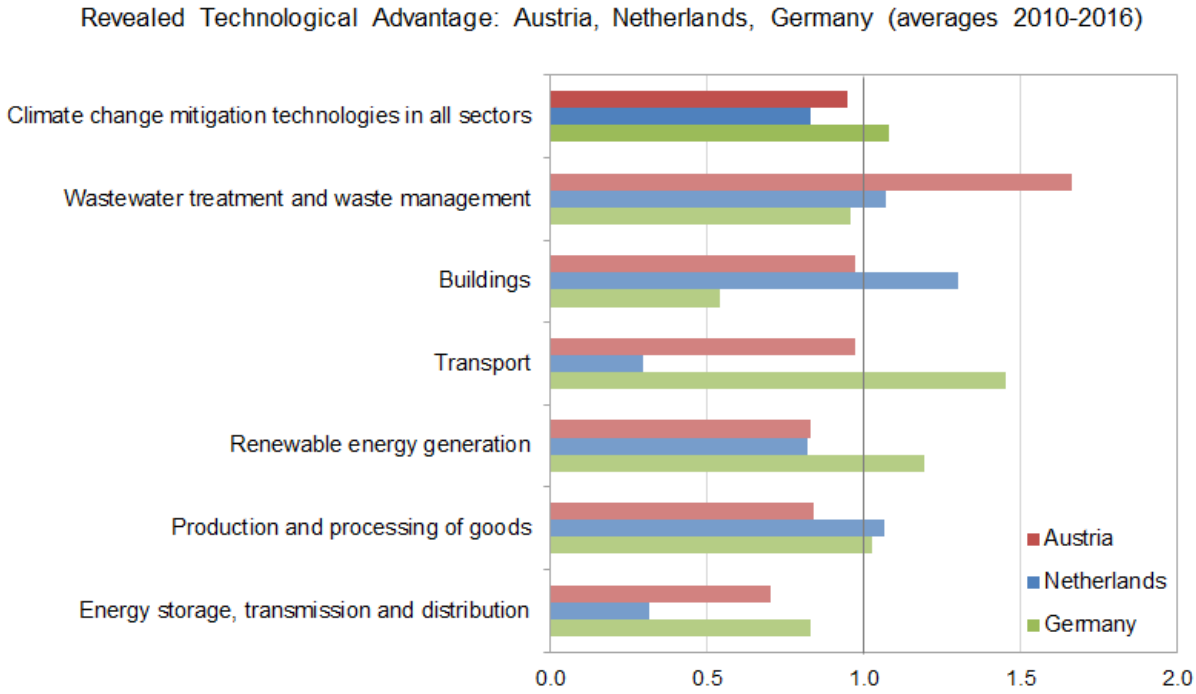


Figure 6.11. RTA indices for ***climate change mitigation technologies by emission sectors*** *according to the OECD ENV-TECH classification (OECD, 2016), averages 2010-2016. Darker shades (top bar) represent all emission sectors on aggregate, lighter shades (bars below) represent individual emission sectors. (Note: "Production and processing of goods" includes some industry sectors and agriculture. In the figure, the energy sector is split into renewable energy generation as well as energy storage, transmission and distribution technologies. See Appendix B for more details.)*

The following figures provide more detail on Austria's innovation and export performance within individual emission sectors, allowing us to draw conclusions on the country's position to exploit new economic opportunities arising from the transition to climate neutrality. For various climate change

mitigation technologies relating to each emission sector, the RTA index is combined with the index of revealed comparative advantage (RCA), yielding four quadrants as described in section 5: *areas of relative strength* are fields where Austria registers both RTA and RCA values above 1, indicating both a technological and an export specialization; in *areas of weakness*, both indices lie below 1, indicating a relative disadvantage in both innovation and exports; *areas of opportunity* register a technological specialization which could be leveraged to generate also an export specialization; and in *areas under threat*, a comparatively weak innovation performance poses a potential threat to the future of a currently advantageous export performance (Fankhauser et al., 2013).

Starting with ***transport***, climate change mitigation technologies related to rail transport stand out as the dominant area of strength. These include energy recovery technologies concerning locomotive propulsion and other energy efficiency technologies like lightweight materials. In addition, climate change mitigation technologies related to conventional vehicles based on the internal combustion engine (ICE) are in the strength's quadrant. However, key transition technologies like those relating to electric/hybrid vehicles and electric vehicle charging are under threat. Policy action to improve Austria's innovation performance in these fields – helping to maintain the current export advantage in the longer term – could include raising R&D funding targeted towards the relevant technologies, in particular energy storage options such as batteries and capacitators (see also Figure 6.14).

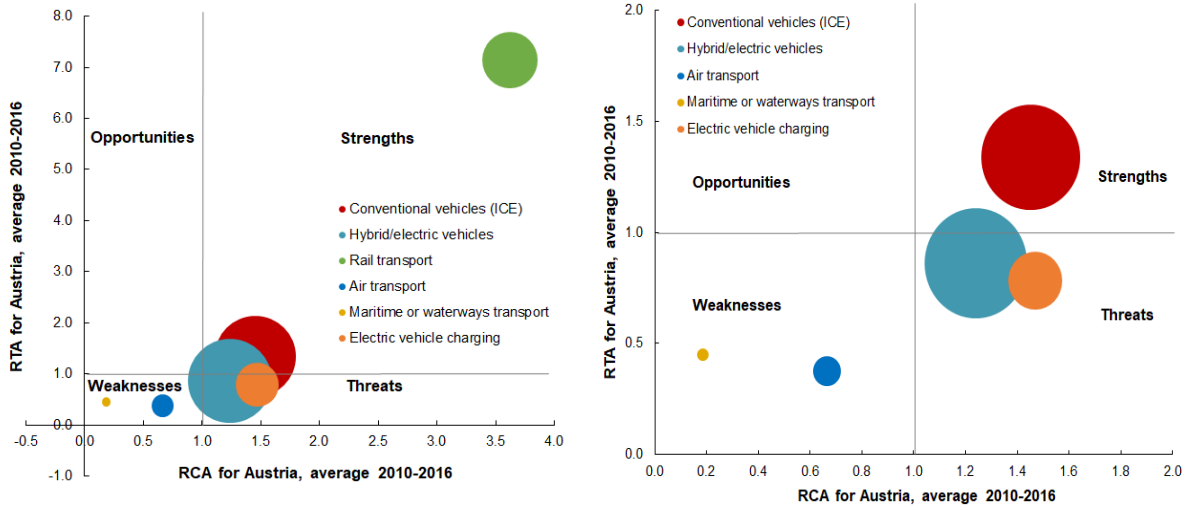


Figure 6.12. Austrian RTA vs. RCA indices in in climate change mitigation technologies related to ***transport, including and excluding rail,*** *averages 2010-2016. (Note: Bubble size corresponds to the value of Austrian exports to the rest of the world in the product groups matched to each technology, relative to the other data points in each graph. Details on the SITC product groups matched to each OECD ENV-TECH technology are given in Appendix B.)*

In ***industry***, climate change mitigation technologies related to cement grinding, lime and metal processing are clear areas of strength. In metals for instance, the current efforts of Austria's main steel producer to develop a production process based on green hydrogen will, if successful, allow it to sell "low-carbon steel" and thus further increase its export share in a world transitioning to carbon neutrality (where carbon border tariffs introduced at the EU level may play a role). In cement production, an area of opportunity, the sector's comparative innovativeness in low-carbon technologies may allow it to develop an export specialization in future. Here, policy instruments such as targeted export promotion initiatives can be applied to support the sector. On the other hand, in the chemicals, glass, ceramics and sand and stone industries, specific R&D support can provide a stimulus for the development of low-carbon innovations, helping to maintain their current export advantage in the longer term.

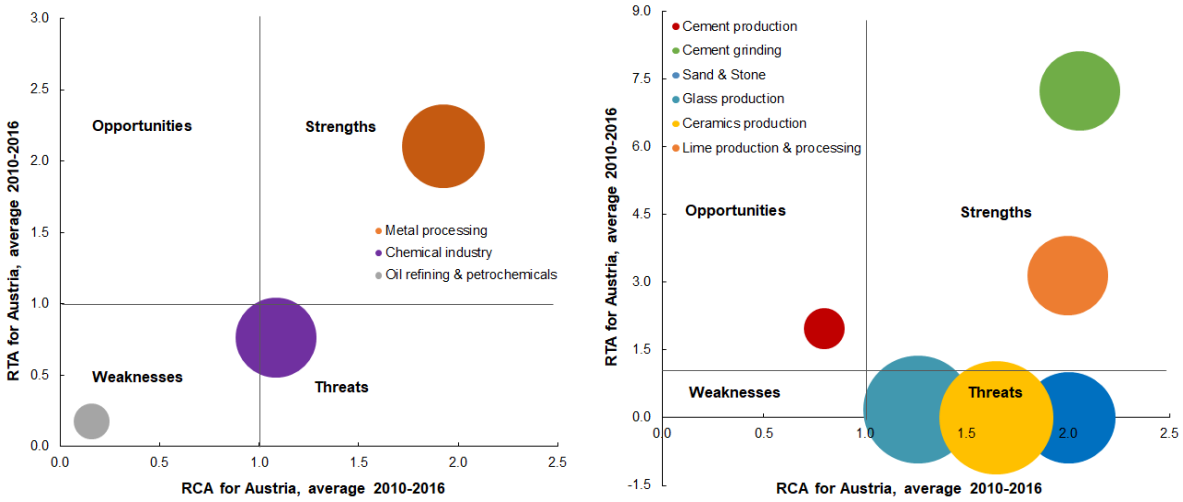


*Figure 6.13: Austrian RTA vs. RCA indices in climate change mitigation technologies related to **industry**, averages 2010-2016. (Note: Bubble size corresponds to the value of Austrian exports to the rest of the world in the product groups matched to each technology, relative to the other data points in each graph. Details on the SITC product groups matched to each OECD ENV-TECH technology are given in Appendix B.)*

For ***buildings***, the left-hand panel of Figure 6.14 shows that climate change mitigation technologies such as energy-efficient lighting, elevators and escalators as well as heating, ventilation or air conditioning (HVAC) are areas of strength. The latter category includes heat pumps, heat recuperation and waste heat systems, absorption/adsorption-based systems for heating or cooling as well as lowest energy and passive house technologies. Other areas of technological specialization, with RTA values greater than 1, are the integration of renewable energy sources such as PV, solar thermal systems and geothermal heat pumps into buildings, and efficient end-user side electric power management and consumption (not shown).[21] In many of these fields, Austria's existing technological and/or export specialization will allow the country to benefit from the economic opportunities opened up by rising international demand for low-carbon technologies resulting from more stringent climate targets.

For ***energy***, the right-hand panel of Figure 6.14 indicates a technological specialization in hydro energy generation together with a small export specialization in product groups related to the field, making this an area of strength. However, wind energy and storage technologies like batteries and capacitators, which are key technologies for the energy transition, are areas of weakness that would merit both export support and innovation policies. Although not shown in the figure,[22] Austria also has a technological specialization, i.e. RTA values greater than 1, in other technologies relating to renewable energy generation, transmission, distribution and storage. These include solar thermal energy generation and solar thermal-PV hybrids, hydrogen technology as well as thermal, mechanical and pumped storage. On the other hand, the RTA lies below 1 for fuel cells, energy generation from solar PV and smart grids in the energy sector, which are also key transition technologies worth encouraging with targeted innovation policies.

[21] For several technologies in buildings and energy, a reliable matching of related SITC product groups and thus computing the RCA index was not possible. Hence, they are not included in the figures and only their RTA values are referred to in the text.

[22] As mentioned in the previous footnote, a reliable matching of related SITC product groups and hence computing the RCA index was not possible for some energy and buildings technologies. Therefore, only their RTA values are referred to in the text.

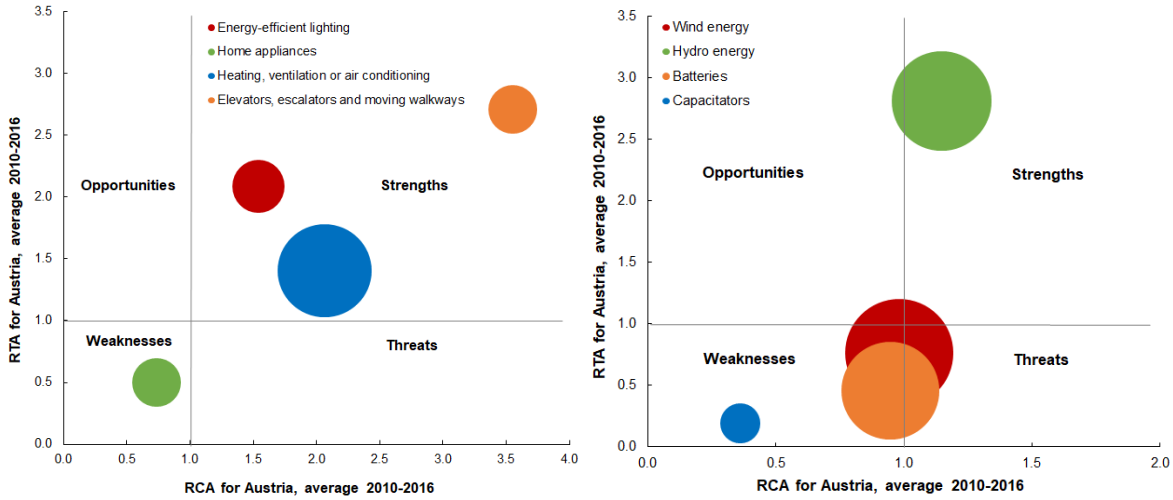


*Figure 6.14. Austrian RTA vs. RCA indices in climate change mitigation technologies related to **buildings** and **energy**, averages 2010-2016. (Note: Bubble size corresponds to the value of Austrian exports to the rest of the world in the product groups matched to each technology, relative to the other data points in each graph. Details on the SITC product groups matched to each OECD ENV-TECH technology are given in Appendix B.)*

7 Core Demands on Framework Conditions

Research presented in this report has made clear that the stricter EU climate targets present numerous opportunities which could be advantageous if seized upon, in particular also for Austria and recovery from the Covid-related economic impacts.

With that said, it is crucial to be aware that almost none of these developments will "just happen". Even worse, if we in Austria merely scale up EU and corresponding national climate targets, and then lean back and see what is happening, the consequences could be more severe than simply missing out on some positive effects. But also, the reverse could come true. If longer-term EU climate targets turn out to be unreliable and are not met, implementing them early will only pay off if such alternative developments have been carefully considered. Climate policy is a field of decision-making under uncertainty. Globally and in the long-term, climate change impacts (both observed and foreseen to substantially increase) appear to be a strong indicator for ultimate global action in climate change mitigation. Yet, the speed of this global action is unknown. While the EU intends to be a front runner, it is yet to be seen whether it will succeed. As a consequence, each Member State is well advised to consider its options well, and to decide on a national pathway robust against possible EU-wide and global developments. For Austria, there are many options in climate change mitigation that would turn out to be win-win situations (both environmentally and economically) even under a wide range of EU and global developments.

Identifying such options and implementing them with collaborative effort will be the task following the EU 55% climate target 2030 decision. On the one hand, as the EU has decided to take this road, there will be countries who actively take advantage of opportunities connected to such a stricter target and will be first movers, and Austria's industries in international competition could lose market shares, inducing an economic downturn in Austria itself. This clearly applies to those industries covered by the EU ETS by their very nature of industrial activity, but also applies to equipment and concepts relevant for the non-ETS sectors. Also, in the latter area a strong home market is the basis for international success and its lack the source of decline and substitution by international products. On the other hand, if the EU27 do not succeed to meet their 2030 target, possibly as too few countries are sufficiently engaged, the respective clean product and technology markets could develop slower. To be on the safe side for both possible developments, Austria could identify fields of no-regret efforts. In particular, renovation of the Austrian building stock has many elements of such a no-regret policy, with enhanced comfort and reduced operating costs, while simultaneously transitioning to climate-neutrality. The same holds for a wide range of policies in the transport sector, clearly improving overall economic productivity and reducing operating costs. If (or when), in addition Austria can benefit from a first mover advantage in international markets, will, however, depend on whether and when a sufficiently large number of EU (and global) countries follows suit in climate change mitigation. Acting as a role model might advance such development in other countries.

Core necessities originate in each of the areas, as identified below. Austria won't reach the new climate targets simply by wishing it. There needs to be a process and a sequence by which we address the core necessities below and thereby enable Austria to reach the goal. A core focus of the federal and provincial governments is required over the next ten years. If policy is not scaled up across every sector, if business is not encouraged to invest, if society in Austria is not engaged at large in this challenge – Austria will not deliver on its enhanced 2030 climate targets. The years immediately ahead are the decisive ones for progress and action to establish the prerequisites.

With the transition of the economy towards a climate-neutral structure, the labor market also needs to be restructured. While the macroeconomic model simulations showed an increase of skilled and unskilled employment throughout, and especially in the early 2020s, this labor demand can only be covered if an appropriately skilled workforce is also available. Therefore, an accompanying farsighted qualification strategy is necessary, taking into account the already existing skill shortage, especially in science, technology, engineering, and mathematics (STEM) jobs (Dornmayr and

Rechberger, 2020), training periods of 3-5 years or more in such areas and the existing qualification of employees in fossil industries and their retraining potential. The currently high unemployment numbers due to the Covid-19 crisis further suggest a need to immediately initiate (re-)training programs for skills and technology deployment e.g. in areas like renewable energy and heating systems.

Given that the transformation task is enormous, it can only be solved by bringing together all the different perspectives and facts, from which good and innovative solutions will emerge. Responsible dialogue among all actor groups concerned – well beyond traditional discussion – is an essential prerequisite for such a transition to be successful. The focus in such dialogues needs to be on the solution, not on winners and losers. A traditional discussion, if it becomes a competition for the better argument, results in winners and losers, and just one or a few who prevail. However, it is not by trying to preserve what we have, that we can find solutions, but by looking forward, by courageously allowing *new* to happen. We here need well-prepared and well-framed dialogue platforms (Fora of Stakeholder Engagement). We can build upon a tradition of best practice examples of such in Austria. For example, the scientific community has initiated such national dialogues since the mid-2010s, e.g. in the context of EU financed Horizon 2020 research projects, integrating all actor groups concerned. Such dialogues need to provide for diversity and for all of us to leave classical "silos", they need to ensure a high quality of exchange and a certain commitment and thus co-responsibility of all participants. This exchange needs to be structured such that solutions emerge. It is the true dialogue among all concerned that facilitates or enables change, also in awareness and mutual understanding. And above all, this is what is needed here.

Industrial and energy policy

In climate neutral industrial development, Austria can be successful in economic terms, if and only if

- **reliable medium and long-term framework conditions on climate and** energy are set, which allow for sound managerial decision-making – only then are climate benign decisions also economically sustainable (and thus possible).

This includes

- stable carbon **market framing and predictability**, based on comprehensive planning, acknowledging the EU internal market as well as international competitiveness,
- reliable renewable energy (in terms of **availability, security, affordability and price reliability**, the latter e.g. by the establishment of carbon contracts-for-difference to fund CO_2 market price differences relative to a previously set pathway)), and
- **expansion of infrastructure** (in particular for electricity, (green) gas, hydrogen), including the regulatory and legal framework for such infrastructure expansion timely set (public approval procedures).

Based on these framework conditions set,

- **dialogue fora** for common development of circular economy implementation need to be operated and actively maintained to enable the coordination of value-added chains across different (also legal) economic entities, i.e. firms.

If the energy transformation is to be achieved within the envisaged time horizon, energy market regulation needs to be established to both

- address **demand** and
- to include adequate **incentives** to substantially **enhance renewable supply across all energy carriers** required (electricity, green gas, hydrogen), and the
- **respective infrastructure** for generation, transmission and/or storage is not only put in place in time, but also **available in a spatially-specific manner** at the very industrial production locations (fully) relying on it.

Austria needs to

- **develop and follow a clear strategy of reliable renewable energy supply** based on the two complementary sources of origin, **domestic and foreign**.

As in particular seasonal variation of solar cannot be adequately compensated by other renewables, not only domestic storage is crucial, but also a strategy based on energy trade, including foreign supply of direct (electricity) or indirect (e.g. hydrogen) solar energy to Austria (and corresponding exports). This has to be settled early and to be adjusted to the respective European and global efforts to allow for the necessary planning reliability.

Box 7.1: Strategic choices for competitiveness and avoidance of large-scale stranded assets

The decrease of GHG emissions by at least 55 percent (relative to 1990) is an ambitious EU goal. Given the very rapid technological progress in all areas that generate or use energy, the most likely cause of problems will not be that this goal is too ambitious. Rather, economic problems may come from the fact that there is a choice between new technologies that are limited to giving a decrease by 55 percent and more advanced technologies that completely avoid emissions.

Climate research indicates that emissions will have to be decreased even more and even faster than by 55% by 2030. If investments allow a decrease of 55% but not a decrease of 80%, they may become stranded assets if a further decrease of emissions is deemed necessary. Projections by climate scientists show that for a realistic chance to remain within 1.5 degrees of warming a decrease by 80% until 2030 is necessary. Climate change is already causing ever more problems, e.g. the widespread wildfires in ecosystems all over the globe, from Arctic regions and Siberia or wild fires in Sweden to catastrophic wild fires in large parts of southern Europe, the southern U.S. and throughout Australia and large swaths of Asia. Accordingly, Kemfert and Jacobson (2020) emphasize that "mediocrity [i.e. the 55 percent reduction goal] is the enemy of the solution". Hence, investments in technologies that give 55% but do not allow 80% are at high risk of becoming stranded assets within a few years. Even worse, from an economic point of view, available new technologies allow achieving a decrease of emissions by 80 percent or more with higher quality of the products at lower costs. History of pollution control provides many examples for this statement. For example, the ozone hole is caused by CFCs. One type of source was old refrigerators and air conditioning devices. When CFCs were banned by legislation the companies that produced refrigerators predicted that devices without CFCs would be considerably more expensive and less energy efficient. A grassroot company was the first one to produce such devices; established manufacturers had to follow that lead and refrigerators are nowadays better, cheaper and much more efficient. Another example, for the decrease of tropospheric ozone the emissions of volatile organic compounds (VOCs) had to be decreased. VOCs by that time were almost omnipresent, e.g. in the exhaust fume of vehicles, as solvents for colors and in several thousand other compounds. It turned out that, for example acrylic paint with water as the solvent often had far better quality, more appealing coloring and was cheaper. Another example is generation of electricity which, in a well-constructed electricity system, could be far cheaper and much more abundant than at present (Dorr and Seba, 2020), see also Box "Projecting electricity costs from Photovoltaics in an integrated system." Naturally, distributed local electricity generation will fulfill an important role in such a system because it increases security of supply and avoids local distribution costs which are high.

In a similar fashion, with the many breakthrough technologies that have recently become available, a goal of emissions decrease of GHGs by 80% will most likely result in improved competitiveness of the European industry and it will avoid bringing about many stranded assets, other than a "mediocre" goal of 55% emissions decrease.

Decreasing emissions by 80% both would be greatly facilitated if green electricity would become considerably cheaper. Governments tend to preserve their electricity system as it is, but the present electricity system and utilities would have high profitability in this new configuration (including for balancing demand and supply) and, moreover, the well-being of the rest of the economy is so important that the electricity sector can well be charged to accept this challenge. Governments should thoroughly check these new possibilities, advance them in their jurisdiction and pronounce them to their constituencies. Cheaper and sufficiently abundant electricity could trigger an innovative wave that also increases European economic competitiveness.

Recognizing that the climate policy challenge is a public goods problem with free riders that cannot be solved by the market under insufficient framework conditions (see Appendix A), innovation needs to be fostered in a competitive environment in the transition phase with

- public funds, such as an **Austrian Industrial Innovation and Transition Fund (AIITF)**. Public funds can exploit a leverage of both private investor and EU funds to enable managerial decision for significant up-front investments in a globally competitive environment.

In designing Austrian policies to that end, following the example of other (European) countries in their emission targets alone is evidently not sufficient. As was Austrian tradition throughout the second half of last century, cultivation of a dialogue between politics, industrial management, labor and the society at large, in this case directed to negotiate a successful – i.e. actually doable – transition to the only economic future there is, that is the task of our decade. Only what we think first, then discuss and cross-check, then adjust again, taking advantage of the knowledge and experience of all with stakes in this all-encompassing transformation, can finally (and successfully) be implemented.

Let us focus on the Austrian steel sector and its environment as one (and the single sector most emission intensive one) example here. Its main competitors for customers in the markets are German, and are thus exposed to the settings as given in Germany. Germany has already adopted an "Action strategy steel" ("Handlungsstrategie Stahl") to establish planning reliability for industry (and thus only enable the transition sought). Such planning reliability is crucial to be established also in Austria. This includes pathways to settling issues of effectively avoiding leakage (indirect (ETS) carbon pricing compensation in the context of the overall charges and levies system in the electricity sector, which to date has been heterogeneously set across the EU), export rules that level the global playing field for carbon border adjustment (CBA) regimes at the EU level (if application of CBA to ETS sectors implies effectiveness only for auctioned permits), renewable energy prices in the context of industrial production competitiveness, fostering of the establishment of lead markets for green steel by according industry rules and (public) demand, national and EU fund (co-) financing of investment, new rule settings for the financial market that foster sustainable finance, ensure energy infrastructure expansion for adequate renewable supply (electricity generation and transmission network, (green) gas and hydrogen).

Buildings

The success of shifting the building sector to climate neutrality depends on a clearly stated strategy including specific milestones and a well-defined timeframe. This strategy needs to be reliable and long-term in order to serve as a basis for actors in the sector. For the market to develop towards more sustainable solutions, both industries and households need to know what is required of them, and when, and under which framework conditions. These guidelines (be they legally binding either in a command-and-control fashion or incentive-based) are necessary to set a firm framework in which all agents are guided to work towards climate neutrality of the building sector.

New buildings need to be built to a higher energy efficiency standard than currently required. A change in the OIB guidelines is necessary to reduce the energy demand of new buildings to a useful energy demand according to OIB 10 line or lower with high-efficiency building technology including mechanical ventilation with heat recovery. This line is the most cost efficient according to OIB (2018). Photovoltaics on the building should not allow a reduction in the efficiency of useful building energy demand as the maximum use of renewables and a high efficiency is needed to replace fossil fuels completely. Furthermore, comprehensive refurbishment must increase significantly. This could be implemented through a revised subsidy scheme, which focuses on comprehensive refurbishments achieving the highest possible reduction in energy demand. In parallel to reducing buildings' energy demand, energy supply must also be addressed. Since 2020, no new oil- or coal-based heating systems may be installed in new buildings (ÖKEVG 2019, 2020). This has to be extended to other fossil fuels (i.e., gas), as well as to the replacement of existing fossil-based heating systems (where possible). In order to successfully phase out fossil fuels, the change to renewable heating, district heating or heat pumps needs to be mandatory and, wherever needed, subsidised. Additionally,

significantly higher taxes on fossil fuels (e.g., CO_2 tax) would increase the replacement rate. For the full phase out until 2040, the change of the remaining fossil-based systems needs to be compulsory and the initialisation of that path needs to start now. Furthermore, actors in the building sector need to be governed to not only reduce buildings' operational emissions and energy demand, but also to reduce embodied emissions in building materials and components under a life-cycle perspective. This is to some extent relevant for thermal measures and heating systems, but even more for new buildings and general renovations. An economy-wide carbon neutrality therefore requires not only the supply side of building materials like cement and steel production, but also for architectural and engineering partners to act with a view towards the development and realization of low carbon buildings, considering both their whole life-cycle as well as the additional functions of the buildings (and their elements), including (heat) energy storage and electricity generation.

Implementing such a framework towards a climate neutral building sector also needs to consider the following important issues:

Technological solutions to replace (decentralized) oil and gas and e- boilers with heat pumps. The use of heat pumps is limited by the quality of the building; the use of heat pumps in old buildings with poor energy performance may lead to discomfort conditions (heat pumps work with lower temperatures than traditional gas and e-boilers) and to very high electricity consumption. Large heat pumps represent a challenge with respect to architectonical integration and regarding the limitation of sound emissions in particular in the urban context.

- **Core demands:** Already available technologies need to be implemented wherever possible. The current ban on oil heating in new buildings needs to be extended to all fossil fuels and include heating system changes in existing buildings as well. In cases where this is **technologically** not yet possible, there needs to be a clear and long-stable framework for industries, including incentives, to develop technological solutions which can be applied to steer all heating systems to renewable sources, district heating, or heat pumps.

Economic investment barriers for rented buildings or flats. This problem arises mostly in apartment buildings, where usually the tenants do not own the structure they live in. Therefore, they do not have an incentive to make changes to the building (and pay for them). In rental buildings, the responsibility of refurbishment usually lies with the owner of the building, which leads to conflicting economic interests, in which the owner would need to pay for a refurbishment, but the tenants have the benefit of reduced heating costs and higher comfort.

- **Core demands:** To ensure high energy efficiency standards of new buildings irrespective of the investor, one means could be to adapt the OIB guidelines to set stricter demands on energy efficiency. But changes in the broader regulation of the capital market (enhancing green investment) would also support such a development. Another possibility for rental buildings would be to define a legal framework for splitting the upfront investments between owners and tenants.

Ownership structures of mixed housing with multiple owners. Another ownership problem occurs in apartment buildings with different owners of the apartments. It often proves challenging to get the approval of all owners in order to refurbish the whole building or agree on measures above the minimum standard.

- **Core demands:** For buildings with mixed ownerships, it is crucial that subsidies favor comprehensive refurbishments of whole buildings over single measures. This will provide an additional incentive to the different actors to work together to refurbish their building instead of individual single measures.

Financing barrier of immediate upfront investments and long-term energy cost savings. An energy efficient solution in the phase-out of fossil-based boilers is the renovation of the building envelope and the replacement of the old boiler with a heat pump. The current high price of heat pumps must therefore be added to the renovation costs, which include not only the envelope improvement but also the update of the distribution and emission parts of the heating system.

- **Core demand:** The installation of new fossil-based systems needs to be prohibited to reduce GHG emissions. Since alternatives often require a major renovation of the whole heating

system instead of just a boiler change, the cost will be higher. Effective subsidy schemes need to be implemented to make the transition to more sustainable energy sources affordable. Subsidies for the refurbishment of the building envelope could also be tied to the simultaneous change of the heating system away from fossil fuels

Limited availability of renewable energy potentials. The decarbonization of the building sector is strongly linked to the energy sector, mainly electricity and district heating. The building sector does not only consume (preferably carbon neutral) energy but can help the decarbonization of the energy sector through higher energy efficiency.

District Heating. A gradual increase of the share of renewables in the district heating supply is necessary, but other relevant issues must also be raised:

- Extension of the district heating grid is often critical in urbanized areas; this is often associated with high upfront investments.
- Upgrade of the existing district heating grids is strictly linked to the upgrade of the building stock supplied.

Electricity production. As mentioned in the above point on district heating, the transition to renewable electricity is not a trivial aspect. Being mostly based on fluctuating energy sources (e.g., sun and wind), the use of storage systems (local and central) must be considered to avoid shortage of electricity in the periods when it is mostly needed.

Biomass (use and supply). Biomass is an extremely valuable source for its wide usability. Many sectors use this source as a primary raw material and its use will increase due to the replacement of plastic-based materials. Even if it currently represents the best solution to replace gas boilers in non-renovated buildings and in district heating systems, stronger competition is to be expected in the years ahead.

Heat pump source exploitation. While air as one main source for heat pumps is theoretically unlimited, the source exploitation in an urban context is one of the main challenges. Besides esthetical aspects (architectonical integration), sound emissions have to be limited. Ground source exploitation is limited as well. Thus, deep energetic renovation of the building stock can be seen as the enabler for a broad transition from fossil heating to heat pumps. The better the energy standard, the lower the required power of the heat pump and the smaller the heat pump. With small and compact heat pumps it is easier or even only at all possible to exploit the energy source, the sound emissions can be reduced to acceptable levels and the architectonical integration is easier.

Skilled labor supply for renovation and installation. For renovation and heating system switches skilled labor is required. For installation of e.g. PV panels such personnel is currently lacking and needs (as has been started) special attention in training programs. But also innovative business model solutions can help: while one may stick to a view that heating systems can only be substituted in summer, others work with mobile heating systems, such that skilled labor is no longer idle in winter.

Transport

Passenger transport

In order to achieve emission reduction in passenger transport, a combination of different policies needs to be implemented. These policies not only have to be of different character according to the Avoid-Shift-Improve classification, but also need to seek a balance between disruptiveness (i.e. significant change) and implementability (i.e. public acceptance); in some literature, a similar balance is referred to as one among push and pull measures. This is an essential condition, as the effectiveness of policies for passenger transport is highly dependent on and vulnerable to public acceptance. This means that a number of disruptive measures are required, i.e. measures that are particularly effective and have a rapid impact (Givoni, 2014). Such measures often belong to the type of push measures and therefore often have a restrictive or prohibitive character. These could include driving bans in inner cities or a ban on new registrations for combustion engines. As such measures may confront public resistance, they – although theoretically highly effective – do not make their way

to actual implementation (Cohen et al., 2016). Therefore, it is required that their counterpart – pull measures – must be implemented either simultaneously or even pre-emptively in order to compensate the more restrictive measure and increase public acceptance (Kent et al., 2017). Examples would be awareness-raising measures, incentives for active and public mobility, subsidies or telework concepts.

Beyond the crucial necessity to strike a balance between push and pull policies for passenger transport, the implementation of transport policies also requires technical framework conditions:

- **The phasing out of combustion engines** and simultaneously phasing-in of electric vehicles (cars, buses) demands a reliable supply of renewable energy. The importance of renewable energy availability has already been emphasized in the sections on industry and buildings, which all are characterized by an increased electricity demand in a climate neutral future.
- **The increase in electric vehicles demands an extension of adequate infrastructure**. A strong focus needs to be given to providing required charging infrastructure for electric vehicles. If infrastructure deployment does not catch up with policies, motorists are hindered in switching to an electric vehicle due to the notion that a lack of charging infrastructure exists.
- **Car-sharing concepts provide a promising solution** for enhancing mode integration, increasing the use rate of each private vehicle, thus reducing the necessary vehicle stock. To date mainly approved in cities, with appropriate changes the concept as currently developed could also prove complementary to public transport in rural areas. Although many people are open to the idea of car sharing, to date only a small percentage actually use it. The establishment of and further innovation in business models for car-sharing could close this gap – making this opportunity accessible and more prominent for providers and users.
- **The adoption of telework** became especially notable during the lock-downs due to Covid-19. Although telework has the potential to reduce emission in passenger transport, positive effects on the emission budget can only be achieved when telework is integrated in a sustainable transport concept. In other words, rebound effects such as an increase in the use of cars with combustion engines or the travel of longer distances (e.g. due to residential location choices at further distances from workplaces being more attractive) have to be addressed. Furthermore, increasing telework still requires adequate embedding of this new concept in the Austrian law to secure proper guidelines for businesses and workers as a core prerequisite.

Freight transport

A successful shift of the freight transport sector to climate neutrality also relies on a clearly stated and consistent strategy, including milestones, a clearly defined timeframe and investments from the government. Such a strategy has to be long-term in order to increase the decision-making reliability for freight companies (road and rail), investors and the different levels of public government (federal, provincial). These actors have to know what is required from them and at which time, either through command-and-control instruments or fostered by economic incentives, so that all actors can consistently work towards achieving climate-neutral freight transport by 2040.

Diesel trucks have to be phased out and replaced by alternative technologies like battery-electric vehicles for short distances and – given current knowledge – most likely fuel-cell electric vehicles and overhead catenary electric vehicles for long distances. Such a transition does not "just" work, as for these new technologies, new infrastructure is needed. Furthermore, new or other energy sources (e.g., hydrogen) are required, for which new markets have to be created. Furthermore, with systematic improvements, higher efficiency in the freight transport sector can be achieved. Rules for new technologies like platooning or automatic drive have also to be considered as they can – if adequate framework conditions are set – contribute to reducing mileage and emissions. An overall trend towards regionalization of production on the demand-side (fostered e.g. by additive production (3D-printing)) is also important for a decarbonization of the freight transport sector. These are the core demands on framework conditions, which have to be provided in order to achieve climate-neutral freight transport by 2040:

- **The chicken-egg problem of infrastructure**. Infrastructure is crucial for a transition to a CO_2-neutral freight transport as without the needed infrastructure, investments into alternative technologies by freight companies will not occur. The aim of a freight company is always to pick up goods at Point A and deliver to Point B. If reaching B is not 100% possible with alternative technologies, these technologies will not be used. In order to secure a possible arrival at B, the necessary infrastructure (H2-filling stations, electricity charging infrastructure and overhead catenary) has to be built. Relevant policy has to provide incentives to investors to allocate capital, with various financing concepts available, e.g. direct support from public spending, or private-public-partnerships (PPPs) in infrastructure construction. With a reframed financial system that fosters the integration of aspects such as Environmental Social Governance (ESG) considerations in a consistent manner, new – and in the long-term reliable – sources for financing the transition would become available.
- **Alternative technologies are still under development and more expensive than diesel** in terms of capital expenditure (CAPEX). Alternative road freight technologies assessed in this report are still under development and not yet available on the market. Only BEV trucks are already available but are more expensive than diesel (again in CAPEX terms). This means that in the next five years the development of these alternative technologies and a push to make them marketable is crucial. Investments into the further development of FCEV and OC-EV are also necessary, as they have to be available on the market within the next five to eight years to a certain extent. Policies have to be designed which incentivize the acquisition of alternative technology vehicles.
- **Openness to alternative technologies.** The freight transport sector is very heterogeneous in its use cases which means that in some use cases battery electric vehicles might be the cheapest solution and in other use cases fuel-cell electric vehicles. Therefore, it is most likely that a mix of technologies will be important in the future zero-emission world. That requires technology openness of today's actors.
- **Limited availability of renewable energy sources**. Climate neutrality of freight transport is strongly linked to the electricity sector as for BEVs and OCEVs electricity is needed directly and for FCEVs green hydrogen (produced from renewable electricity).
- **Electricity production.** As already pointed out in the sections on industry and buildings, the transition to renewable electricity is not a trivial aspect. Being mostly based on fluctuating energy sources (e.g., sun and wind) storage systems (local and central) need to be integrated to avoid shortage of electricity in the periods when it is mostly needed.
- **Green hydrogen production.** The production of green hydrogen will most probably not only take place based on solely domestic electricity, as domestically-available electricity will be in competition for direct use for other purposes. This implies that either electricity or hydrogen will also be imported (depending on the global grid and trade structure; possibly but not necessarily also on a net basis). Furthermore, producing hydrogen in Austria is quite expensive compared to locations where the solar electricity production rate is two times or more that of Austria (considered across the annual cycle). Therefore, imports of green hydrogen have to be considered as a core option and rules and infrastructure for such need to be designed and implemented.
- **Biomass (use and supply).** Biomass is an extremely valuable source for its wide usability. Many sectors use this source as primary raw material and the demands on it will be increasing on the path to a zero-emissions economy; such an increase in use will increase the competition for it.
- **Synthetic fuels (PtL and PtG).** As their efficiency is not very high, an application in freight transport sector may not be feasible. Nevertheless, with all likelihood there will be applications for their use in freight shipment. As not all of the production of synthetic fuels might occur in Austria (for competition of feedstocks), imports of synthetic fuels have to be considered and rules for imports designed.

Austria cannot solve the transition to a zero-emission future on its own, as vehicles of foreign freight companies drive more than half of the ton-kilometers driven on Austrian roads. A strategy in which other countries are not involved will lead to inefficient investments and infrastructure development. Hence, a common strategy on at least a regional level (with neighboring countries), or better on a European level is needed.

Social acceptance of alternative technologies, especially overhead catenary vehicles, is not assured. A pilot project of overhead catenary electric vehicles in Baden-Württemberg demonstrated that social acceptance is not a given. Policy thus needs to invest into information and discussion about alternative technologies, especially where people are directly affected by them. This process necessarily has to start now.

Innovation

In order to maintain Austria's international competitiveness while also achieving the enhanced climate targets, **innovation policy should focus on key technologies necessary for the transition to climate neutrality**. Austria has strengths in a number of low-carbon technologies, from rail transport to metal processing and HVAC (heating, ventilation and air conditioning) technologies, enjoying both an export and a technological advantage compared to the rest of the world.

In other areas, however, current export specializations risk being eroded in the future due to low rates of innovation. Examples include technologies related to electric vehicles, including charging technologies, and low-carbon technologies for the chemicals industry. **Basic R&D subsidies** targeted at these fields should be increased by topping up funding for existing R&D support programmes with an explicit climate focus, as those tend to be heavily oversubscribed (Schneider et al., 2020). **Additional tax incentives** could be introduced to foster inventions, for instance by implementing a dedicated decarbonization focus into the Austrian R&D tax credit (Forschungsprämie), as was done for the 2020 investment subsidy (Investitionsprämie). **Start-up funding and adoption subsidies** for low-carbon technologies could be expanded to support their successful market introduction. The regulatory framework, including **technology standards**, should be updated regularly to ensure it supports the latest low-carbon technologies. Finally, expanding **public procurement** for low-carbon technologies and strengthening the best-bidder principle are also important for creating a domestic market.

In fields where Austria is not only at a technological but also at an export disadvantage, such as batteries and wind energy generation, **export promotion instruments** should additionally be strengthened. The Austrian business landscape is dominated by small and medium-sized enterprises, especially in energy technology fields, for which expanding into international markets is often difficult. Export initiatives should therefore be **targeted particularly towards SMEs** and provide strong **international networking support**.

Last but not least, achieving the EU 2030 climate targets also requires **embracing new innovation policy instruments** such as regulatory sandboxes, experimental frameworks and an increased focus on services, which all help to promote progress along the Avoid-Shift-Improve dimensions this study puts forward.

8 Discussion and Recommendations

Wir brauchen einen ganz anderen Mut!
Stefan Zweig

Enhanced climate-oriented investment can address both the economic and climate crisis

Austrian actors are preparing and advancing low-carbon solutions (e.g. electrification, hydrogen-based production, and circular economy approaches). Stepping up the European 2030 climate targets implies an earlier implementation of these mitigation options. Economy-wide macroeconomic simulation shows that this is connected to significant economic implications. The direction is governed by the relevant framework conditions and the current window of opportunity. With the post-Covid recession, it is expected that at least for the early transition years of such an upscaling, no relevant crowding out of investments will take place, as production facilities are underutilized and financial investors seek (green) investment projects. Automatic economic stabilizers (e.g. unemployment benefits, ad valorem tax revenues, etc.) lack comprehensiveness and profoundness to address this underutilization. Hence, governments step in by bolstering effective demand in order to ameliorate the worst effects of unprecedented lock-down measures. Such public investment – even more so at the high levels which occur – is only justified economically if it fosters long-term sustainable structures, and thus needs to be channeled into climate neutral (infra)structures and away from fossil energy. Thereby policy can do best when addressing both crises at the same time – the climate and economic crises.

Temporary window of opportunity turns transformation costs into benefits

Over the last decades mankind has learned that not only labor and production capital create value added and welfare (Dasgupta, 2021), but that human wellbeing also crucially depends on the quality of natural services (ecosystem services, such as productive use of natural resources and amenities), yet one main economic indicator, gross domestic product (GDP), still only reflects the former. As a consequence, if economic resources are devoted to improving or maintaining environmental quality (or reducing environmental costs), as climate mitigation is, or enhancing non-marketed services (higher comfort in renovated buildings) this will increase *actual* productivity (enhancing environmental and comfort services). But when measured against the traditionally defined GDP, it might *reduce* productivity, as then some additional output is not reflected. In the following we nevertheless do utilize GDP as one indicator, because it is strongly correlated with employment, but also because it is still used broadly in public discussion. We stress, however, to be careful in its interpretation. And we complement our analysis with a welfare indicator that seeks to more comprehensively depict welfare dimensions neglected by GDP.

For an EU55 consistent climate policy in Austria (and relative to a scenario where we remain on the former policy trajectory of -40% emissions reduction by 2030), dynamic macroeconomic model simulation indicates a higher gross domestic product (GDP) for Austria in the mid-2020s due to an earlier investment cycle. The increase is also due to post-Covid underutilization of capital. If (hypothetically) full crowding out would be assumed, GDP could decline. This implies that the current recession provides a framework, under which climate-friendly investments are particularly connected to additional and near-term economy-wide benefits, clearly visible also in terms of GDP. Note that our comparison scenario EU40 (as well as EU55) includes climate neutrality by 2040. Relative to EU55, the comparison scenario EU40 would thus have larger climate-relevant investments in the 2030s. With earlier climate policy (EU55) some of these investments occur sooner

(i.e. already in the 2020s), with the thus implied additional economic activity of this fraction occurring already in the 2020s rather than in the 2030s. In the period thereafter – starting in 2040, with less investment difference – accumulated learning effects of early European (ETS) and Austrian (non-ETS) implementation and lower operating costs of climate-friendly technologies imply a GDP higher than in the EU40 scenario.

This holds for the case of a simultaneous climate and economic policy package in the aftermath of the Covid-19 pandemic.

Postponing climate policy action is unwise and expensive

Sequential action is costlier because only a shorter time frame would be available for achieving the same stricter target and investments in long-lived emission-intensive capital stock would bear the risk of stranding. From a national perspective, these results indicate that a simultaneous implementation of climate mitigation measures and Covid-19 response measures clearly outperform a sequential strategy throughout the modelled time horizon from now until 2050.

A stricter climate target performs better also in terms of traditional GDP

Macroeconomic model simulations support the availability of cost-effective climate mitigation options. We here compare the cumulative GDP effect for the period 2020-2050 of the measures connected to the EU55 target with measures for the earlier EU 40% target. With the EU55 target, the annual Austrian GDP is on average +0.2% higher until 2050.

Setting the adequate prerequisites is indispensable

The framework conditions indispensable to be implemented as prerequisites such that economic gains for Austria can be achieved when striving for stricter climate targets relate to each and every sector. The detailed list is given in Chapter 7. Austria won't reach the new climate targets simply by wishing it. There needs to be a process and a sequence by which we address these core necessities listed in Chapter 7 and thereby enable Austria to reach the goal. A core focus on their implementation of the federal and provincial governments is required over the next ten years. If policy is not scaled up across every sector, if business is not encouraged to invest, if society in Austria is not engaged at large in this challenge – Austria will neither deliver on its enhanced 2030 climate targets nor reap economic gains related. The years immediately ahead are the decisive ones for progress and action to establish the prerequisites to strengthen Austria as industry location.

Stepping up the climate target comes with significant co-benefits

Climate policy comes with a range of welfare improvements. For example, enhanced building quality raises living comfort, more active mobility implies significant health benefits (increased biking and walking reduces incidence of illness, in particular cardiovascular illnesses), and electrolysis improves steel quality – even beyond the directly intended benefit of climate change mitigation. Most of these co-benefits are difficult to measure or transform to a uniform indicator, including a monetary one. However, in one area of co-benefits, air quality improvements, such a harmonized measure is available from comparatively robust quantifications. We therefore indicate the order of magnitude of co-benefits of climate policy due to concurrently induced air-quality improvements. Air quality co-benefits amount to at least annually EUR 0.8 bn. (1 bn.) by 2030 for EU40 (EU55) policy, and rise to EUR 2 bn. by 2050.

A stricter near-term climate target avoids expensive fossil lock-in in the buildings sector and enhances technological leadership in Austrian strongholds

With the former EU40 target translated to the buildings sector in Austria, a lock-in of fossil fuel-based heating systems would likely have taken place. Achieving a decarbonized buildings sector by 2040 would then come with (massive) additional upfront investments and stranding of capital assets as in 2030 fossil fuel-based heating systems would still be maintained and would need to be

replaced before their end of life in 2040. Targeting net carbon neutrality in Austria's building sector by 2040, reduction measures must start without delay and with "2040-ready" components. The more stringent EU55 scenario is consistent with this 2040 target and avoids the additional post-2030 costs of a fossil lock-in of the buildings sector.

Examples for further lock-in risks can be found in all sectors. In the buildings sector there might be an incentive to focus on the replacement of oil heating system by gas heating systems, which might reduce emissions by 2030 to some extent, but which would create a lock-in for the remaining life-time of the installed gas heating systems. In the transport sector a lock-in might emerge with further heavy investment in road infrastructure (to promote electric cars) instead of trying to first avoid individual transport by investing in rail infrastructure and other public (or shared) transport systems. In industry a lock-in might be created when further focusing R&D on marginal energy efficiency improvements, instead of on the full replacement of currently existing technologies.

Current forecasts of Austrian road freight transport mileage predict increases into the future, even though these are in conflict with environmental targets. Therefore, industry representatives, notably of the transport engineering industry, increasingly point out that Austria needs to develop alternative strategies where mileage declines rather than growth. Decentralized production systems, such as additive manufacturing (3-D-printing) and additional directed digitalization can significantly reduce overall freight transport demand. R&D into further strategies for decoupling freight mileage and economic performance can be fostered also by stricter emission reduction targets. The earlier such strategies are developed, the less expensive they are in terms of development and in terms of avoiding sunk costs and stranded assets in transport and production infrastructure.

Competitive advantage in decarbonizing technologies for buildings

With the decarbonization of the buildings sector in Austria, the deployment of technologies such as low-carbon building components, heat recovery and heating systems will become necessary. In all of these areas Austria has already built-up a competitive advantage and, with a more stringent policy target, could further strengthen its position on the international market. While for structural building components necessary technologies are already on the market, there is a need especially for development of small, decentralized heat pump systems for apartments in multi-family houses (including ventilation, heating, cooling and domestic hot water production) as well as large scale heat-pump systems. In an EU55 scenario, such technological solutions will be demanded in large quantities within the next few years. Investing in the development of such technologies would allow Austria to not only supply to its own domestic demand but could generate a technology leader position on the international market.

Austria is well-positioned in key low-carbon technologies to exploit new export opportunities

An analysis of Austria's current performance in emissions-reducing innovations and related export fields shows that the country can build upon areas of strength not only in buildings technologies, such as heat pumps, bioenergy combustion, nearly zero-energy buildings or passive houses, but also in rail transport as well as low-carbon technologies for the steel and cement industries. In all these areas, Austria is well-positioned to exploit new export opportunities that more stringent climate targets create by increasing international demand for climate-neutral products and processes. In other key transition technologies, targeted innovation and export policy instruments should be considered to maintain or further develop Austria's international competitiveness. Examples include technologies related to electric vehicles including batteries and charging technologies as well as energy generation from solar PV and wind.

Renewable electricity presents global challenges for Europe and at the same time offers opportunities in digitalization and green industry development

During the transition towards climate neutrality, many areas of the Austrian economy will be undergoing an electrification (mobility, heating, electrolysis-based hydrogen for industrial use, etc.). With a current (2019) national electricity demand at 72 TWh, our analysis shows that by 2030

electricity demand in Austria will rise by 17 to 20 TWh, plus the significant demand for new routes in industry and for domestically-produced hydrogen for Carbon Capture and Use processes. Each of the latter could add an equivalently sized additional demand on their own. For these latter industry sectors, and starting the analysis from the final service supplied, it quickly becomes evident that there are many options to achieve climate neutrality. Ceilings in buildings, for example, due to lucid shuttering formwork can be produced with 40-60% less concrete (and thus cement), while increasing bearing strength and offering additional functionalities as activated building components for energy storage (which allow new fields of generation of value added for respective enterprises). If a significant share of the (global) climate neutrality in these sectors is based on (renewable) electricity – and if Austria takes advantage of its position to acquire an over-proportional share of it (i.e. if the current strong competitive position in branches like steel and cement is safeguarded) – domestic demand for affordable (industry competitive) renewable electricity will clearly exceed domestic supply in a fully transformed economy. A long-term available potential not significantly beyond 100 TWh will be confronted by a long term (2050) demand – depending on which scenario comes true – of up to 145 TWh. With a policy in accordance with the EU 55% emission reduction (or higher) by 2030, electricity demand will most likely already by 2030 exceed domestic renewable supply.

The very same excess demand for energy has been prevalent in the past and Austria has focused on and benefited from its comparative advantages, for instance, by importing cheap fossil resources and exporting high-quality steel products in turn. Similarly, the benefits of trade are capable of more than compensating for the outlined domestic shortages of renewable energy. The comparative advantage in selected industrial production for Austria tends to be higher than the one in energy supply, and gains in value added in this case occur for both trading partner countries (industrial and energy production, export and import country). Choices still have to be made in terms of the form in which renewable energy is imported in Austria, either directly as electricity, bound in energy carriers (such as green hydrogen), or bound in intermediate products (such as iron pellets), and the respective shares of each of these elements. It is likely – and promising – that some share will be renewable electricity imports (and corresponding exports, possibly balancing imports across seasons).

Global powers, notably China, are pushing the global electricity market through new technologies and with sophisticated software. As this electricity will be affordable, due to the new capabilities of batteries and direct current transmission lines of firm supply, and green, customers all over the world will buy it, also in Europe. This is a signal for Europe to speed up its activities in the field of green electricity as much as it can, i.e. pursue the most ambitious goals for climate mitigation, in order to give a strong incentive to industries, and embed this in a strong program for sustainable digitalization. It goes without saying that an electricity grid that connects billions of prosumers also poses a strong challenge for development of new software. Ambitious projects in the field of renewable electricity will also constitute a lifeline for a green European industry.

Appendix A. On the Economics of Transformation

The economic system's objective and the challenges of transformation

The economic system's objective is clearly defined within the economics discipline. Nobel laureate James Meade, for example, in his "Economic Analysis and Policy" (Meade, 1937), analyses the conditions under which the economic system "can provide the highest possible standard of living […] possible with a given knowledge of industrial technique to obtain from a given supply of natural resources" (p. xiii). His perspective points out the probably core objective of our economic system: to supply and distribute the ingredients to allow for our wellbeing, for our standard of living, such that both our basic needs are met and for most also quite some beyond.

The economic system, when organized as a market economy, is in need of regulation to ensure such a high standard of living in the presence of market failures (such as externalities and public goods). The classical economist generally thought of as *the* free market economist, Adam Smith, in this context emphasized in particular the high value of public supply of education and the respective importance of public market intervention: "The State derives no inconsiderable advantages from the people's instruction. […] The expense of the institutions for education and religious instruction, is likewise, no doubt, beneficial to the whole society, and may, therefore, without injustice, be defrayed by the general contribution to the whole society." ((Smith, 1776), 642). Arthur Cecile Pigou emphasized the need to correct for externalities, including environmental ones (Pigou, 1920).

Mankind over the last decades is increasingly observing that the current system of production is eroding its very (natural) basis that the classical economists at their time took "as a given supply", an erosion taking place at a larger scale and higher speed than ever observed in human history. We note that the concept of planetary boundaries indicates that human activity is already acting outside what can be sustained for quite some of these boundaries (phosphor and nitrogen cycle, biodiversity) or is on collision course (climate change) (Rockström et al., 2009; Steffen et al., 2015). The global community has both identified the according challenges and agreed upon global targets to be achieved in order to avoid catastrophic outcomes: the Sustainable Development Goals (United Nations General Assembly, 2015), and for two areas specified in further detail: combating climate change (the Paris Agreement (UNFCCC, 2015) within the UN Framework Convention on Climate Change, (United Nations, 1992)) and combating desertification (United Nations, 1994).

The European Commission and Parliament issued according suggestions to change course within Europe. We here focus on addressing the climate challenge. (European Commission, 2020a, 2020b)

Addressing such challenges, the according transformation of the system, is complex and a huge effort. It requires a strategy, the devotion of resources, coordination and acceptance to transform our socio-economic system and at the same time enhance societies' standard of living, also denoted welfare. If we take a look at another classical economist, Joseph Schumpeter, in his English translation of "Theorie der wirtschaftlichen Entwicklung" (published in German in 1911) he states "Production is, on one side, conditioned by the physical properties of material objects and natural processes. In this respect it can for economic activity, as John Rae has observed, be only a question of observing the outcome of natural processes and making the most of them. […] The chief source of [..] gains and losses is spontaneous changes in the data [which refers to technological knowledge and natural resources] with which the individual is accustomed to reckon. They create new situations, adaptations to which require time. And before that can happen a great many positive or negative discrepancies between cost and receipts occur in the economic system. Adaptation always offers difficulties. The mere knowledge of the changed state of affairs is not attained in most cases with the desirable promptness. To draw conclusions from the knowledge is again a big step, which meets many obstacles in unpreparedness, the lack of means, and so on." ((Schumpeter, 1934), 11 & 33)

Appendix B. Innovation and Export Classifications

Low-carbon technologies

Table B.1. OECD ENV-TECH climate change mitigation technologies by emission sectors (OECD, 2016).

Transport
Road transport (conventional, hybrid and electric vehicles)
Rail transport
Air transport
Maritime or waterways transport
Enabling technologies in transport (electric vehicle charging, application of fuel cell and hydrogen technology to transportation)
Buildings
Integration of renewable energy sources in buildings
Energy efficiency in buildings (lighting, HVAC, home appliances, elevators, ICTs, end-user side)
Architectural or constructional elements improving the thermal performance of buildings
Enabling technologies in buildings (e.g. application of fuel cells, smart grids in buildings)
Production or processing of goods
Metal processing
Chemical industry
Oil refining and petrochemical industry
Processing of minerals
Agriculture, livestock and agroalimentary industries
Final industrial or consumer products
Sector-wide applications
Enabling technologies with a potential contribution to greenhouse gas emissions mitigation (e.g. computing systems, fuel cells, management or planning, financial instruments)
Energy generation, transmission or distribution
Renewable energy generation (wind, solar PV, hydro etc.)
Energy generation from fuels of non-fossil origin (e.g. biofuels)
Combustion technologies with mitigation potential
Efficient electrical power generation, transmission or distribution
Enabling technologies in the energy sector (energy storage, hydrogen technology, fuel cells, smart grids in the energy sector)
Wastewater treatment or waste management
Wastewater treatment
Solid waste management (waste collection, processing or separation, and reuse, recycling or recovery technologies)
Enabling technologies or technologies with a potential or indirect contribution to greenhouse gas emissions mitigation
Capture, storage, sequestration or disposal of greenhouse gases
CO_2 capture and storage
Capture or disposal of greenhouse gases other than CO_2 (N_2O, CH_4, PFC, HFC, SF6).

Matching of low-carbon technologies to export product groups

Table B.2. OECD ENV-TECH technologies matched to SITC Rev. 4 product group

Note: Not all technologies could be matched to a product group(s)

TRANSPORT

Conventional vehicles (based on internal combustion engine)	
SITC division	
713	Internal combustion piston engines and parts thereof
78	Road vehicles: motor vehicles, parts and accessories of that group, motorcycles & trailers
Hybrid / electric vehicles	
716	Rotating electric plant
771 to 773	Electrical machinery, apparatus and appliances except for medical equipment (electrical power machinery, electrical apparatus for switching or protecting electrical circuits, equipment for distributing electricity)
778.1	Batteries and electric accumulators and parts thereof
78	Road vehicles: motor vehicles, parts and accessories of that group, motorcycles & trailers
Rail transport	
791	Railway vehicles
713	Internal combustion piston engines and parts thereof
716	Rotating electric plant
Air transport	
792	Aircraft and associated equipment
713.1	Internal combustion piston engines for aircraft and parts thereof, n.e.s.
714.41	Reaction engines for turbo-jets
714.91	Parts of engines for turbo-jets or turbo-propellers
Maritime or waterways transport	
793	Ships, boats and floating structures
713.3	Internal combustion piston engines, marine propulsion
Electric vehicle charging	
771 to 773	Electrical machinery, apparatus and appliances except for medical equipment (electrical power machinery, electrical apparatus for switching or protecting electrical circuits, equipment for distributing electricity)
87.3	Meters and counters

BUILDINGS

Energy-efficient lighting	
SITC division	
778.2	Electric filaments or discharge lamps
813.1	Lamps and lighting fittings
Heating, ventilation, air conditioning (HVAC)	
741	Heating and cooling equipment and parts thereof, n.e.s.
812	Sanitary, plumbing and heating fixtures and fittings, n.e.s.
Home appliances	
775	Household-type electrical and non-electrical equipment n.e.s.
Elevators, escalators, moving walkways	
744.8	Lifting, handling, loading and unloading machinery
744.93	Their parts

PRODUCTION AND PROCESSING OF GOODS

Metal processing	
SITC division	
67	Iron and steel
68	Non-ferrous metals
69	Manufactures of metals, n.e.s.
Chemical industry	
5	Chemicals and related products
Oil refining and petrochemical industry	
33	Petroleum, petroleum products and related materials
34	Gas, natural and manufactured
51	Organic chemicals
Production of cement	
661.2	Portland cement, aluminous cement, slag cement, supersulphate cement and similar hydraulic cements (66 – Non-metallic mineral manufactures)
661.8	Construction materials of asbestos-cement and fibre-cement of unfired non-metallic minerals
Cement grinding	
273.2	Gypsum, plasters, limestone flux, limestone and other calcareous stone of a kind used for the manufacture of lime or cement
728.11	Machine tools for working stone, ceramics, concrete, asbestos-cement or like mineral materials
728.3	Machinery for sorting, screening separating, washing, crushing, grinding, mixing or kneading earth, stone, ores or other mineral substances; machinery for agglomerating, shaping or moulding solid mineral fuels, ceramic paste, unhardened cement, plastering materials or other mineral products
Manufacturing or processing of sand and stone	
273	Stone, sand and gravel
728.11	Machine tools for working stone, ceramics, concrete, asbestos-cement or like mineral materials
728.3	Machinery for sorting, screening separating, washing, crushing, grinding, mixing or kneading earth, stone, ores or other mineral substances; machinery for agglomerating, shaping or moulding solid mineral fuels, ceramic paste, unhardened cement, plastering materials or other mineral products
Production or processing of lime	
273.2	Gypsum, plasters, limestone flux, limestone and other calcareous stone of a kind used for the manufacture of lime or cement
661.1	Quicklime, slaked lime, hydraulic lime
728.11	Machine tools for working stone, ceramics, concrete, asbestos-cement or like mineral materials
728.3	Machinery for sorting, screening separating, washing, crushing, grinding, mixing or kneading earth, stone, ores or other mineral substances; machinery for agglomerating, shaping or moulding solid mineral fuels, ceramic paste, unhardened cement, plastering materials or other mineral products
Glass production	
664	Glass (66 – Non-metallic mineral manufactures)
665	Glassware
728.11	Machine tools for working stone, ceramics, concrete, asbestos-cement or like mineral materials
728.41	machines for manufacturing or hot-working glass or glassware
Production of ceramic materials or ceramic elements	
662	Clay construction materials and refractory construction materials
666	Pottery
728.3	Machinery for sorting, screening separating, washing, crushing, grinding, mixing or kneading earth, stone, ores or other mineral substances; machinery for agglomerating, shaping or moulding solid mineral fuels, ceramic paste, unhardened cement, plastering materials or other mineral products

ENERGY GENERATION, TRANSMISSION AND DISTRIBUTION

Wind energy	
SITC division	
718.9	Engines and motors n.e.s. (e.g. wind engines)
716.2	Electric motors
716.4	Electric rotary converters
716.5	Generating sets
716.9	Parts
Hydro energy	
718.1	Hydraulic turbines and water wheels and parts thereof
716.2	Electric motors
716.4	Electric rotary converters
716.5	Generating sets
716.9	Parts
Batteries	
778.1	Batteries and electric accumulators and parts thereof
Capacitators	
778.6	Electrical capacitators (fixed, variable and adjustable)

Appendix C. Detailed Description of the WEGDYN Model

Regional and sectoral aggregations

Table C.1: WEGDYN model region aggregates

Aggregated region	Model code	Comprising GTAP9 regions
Germany*	DEU	Germany
Austria*	AUT	Austria
Italy*	ITA	Italy
China	CHN	China
Rest of Europe*	REU	UK, France, Belgium, Luxemburg, Netherlands, Czech Republic, Hungary, Poland, Slovenia, Slovakia, Switzerland, Sweden, Ireland, Denmark, Finland, Norway, Estonia, Latvia, Lithuania, Rest of EFTA (*Liechtenstein, Iceland*), Rest of the world (*Antarctica, French Southern Territories, Bouvet Island, British Indian Ocean Territory*), Cyprus, Greece, Malta, Spain, Portugal, Bulgaria, Croatia, Romania, Albania, Rest of Europe (*Bosnia and Herzegovina, Macedonia, Serbia and Montenegro, Faroe Islands, Gibraltar, Monaco, San Marino*)
North America	NAM	USA, Canada, Rest of North America (*Bermuda, Greenland, Saint Pierre and Miquelon*)
Rest of the World	RST	Australia, New Zealand, Russian Federation, Kazakhstan, Belarus, Ukraine, Armenia, Georgia, Kyrgyzstan, Rest of former Soviet Union (Tajikistan, Turkmenistan, Uzbekistan), Rest of Eastern Europe (Moldova), Hong Kong, Singapore, South Korea, Japan, Turkey, Israel, India, Bangladesh, Thailand, Indonesia, Vietnam, Pakistan, Tunisia, Malaysia, Taiwan, Philippines, Cambodia, Lao People's Democratic Republic, Rest of South-East Asia (Myanmar, Timor-Leste), Sri Lanka, Rest of South Asia (Afghanistan, Bhutan, Maldives), Rest of East Asia (Korea, Macau), Rest of Oceania, Nepal, Brunei Darussalam, Mongolia, Brazil, Mexico, Argentina, Bolivia, Guatemala, Honduras, Nicaragua, Peru, Rest of South America, Chile, Colombia, Dominican Republic, Ecuador, El Salvador, Paraguay, Uruguay, Costa Rica, Panama, Rest of Central America, Trinidad and Tobago, Caribbean (Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Cuba, Dominica, Grenada, Haiti, Montserrat, Netherlands Antilles, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Turks and Caicos Islands, Virgin Islands (US)), Jamaica, Puerto Rico, Saudi Arabia, United Arab Emirates, Egypt, Nigeria, Venezuela, Rest of North Africa (Algeria, Lybia), Rest of Western Asia (Iraq, Lebanon, Palestinian Territory, Occupied, Syrian Arab Republic (Syria), Yemen), Azerbaijan, Iran, Bahrain, Kuwait, Oman, Qatar, Morocco, Rest of South Central Africa, Jordan, South Africa, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Senegal, Togo, Tunisia, Rest of West Africa, Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Rest of South African Customs Union

Notes: *EU27+

Table C.2 WEGDYN model sector aggregates (superscripts 1-5 denote attribution to one of the five groups: 1. Resource using sectors, 2. Agricultural sectors, 3. Refined petroleum and coal products, 4. Process-emission generating sectors, 5. Non-resource using sectors)

Acronym	Sector aggregates in the model	Comprising GTAP9 sectors
AGC [2]	Agricultural products -crops	Agricultural sectors (1-8)
AGL [2]	Agricultural products -livestock	Agricultural sectors (9-12)
FOF [1]	Forestry and Fishery	forestry (13) and fishing (14)
COA [1]	Coal	Coal Mining (15)
OIL [1]	Crude Oil	Oil extraction (16)
GAS [1]	Natural Gas	Natural Gas extraction (17), manufacture of gas, distribution, steam and hot water supply (44)
OMN [1]	Other mining	other mining (18)
ELY [5]	Electricity	Production, collection and distribution of electricity (share of 43)
FBT [5]	Foodstuffs and feedingstuffs, beverages and tobacco products	All food processing sectors (19-25), beverages and tobacco products (26)
TWO [5]	Textile industry and other manufacturing	Textiles (27), Wearing apparel (28), Leather products (29), Wood products (30), Manufacture of paper products and publishing (31), Other Manufacturing: includes recycling (42)
OME [5]	Machinery, data processing equipment, electronic and optical products, Electronic Equipment, Motor, Motor vehicles and parts and other Transport Equipment	Other Machinery & Equipment: electrical machinery and apparatus n.e.c., medical, precision and optical instruments, watches and clocks (41), Electronic Equipment: office, accounting and computing machinery, radio, television and communication equipment and apparatus (40), Motor, Motor vehicles and parts: cars, lorries, trailers and semi-trailers (38), Other Transport Equipment: Manufacture of other transport equipment (39)
P_C [3]	Refined oil products	Petroleum, coal products (32)
CRP [4]	Chemical industry	Chemical, rubber, plastic products (33)
I_S [4]	Iron and Steel	Manufacture of basic iron and steel and casting (35)
NMM [4]	Manufacture of other non-metallic mineral products, precious and non-ferrous metals, and fabricated metal products	Manufacture of other non-metallic mineral products (34), precious and non-ferrous metals (36), , fabricated metal products (37)
WAT [5]	Transport –Water	Water (49)
AIT [5]	Transport –Air	Air (50)
LAT [5]	Transport – Land	Other Transport (including road and rail transport) (48)
SER [5]	Other services and utilities	Water (45), Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel (47), financial services (52), post and telecom (51), Recreational & service activities (55), dwellings (57) real estate & other business (54)
PIN [5]	Private insurance	insurance (53)
OSG [5]	Public services	other services (government): public administration (56)
CON [5]	Construction	construction (46)

Specification of production sectors, final demand and foreign trade

As given in Table C.2, WEGDYN features a multitude of different production sectors. All of them are implemented as nested constant elasticity of substitution (CES) production functions. These CES functions, however, differ for different groups of sectors to capture key characteristics of production technologies. These groups are:

1. **Resource using sectors**: Coal Extraction, Oil Extraction, Gas Extraction, Other Mining, Forestry & Fishery. These sectors all use limited natural resource to operate. These sectors thus provide raw materials to the market.
2. **Agricultural sectors**: Agricultural crop and agricultural livestock sectors, using land as production factor. Land is exclusively used by these two sectors.
3. **Refined petroleum and coal products**: This sector aggregate uses fossil raw materials to produce refined fossil fuels (essentially oil and coal).
4. **Process-emission generating sectors**: Sectors that emit process-emissions, i.e. greenhouse gas emissions that do not originate from the combustion of fossil fuels but stem from chemical processes in the production. This group comprises the Iron & Steel sector, non-metallic minerals (including cement) as well as the chemical industry.
5. **Non-resource using sectors**: This groups comprises all remaining sectors.

In addition to the described sectoral structure, the Electricity sector is further divided into 12 sub-sectors according to the GTAP-POWER database (Peters, 2016), comprising seven base-load electricity generation technologies (Nuclear, Coal, Gas, Wind, Hydro, Oil, Other) as well as four peak-load technologies (Gas, Hydro, Oil, Solar). Transmission and distribution-sector is an additional separate sub-sector.

Within the European regions there is a private household which is endowed with the production factors skilled labor, unskilled labor, capital as well as natural resources (fossil resources, land and CO_2 emission allowances). These factors and resources are provided to the market and thus create income. The resulting income is spent for either consumption or investment (savings), subject to a fixed savings rate. Private consumption is specified as a nested CES consumption function. In each EU region there is also a public household, which collects taxes and provides transfers to the private household. Net-tax income is used to finance the supply of public services; i.e. government consumption, which is specified as a Leontief consumption function (i.e. fixed expenditure shares within the consumption bundle). Tax rates are assumed to be fixed; thus government income is flexible. By default transfers to the private household are assumed to scale linearly with tax income. In the non-European regions, there is only one representative household in each region, which comprises both the private and public household as one single agent.

Foreign trade is implemented via the "Armington assumption" (Armington, 1969), under which each region differentiates between domestically produced and imported commodities/services. We assume a fixed current account balance (growing with GDP). This means that the structure of trade patterns can change due to interventions in the economic system, but not so total net export.

Recursive dynamics and Baseline calibration

In WEGDYN time steps are modelled explicitly, which are connected via capital accumulation: $K_{t+1} = K_t*(1-\delta) + I_t$. The capital stock (K) of the next year period (t+1) is determined by the current year (t) capital stock, minus deprecation according to the depreciation rate (δ), plus current period Investments (I). The recursive dynamic model specification implicitly assumes myopic behavior of all economic agents, that is, they do not include future expectations in their decision but optimize within the current period. Depreciation rates and 2011 regional capital stocks are taken from GTAP9. In order to prevent very strong/weak capital accumulation until 2050 due to possible high/low investment levels in the benchmark year 2011, the savings rate is assumed to converge in all regions to 25% until 2050 (based on World Bank (2019)). The endogenously derived capital stock thus drives the availability of the production factor capital (i.e. the annual capital rent of the capital stock). The

availability of labor is given exogenously via the growth of the working age population in each region, according to SSP2. Total factor productivity is determined endogenously to meet the SSP-specific GDP growth rates. Acknowledging the current economic recession in the aftermath of the Covid-19 pandemic, the model accounts for idle capacities and additional investment demands connected to "green" transformational measures do not crowd out generic investments. Where relevant, we highlight in the results section the difference in the outcome of this modelled mechanism.

The Baseline calibration process involves two steps: In step 1 the generic SSP2 Baseline is calibrated; i.e. socio-economic developments without any additional climate policy as given in 2011 are constructed. The socio-economic development is driven by exogenously given population growth, endogenous total factor productivity (TFP) changes, exogenously given autonomous energy efficiency improvements as well as exogenously given electricity generation cost digressions. Fossil fuel supply is set endogenously to meet the SSP-specific fossil fuel price forecast. For a full overview on the parameter settings see Table C.3. In step 2, currently existing measures are added; i.e. reaching the EU target of -40% greenhouse gas emissions by 2030, relative to 1990. This target is reached via a multitude of measures and policies as given in Table 4.1, with the CO_2 price as slack variable that guarantees to exactly meet the desired target (i.e. by capping emission targets and allowing for a corresponding endogenous CO_2 price).

Table C.3. Calibration parameter settings in WEGDYN

Parameter	Assumption and references
Fossil fuel price forecast	following IEA (2018) "current policies scenario" until 2050: Coal: -0.3% p.a. Oil: +1.5% p.a. Gas: +1.4% p.a.
AEEI (in non-ELY sectors)	1-3% p.a., depending on region (developed versus developing) and energy type (based on Dai et al. (2017))
Elasticity of substitution within energy bundle	default GTAP (0.16)
Armington elasticity	default GTAP (Aguiar et al., 2016)

Appendix D. Building Model Calibration

Building stock and scenario model

In order to define the possible paths leading to a low CO_2emissions building sector, a building stock-scenario model is defined, starting from the one used to develop the *Tirol2050* scenario (Ebenbicher et al., 2018). This model is able to outline, for specific building categories, the energy carriers' distribution and development in the next years under different sets of inputs.
The building stock (available from Statistik Austria 2011) is further subdivided in residential and non-residential buildings. Within the tool, the following distinction is also made:

- Residential Buildings:
  - Single Family Houses (SFH): building with 1-2 flats
  - Small Multi Family Houses (sMFH): building with 3-10 flats
  - Large Multi Family Houses (lMFH): building with more than 11 flats
- Non-residential Buildings

Another important parameter taken into account in the energy analysis is the period of construction of the building. The building stock finally used as input in the scenario model is presented in Table D.1.

Table D.1. Building stock used as input in the scenario model for the reference year (2018)

		SFH		sMFH		lMFH	
Building Period		Nr. Buildings	specific cond. Gross floor Area per Building [m^2_{GFA}]	Nr. Buildings	specific cond. Gross floor Area per Building [m^2_{GFA}]	Nr. Buildings	specific cond. Gross floor Area per Building [m^2_{GFA}]
	1919	231698	164.9	36282	521.4	17196	1541.1
1920	1944	127825	142.7	18965	434.9	5562	1169.0
1945	1960	192949	152.7	20456	464.2	8438	1249.2
1961	1970	223703	167.6	20558	517.5	12252	1532.5
1971	1980	264742	178.4	17738	520.0	11047	2065.4
1981	1990	250756	178.5	18108	574.8	6697	1859.2
1991	2000	213452	180.8	21386	586.4	6736	1826.7
2001	2010	204927	227.3	20693	657.8	7225	2147.2
2011	2017	136618	227.3	13795	657.8	4817	2147.2

For the residential buildings a more detailed distinction is provided in order to account for the different available solutions in terms of HVAC size and typology and of envelope conditions. Since the non-residential buildings represent a small fraction of the total building stock, a more simplified analysis is conducted.

The energy demand for space heating, domestic hot water and household electricity of the existing building stock are respectively defined from available databases ("TABULA WebTool," 2020) and from previous studies (Pfeifer, 2017) and are presented in Table D.2, Table D.3 and Table D.4.

Table D.2. Heating demand (useful energy) of the existing building stock used as input in the scenario model (Tabula Web Tool, 2020), considering prebound effects and pre-renovation.

		Heating demand (useful energy) of existing buildings [kWh/m²GFA/a]		
Building Period		SFH	sMFH	lMFH
	1919	108.6	101.1	87.1
1920	1944	122.5	106.7	100.1
1945	1960	107.4	106.0	89.8
1961	1970	115.8	105.7	89.6
1971	1980	115.8	105.7	89.6
1981	1990	83.7	80.9	39.5
1991	2000	80.6	74.2	67.0
2001	2010	59.4+)	60.0+)	55.0+)
2011	2017	74.0	69.6	62.7

+) most likely an inconsistency in the database

Table D.3. Final energy demand of existing buildings for domestic hot water preparation (Pfeifer, 2017).

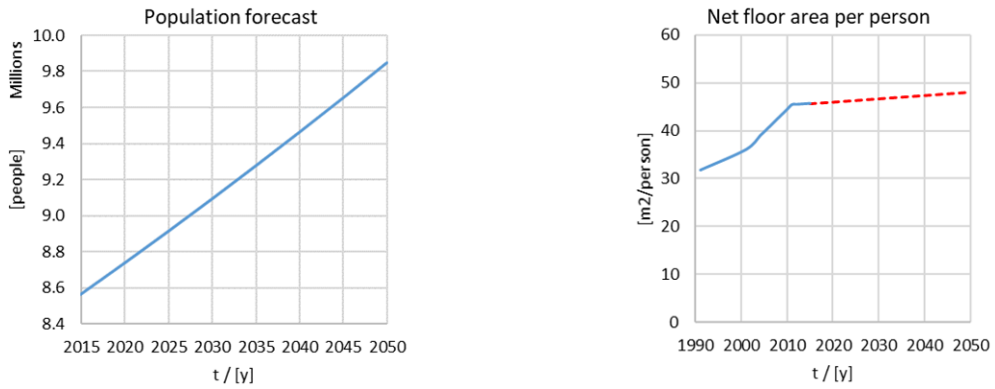
		DHW final energy demand of existing buildings [kWh/m²GFA/a]		
Building Period		SFH	SMFH	lMFH
	1919	23.0	24.2	20.8
1920	1944	24.0	25.2	20.7
1945	1960	23.8	25.9	20.6
1961	1970	23.6	25.6	22.7
1971	1980	23.5	25.6	23.7
1981	1990	23.8	25.5	23.4
1991	2000	23.9	25.6	23.5
2001	2010	23.5	25.3	23.7
2011	2017	24.4	27.4	25.5

Table D.4. Energy demand of existing buildings for household electricity, excluding the energy required for space heating and domestic hot water preparation (Pfeifer, 2017).

Electricity demand (excluding DHW or SH preparation) [kWh/m²GFA/a]		
SFH	sMFH	lMFH
34.0	29.7	30.8

In order to account for non-occupied buildings and non-heated spaces, calibration factors are used on the existing building stock to match the energy demand available from (Statistik Austria, 2019b): 0.82 for space heating, 0.75 for domestic hot water preparation and 0.65 for electrical energy.

The development of the building stock in the following years is consistently calibrated to future population increase (Kc and Lutz, 2017) and accounts for the developments regarding the demolishment rate of existing buildings and the extension of the building stock (see Figure D.1).



(a) (b)

Figure D.1. (a) Rate of population increase and (b) development of the useful floor area per person.

Several scenarios are then defined using different renovation rates, HVAC exchange rates and renovation quality; all these measures are assumed to start in 2021. According to the targets proposed in *#mission2030* (BMNT und BMVIT, 2018, p. 20), it is assumed that no fossil-based HVAC systems are installed after 2020; heat pumps, district heating and biomass will therefore play the major role in the next years.

The efficiency of the heating system is then taken into account in the evaluation of the final energy demand of the evaluated scenarios from the useful energy. A linear increase of the efficiency of the heating systems with the years is considered in the scenario model (Table D.5). The same procedure is applied to evaluate the final energy consumption for domestic hot water production (Table D.6).

Table D.5. Efficiency factors of the different heating systems used in the scenario model.

	Efficiency η_{SH}	
Heating system	**2018**	**2050**
Oil	0.89	
Gas	0.92	
Coal	0.71	
Biomass	0.73	0.75
District Heating	0.91	0.92
DE	1.00	1.00
Heat Pump	3.18	3.46
Storage and Distribution	0.88	0.88

Table D.6. Efficiency factors for the domestic hot water production systems used in the scenario model.

	Efficiency η_{DHW}	
DHW preparation system	**2018**	**2050**
Combined production with space heating		
Oil	0.88	0.88
Oil combined with solar thermal	1.01	1.02
Gas	0.97	0.97
Gas combined with solar thermal	1.04	1.05
Coal	0.69	0.70
Biomass	0.73	0.75
Biomass combined with solar thermal	0.89	0.90
District Heating	1.00	1.00
DE combined with solar thermal	1.00	1.00
Heat pump	3.18	3.46
Separate generation using a separate boiler		
Gas	0.94	0.95
Separate generation using electrical energy		
DE	1.00	1.00
Separate generation using a separate heat pump		
Heat pump	2.61	2.77
Storage	0.78 (SFH) 0.84 (sMFH) 0.9 (lMFH)	
Distribution	0.78 (SFH) 0.72 (sMFH) 0.7 (lMFH)	

Renovated and new buildings

The model considers that every year a certain percentage of buildings are subjected to renovation. Furthermore, it is assumed that a renovation always includes an HVAC change. The tool considers three renovation qualities (as presented in Table D.7). Moreover, the quality of the new buildings, which account also for the ones re-built after demolishment, is taken into account (Table D.8).

Table D.7. Renovation quality of the analyzed building categories used in the evaluated scenarios.

	Heating demand (useful energy) [kWh/m²$_{GFA}$/a]			
Scenario	SFH	sMFH	lMFH	Non-residential
BAU	56.2	46.6	39.4	31.2
Deep	48.4	38.9	33.8	32.0
Best	29.6	24.1	21.2	20.2

Table D.8. New buildings: quality of the analyzed building categories used in the evaluated scenarios.

	Heating demand (useful energy) [kWh/m²$_{GFA}$/a]			
Scenario	SFH	sMFH	lMFH	Non-residential
BAU	30	25	21	20
Deep / Best	10	9	9	14

The energy demand for domestic hot water production is also updated whenever a renovation occurs and in new buildings (Table D.9).

Table D.9. New and renovated buildings: useful energy demand for domestic hot water production.

	DHW energy demand (useful energy) [kWh/m²$_{GFA}$/a]			
Scenario	SFH	sMFH	lMFH	Non-residential
all	13.1	11.8	13.4	7.5

HVAC change

Besides the renovation, which always involves an HVAC change, the model considers also the HVAC change as single measure. It is assumed that a period of 25 years should pass between two measures. For example: a building, which has an HVAC change in 2021, will not be renovated before 2046, and a building built in 2010 will not have any kind of change before 2035.

Sensitivity analysis of the scenario results

The total CO_2 emissions of the studied scenarios can be evaluated using the conversion factors as presented in Figure D.2. Two energy mixes are defined to account for the reduction of CO_2 emissions in district heating and in the electricity production (see Figure D.3).

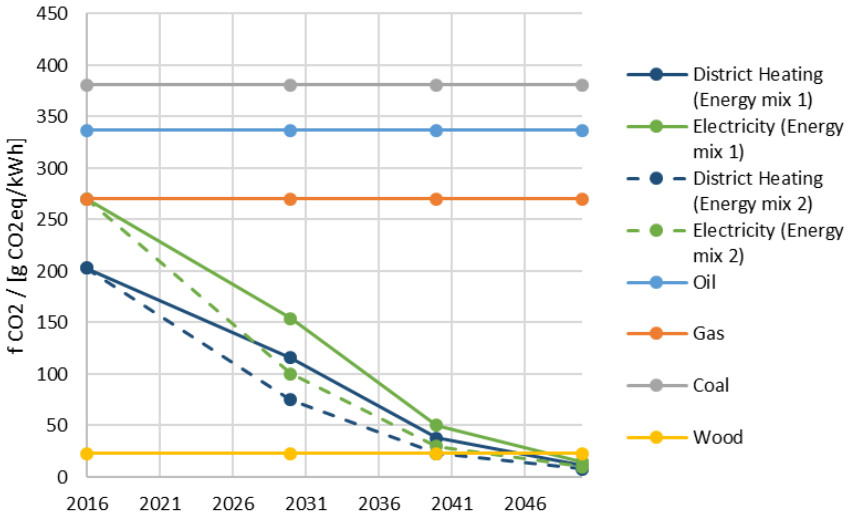


Figure D.2. CO_2 conversion factors for the total emissions. Two energy mixes (Energy mix 1 and Energy mix 2) are taken into consideration in the evaluation of the CO_2 emissions from district heating and electricity to account for the possible development of these two sectors

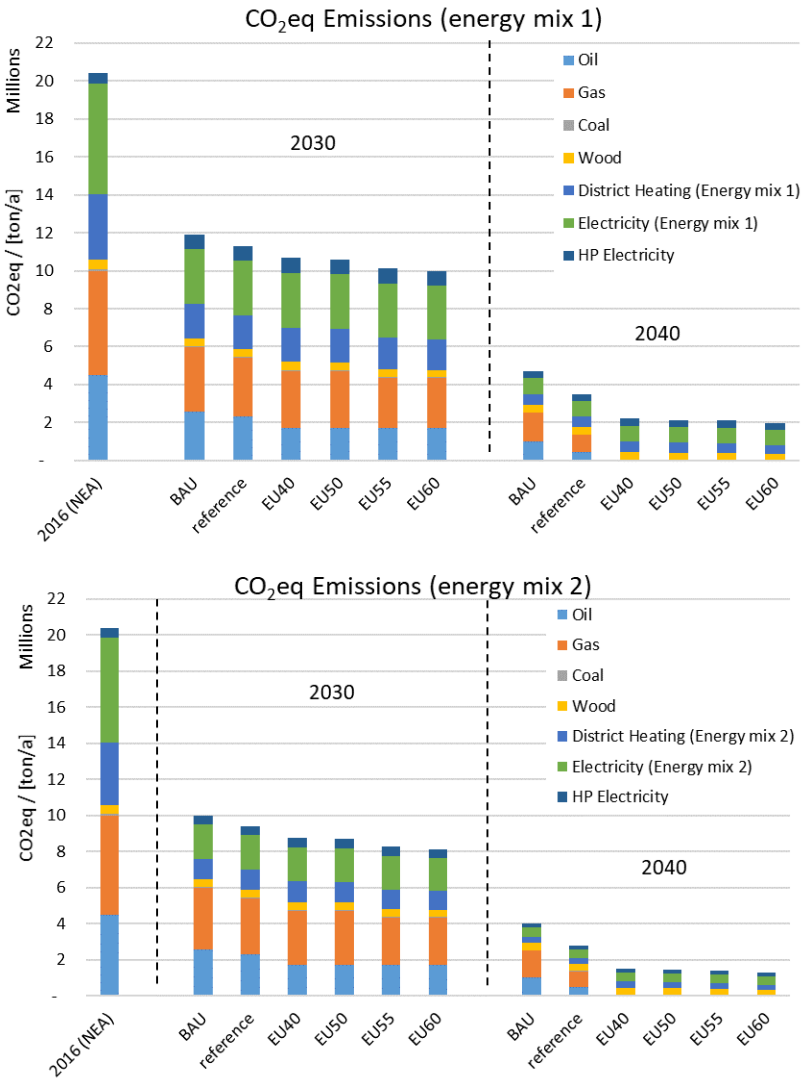


Figure D.3. Total CO_2 emissions defined according to the factors in Figure D.2 for the evaluated scenarios and the two defined energy mixes.

Renovation package tool and database

The residential building stock is subdivided in the categories used in the scenario model: Single Family Houses (SFH), Small Multi Family Houses (sMFH) and Large Multi Family Houses (lMFH).

A reference building is defined for each building group and a 3D representation is reported in Figure D.4. The main geometrical inputs are listed in Table D.10.

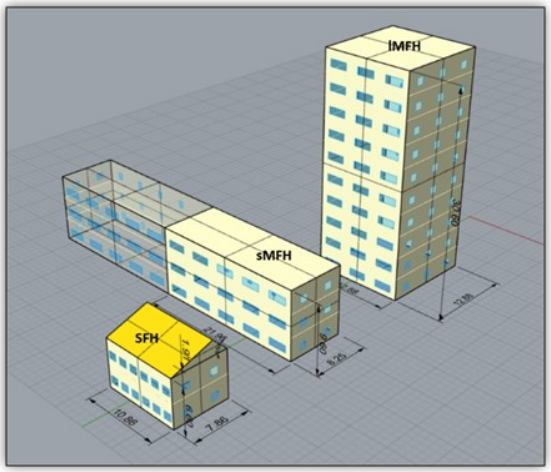


Figure D.4. Sketch of the reference SFH, sMFH and lMFH.

Table D.10. Dimensions of the SFH, sMFH and lMFH.

Building description	SFH	sMFH	lMFH
External area of the vertical envelope [m2]	270.4	500.8	1576.8
External area of the roof [m2]	103.1	181.2	165.9
Ground floor area [m2]	89.8	181.2	165.9
Window area [m2]	23	55	187
Window area SOUTH [m2]	12	30	84
Window area EAST [m2]	4	(adiabatic wall)	46
Window area WEST [m2]	4	15	46
Window area NORTH [m2]	3	10	11
n. of windows	23 (1m x 1m)	46 (0.9m x 1.35m)	156 (0.9m x 1.35m)
n. floors	2	3	10
n. flat	1	6	20
Net floor area [m2]	143.7	434.8	1358.0
Gross Floor Area [m2]	179.6	543.5	1697.5
External Volume [m3]	685.7	1739.2	5078.0
Envelope external area [m2]	463.3	863.1	1908.7
Lc (V/S)	1.5	2.0	2.7

The Tabula Web tool ("TABULA WebTool," 2020) offers statistical data regarding the structures and useful heating demand (HD) of typical SFH, sMFH and lMFH built in different periods:

- Before 1919
- 1919-1944
- 1945-1960
- 1961-1980
- 1981-1990
- 1991-2000
- 2001-2009
- After 2010

Moreover, Tabula provides, for each building type in each period, the HD calculated according to EN ISO 13790 (ÖNORM, 2008) (seasonal method) and a HD calibrated to the level of measured consumption in order to represent the pre-bound effect (accounting for non-heated rooms, lower set point temperature, different ventilation rate, partial renovation etc.) (Sunikka-Blank and Galvin, 2012)

Table D.11 describes the path towards the definition of the renovation packages.

Table D.11. Description of the steps for the definition of the renovation packages.

Steps	Description	Boundary conditions	Target HD GFA: gross floor area			
1 – Calibration	The structures suggested by Tabula are used and the HD calculated with the PHPP (EN 13790) and recaclulated to the OIB method		-			
2 – Pre-renovation	The building defined in the calibration step are pre-renovated in order to meet the Tabula calibrated HD for each period and each building type (Table D.2, Table D.5)	V1: $T_{set} = 19°C$; ACH = 0.15 1/h V2: $T_{set} = 20°C$; ACH = 0.60 1/h V3: $T_{set} = 20°C$; ACH = 0.15 1/h	Periods	SFH	sMFH	lMFH
				HD [kWh/m²$_{GFA}$/a]		
			1919	108.6	101.1	87.1
			1920-1944	122.5	106.7	100.1
			1945-1960	107.4	106.0	89.8
			1961-1980	115.8	105.7	89.6
			1981-1990	83.7	80.9	39.5*
			1991-2000	80.6	74.2	67.0
			2001-2010	59.4	60.0	55.0
3 – Best Renovation	The pre-renovated buildings are further renovated in order to meet the target HD	$T_{set} = 22°C$; ACH = 0.3 1/h (always with MVHR)		SFH	sMFH	lMFH
				HD [kWh/m²$_{GFA}$/a]		
				29.6	24.1	21.2
4 – Deep Renovation		$T_{set} = 22°C$; ACH = 0.3 1/h (MVHR only if necessary)		SFH	sMFH	lMFH
				HD [kWh/m²$_{GFA}$/a]		
				48.4	38.9	33.8
5 – BAU Renovation		$T_{set} = 22°C$; ACH = 0.3 1/h (MVHR only if necessary)		SFH	sMFH	lMFH
				HD [kWh/m²$_{GFA}$/a]		
				56.0	47.0	39.0
6 – 2011 Renovation		$T_{set} = 22°C$; ACH = 0.3 1/h (MVHR only if necessary)		SFH	sMFH	lMFH
				HD [kWh/m²$_{GFA}$/a]		
				67.0	56.0	48.0

* likely an inconsistency in the database

The first step is the *Calibration,* where the building constructions defined in Tabula, for each period, are used in order to calculate the HD of each building type in every period applying three different boundary conditions, considering different combinations of temperature and air change rate. This HD, calculated with the Passive House Planning Package (PHPP) (Feist, 2020), is compared against the HD provided by Tabula calculated according to EN ISO 13790. The Tabula database has different building geometries in each period, while in this study only one characteristic building for each building category (SFH, sMFH and lMFH) is implemented (see Table D.10). The calibration step is important to define the starting point of the whole process, since in this step all the models are set up with the correct constructions. The results of this step are presented in Table D.12.

Table D.12. Heating demand (useful energy) of the buildings resulting from Calibration (Tabula Construction Data Base, Energy Balance Calculation).

	Building Period	1919	1920-1944	1945-1960	1961-1980	1981-1990	1991-2000	2001-2010
					[kWh/(m^2_{GFA} a)]			
SFH	V1_(19°C, 0.15 ACH)_cal	220.1	258.7	194.2	215.4	170.0	73.5	49.0
	V2_(20°C, 0.6 ACH)_cal	268.3	310.5	240.4	262.9	213.4	107.7	80.4
	V3_(20°C, 0.15ACH)_cal	240.7	282.9	212.8	235.4	186.0	80.7	54.0
sMFH	V1_(19°C, 0.15 ACH)_cal	125.8	158.2	135.4	142.1	74.2	45.8	27.7
	V2_(20°C, 0.6 ACH)_cal	165.2	200.6	175.4	182.9	108.4	77.0	56.8
	V3_(20°C, 0.15 ACH)_cal	137.8	173.1	148.0	155.4	81.3	50.5	30.9
lMFH	V1_(19°C, 0.15 ACH)_cal	91.0	142.0	115.1	96.5	66.9	32.1	26.1
	V2_(20°C, 0.6 ACH)_cal	127.4	183.2	153.8	133.4	100.6	62.1	55.5
	V3_(20°C, 0.15 ACH)_cal	99.6	155.2	125.9	105.6	73.2	35.6	29.1

The second step is the *Pre-renovation,* where roof and wall insulation and window U-value are modified in order to reach the target HD for the pre-renovation (which considers the pre-bound effect), see Table D.12, used as input in the scenario model (Table D.2).

The last step is the *Renovation*, where the buildings are renovated according to the renovation targets imposed in the scenario tool. The boundary conditions considered for the renovation are always 22°C and 0.3 ACH, but different renovation depths are considered (i.e., from "2011" to "Best"). A schematic representation of the algorithms used in the definition of the renovation packages is presented in Figure D.5.

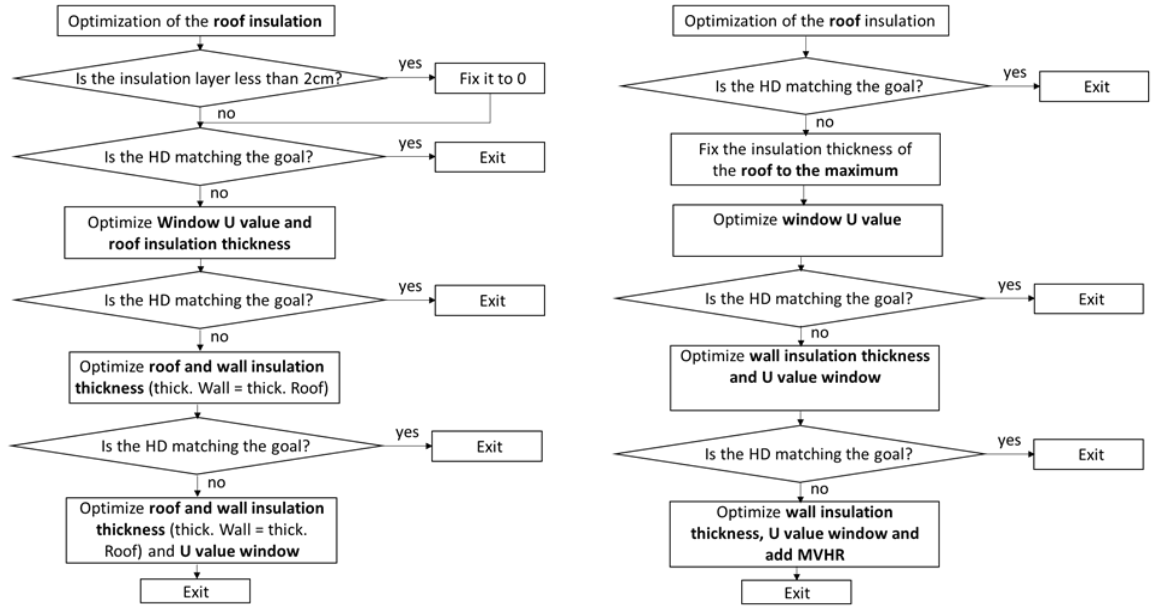


Figure D.5. (a) Pre-renovation algorithm. (b) Renovation algorithm. The MVHR is always present in the "Best Renovation" cases, while in other renovations is added only if necessary, to reach the target HD.

Table D.12 presents the inputs used in the PHPP calculation of all the cases. The thermal bridges are reduced in the renovated buildings. The optical properties of the windows, shadings and frame ratio are kept constant as well as the internal gains. The reference Austrian weather, according to OIB 2019 (Österreichisches Institut für Bautechnik, 2019), is used.

Table D.13. Inputs for all the reference buildings (SFH, sMFH, IMFH).

Thermal bridges (calibration and pre renovation)	0.1 [W/(m²K)] * Envelope Area [m²]
Thermal bridges (Deep, Bau, 2011 renovation)	0.05 [W/(m²K)] * Envelope Area [m²]
Thermal bridges (Best renovation)	0.025 [W/(m²K)] * Envelope Area [m²]
g-value windows	0.6
Frame ratio	30%
Total solar gain reduction factor (shading * dirt * g correction)	0.54
Internal Gains	3 [W/m²]
Weather	Reference Climate AT OIB 2019
MVHR heat recovery efficiency (when present)	85%

The HDs (in terms of useful energy) calculated with PHPP (Passive House Planning Package) for *Calibration*, *Pre-renovation* and *Renovation* are reported in Figure D.6 for SFH, Figure D.7 for sMFH and Figure D.8 for lMFHc (periods after 1980 are disregarded in the definition of the renovation packages).

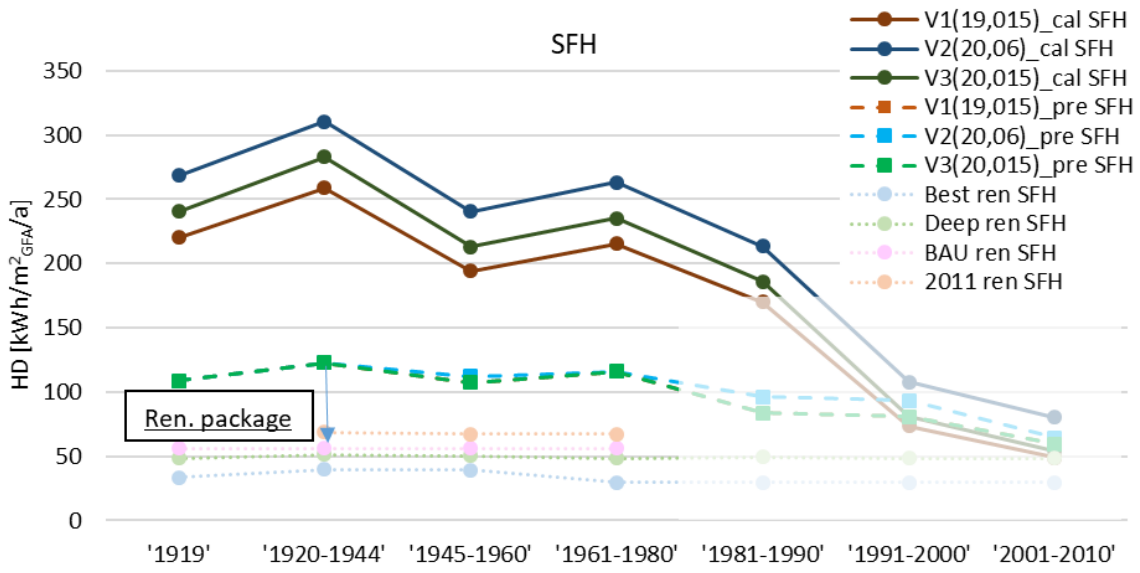


Figure D.6. Calibration, pre-renovation and renovation results for each period for SFH. Periods after 1980 are disregarded in the renovation packages. The Renovation step, considered also in the scenario model, starts with a pre-renovated building stock (from dashed lines to point lines).

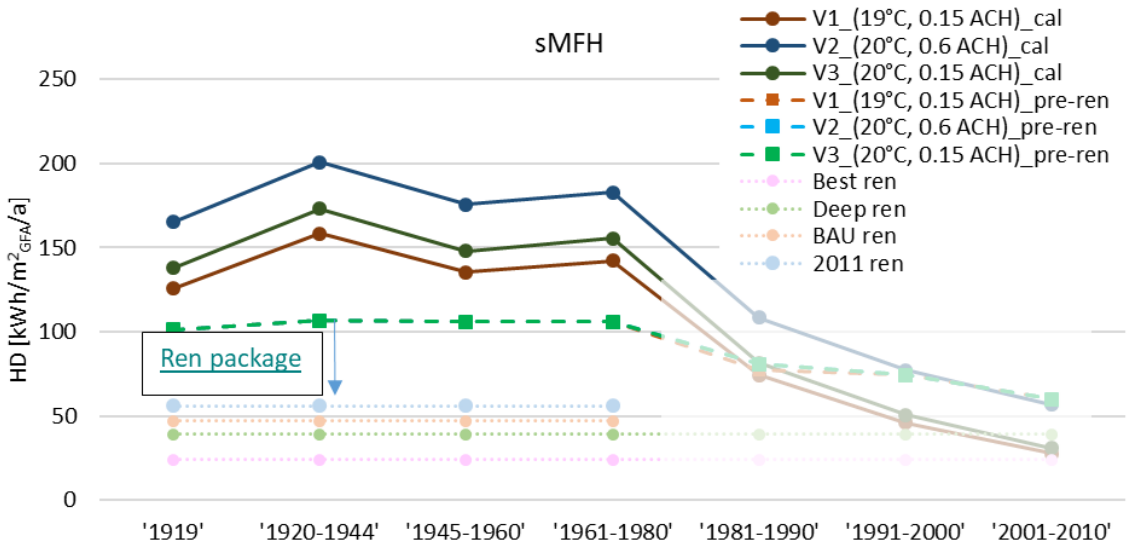


Figure D.7. Calibration (cal), pre-renovation (pre-ren), with different boundary conditions (V1, V2 and V3) and renovation (ren) results for each period for sMFH. Periods after 1980 are disregarded in the renovation packages.

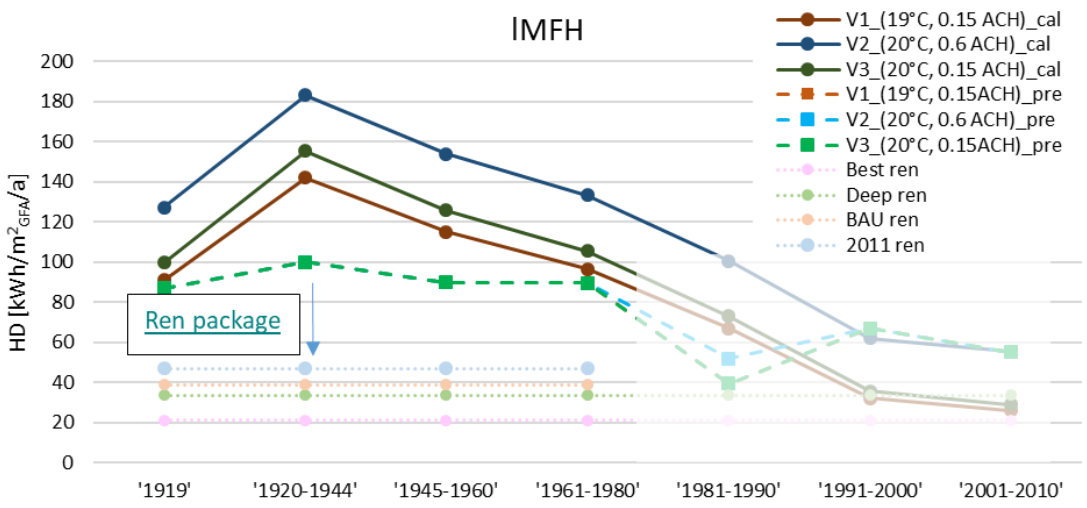


Figure D.8. Calibration (cal), pre-renovation (pre-ren), with different boundary conditions (V1, V2 and V3) and renovation (ren) results for each period for lMFH. Periods after 1980 are disregarded in the renovation packages

Each renovation package is described by the additional equivalent insulation thickness of walls and roof, by the necessity of changing the windows and eventually installing the MVHR. For each renovation depth (2011, BAU, Deep and Best as in Table D.11) three different renovation packages are defined, one for each pre-renovation boundary condition (V1, V2 and V3 as in Table D.11). The resulting renovation packages for the three building subgroups are presented from Table D.14 to Table D.25.

Table D.14. "2011 Renovation" packages for SFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	2011 ren SFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	keep	change	change	keep
	Equivalent additional Insulation wall [cm]	26	26	26	17
	Equivalent additional Insulation Roof [cm]	26	26	26	26
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	change	change	keep
	Equivalent additional Insulation wall [cm]	20	21	20	13
	Equivalent additional Insulation Roof [cm]	20	21	20	22
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	change	change	keep
	Equivalent additional Insulation wall [cm]	25	25	25	16
	Equivalent additional Insulation Roof [cm]	25	25	25	25
	MVHR installation	No	No	No	No

Table D.15. "BAU Renovation" packages for SFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	BAU ren SFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	19	26	26	26
	Equivalent additional Insulation Roof [cm]	26	26	26	26
	MVHR installation	Yes	Yes	Yes	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	13	21	20	22
	Equivalent additional Insulation Roof [cm]	20	21	20	22
	MVHR installation	Yes	Yes	Yes	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	18	25	25	25
	Equivalent additional Insulation Roof [cm]	25	25	25	25
	MVHR installation	Yes	Yes	Yes	No

Table D.16. "Deep Renovation" packages for SFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	Deep ren SFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	keep	change	change	keep
	Equivalent additional Insulation wall [cm]	26	26	26	19
	Equivalent additional Insulation Roof [cm]	26	26	26	26
	MVHR installation	Yes	Yes	Yes	Yes
V2(20,06)	Windows have to be changed:	keep	change	change	keep
	Equivalent additional Insulation wall [cm]	20	21	20	15
	Equivalent additional Insulation Roof [cm]	20	21	20	22
	MVHR installation	Yes	Yes	Yes	Yes
V3(20,015)	Windows have to be changed:	keep	change	change	keep
	Equivalent additional Insulation wall [cm]	25	25	25	18
	Equivalent additional Insulation Roof [cm]	25	25	25	25
	MVHR installation	Yes	Yes	Yes	Yes

Table D.17. "Best Renovation" packages for SFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	Best ren SFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	change	change	keep
	Equivalent additional Insulation wall [cm]	36	36	36	36
	Equivalent additional Insulation Roof [cm]	36	36	36	36
	MVHR installation	Yes	Yes	Yes	Yes
V2(20,06)	Windows have to be changed:	change	change	change	keep
	Equivalent additional Insulation wall [cm]	30	31	30	32
	Equivalent additional Insulation Roof [cm]	30	31	30	32
	MVHR installation	Yes	Yes	Yes	Yes
V3(20,015)	Windows have to be changed:	change	change	change	keep
	Equivalent additional Insulation wall [cm]	35	35	35	35
	Equivalent additional Insulation Roof [cm]	35	35	35	35
	MVHR installation	Yes	Yes	Yes	Yes

Table D.18. "2011 Renovation" packages for sMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	2011 ren sMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	5	6	6	6
	Equivalent additional Insulation Roof [cm]	26	29	25	29
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	3	4	4	4
	Equivalent additional Insulation Roof [cm]	27	27	28	27
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	5	6	5	5
	Equivalent additional Insulation Roof [cm]	26	29	29	28
	MVHR installation	No	No	No	No

Table D.19. "BAU Renovation" packages for sMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	BAU ren sMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	9	9	9	9
	Equivalent additional Insulation Roof [cm]	26	29	25	29
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	6	8	7	7
	Equivalent additional Insulation Roof [cm]	27	27	28	27
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall (with λ=0.038 W/(m K)) [cm]	9	9	9	9
	Equivalent additional Insulation Roof (with λ=0.038 W/(m K)) [cm]	26	29	29	28
	MVHR installation	No	No	No	No

Table D.20. "Deep Renovation" packages for sMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	Deep ren sMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	16	16	16	16
	Equivalent additional Insulation Roof [cm]	26	29	25	29
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	13	14	14	14
	Equivalent additional Insulation Roof [cm]	27	27	28	27
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	16	16	15	16
	Equivalent additional Insulation Roof [cm]	26	29	29	28
	MVHR installation	No	No	No	No

Table D.21. "Best Renovation" packages for sMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	Best ren sMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	10	10	10	10
	Equivalent additional Insulation Roof [cm]	36	39	35	39
	MVHR installation	Yes	Yes	Yes	Yes
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	7	8	8	8
	Equivalent additional Insulation Roof [cm]	37	37	38	37
	MVHR installation	Yes	Yes	Yes	Yes
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	10	10	10	10
	Equivalent additional Insulation Roof [cm]	36	39	39	38
	MVHR installation	Yes	Yes	Yes	Yes

Table D.22. "2011 Renovation" packages for lMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	2011 ren lMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	7	8	7	7
	Equivalent additional Insulation Roof [cm]	26	29	30	29
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	5	6	5	5
	Equivalent additional Insulation Roof [cm]	28	28	28	26
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	7	8	7	7
	Equivalent additional Insulation Roof [cm]	29	29	29	27
	MVHR installation	No	No	No	No

Table D.23. "BAU Renovation" packages for lMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	BAU ren lMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	11	12	12	12
	Equivalent additional Insulation Roof [cm]	26	29	30	29
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	9	11	10	10
	Equivalent additional Insulation Roof [cm]	28	28	28	26
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	11	12	11	12
	Equivalent additional Insulation Roof [cm]	29	29	29	27
	MVHR installation	No	No	No	No

Table D.24. "Deep Renovation" packages for lMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	Deep ren lMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	17	18	18	18
	Equivalent additional Insulation Roof [cm]	26	29	30	29
	MVHR installation	No	No	No	No
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	15	16	16	16
	Equivalent additional Insulation Roof [cm]	28	28	28	26
	MVHR installation	No	No	No	No
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	17	18	17	18
	Equivalent additional Insulation Roof [cm]	29	29	29	27
	MVHR installation	No	No	No	No

Table D.25. "Best Renovation" packages for lMFH (assuming an insulation material with λ=0.038 W/(m K)).

Pre Ren. ->	Best ren lMFH	'1919'	'1920-1944'	'1945-1960'	'1961-1980'
V1(19,015)	Windows have to be changed:	change	keep	keep	keep
	Equivalent additional Insulation wall [cm]	10	11	11	10
	Equivalent additional Insulation Roof [cm]	36	39	40	39
	MVHR installation	Yes	0	0	0
V2(20,06)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	8	9	9	8
	Equivalent additional Insulation Roof [cm]	38	38	38	36
	MVHR installation	0	0	0	0
V3(20,015)	Windows have to be changed:	keep	keep	keep	keep
	Equivalent additional Insulation wall [cm]	10	11	10	10
	Equivalent additional Insulation Roof [cm]	39	39	39	37
	MVHR installation	Yes	Yes	Yes	Yes

Appendix E. Hydrogen-based Iron and Steel Production

Appendix E has been compiled in close collaboration with and main contributions by Jakob Mayer (University of Graz), Johannes Rieger (K1-MET GmbH) and Johannes Schenk (Montanuniversität Leoben; K1-MET GmbH).

Transition to iron production using hydrogen

The production of iron and steel from its ores involves a reduction reaction that removes oxygen from the ores and some further impurities. The dominating technology for the reduction is the Blast Furnace (BF), which uses mainly coke and partially coal for the production of hot metal. In Europe, this route has a roughly 60% share of the total crude steel production. Hot metal is a liquid iron product, which is further processed to crude steel in the basic oxygen furnace (BOF). An alternative is the production of direct reduced iron (DRI), a solid iron material (called sponge iron) being generated with direct reduction (DR) technologies. The DR process can be operated with natural gas or coal. The sponge iron is converted to crude steel in an Electric Arc Furnace (EAF). All routes have carbon dioxide from fossil energy sources as a chemical byproduct. The production of iron and steel accounts for about 6-7% of anthropogenic CO_2 emissions. Environmental regulations are a main reason for this industry to go for a transition to new carbon-lean processes.

Innovative approaches for the mitigation of CO_2 consider iron and steel production with hydrogen or the direct use of electricity. Prerequisite for that is that both are produced from renewable energy sources. New technologies based on CCS, hydrogen and electricity have been evaluated in the European Ultra Low CO_2 Steelmaking (ULCOS) program (2004-2008) including (1) Blast Furnace with top-gas recycling (TGR-BF), (2) a new smelting reduction process (HIsarna), (3) advanced direct reduction (ULCORED) and (4) electrolysis of iron ore (ULCOWIN and ULCOLYSIS). Most of these alternative routes are not ready for commercial application and require additional 10 to 20 years to reach the technological readiness level for industrial operation. An exception is the production of DRI with hydrogen in a shaft furnace, which is downstream melted in an EAF to crude steel. The DRI process with reforming CH_4 to H_2 and CO is state of the art and the transformation to H_2 is based on the large scale and economic availability of hydrogen from renewable sources. Developments for this technological concept are currently in the pilot stage and the first commercial scale plant could start its operation within this decade (Roland Berger, 2020; SSAB et al., 2021).

The European steel industry committed to contribute to the European Commission's CO_2 mitigation goals. Therefore, there is a clear need for a new breed of primary steelmaking technologies that can produce carbon-neutral steel. At present, the European industry is heading into production of DRI in a shaft furnace process with natural gas and use in an EAF to replace partly the BF/BOF route with the final goal of using hydrogen instead natural gas for reduction of the ores. The present main effort is to increase the share of hydrogen towards 100%. Carbon Direct Avoidance (CDA) is the steel related technological pathway for a replacement of carbon by fossil-free reductants (e.g. hydrogen) and/or direct use of renewable electricity to directly avoid CO_2 emissions (EUROFER, 2019) for the iron ore reduction. This appendix summarizes the main cost assumptions of the conventional emission-intensive process (BF-BOF) and the innovative (almost) emission-free steelmaking process based on hydrogen (H_2-DR-EAF), which are used for the macroeconomic assessment. We first, concentrate on a techno-economic comparison of the status quo and, second, provide an outlook on foreseeable cost developments of the hydrogen-based process.

Hydrogen usage for DRI production

The BF-BOF route emitting mainly direct greenhouse gases is the starting point for the scenario of a stepwise decarbonization. Shifting to the DRI process using hydrogen in a shaft furnace must be considered as a future final scenario. Depending on the technical and economic availability, the

share of hydrogen will be increased (Buergler and Prammer, 2019) to a fully H_2-based direct reduction. H_2-based DRI is ready to be implemented stepwise into brownfield plants when H_2 from renewable sources is available on the large and economic scale.

As an intermediate stage in the decarbonization scenario, the concept of a hybrid steel plant can be considered, in which the BF-BOF route and DR-EAF route based on natural gas will coexist. at one site. This parallel use of both routes at one brownfield plant enables a stepwise ramp up of the DRI-EAF route. DRI, or in agglomerated form known as Hot Briquetted Iron (HBI), are very flexible input materials. As a high-quality scrap substitute, DRI and HBI can be processed into crude steel in a BOF or an EAF with scrap and hot metal. Additionally, a charging into the BF is possible for lowering the demand on reducing agents in the BF process and for increasing the performance (SSAB et al., 2021). Although technically feasible in the future, a fully transition to a carbon-neutral steel industry is only achievable through massive CAPEX and ample availability of green electricity.

For the status quo, Table E.1 shows operating (OPEX) and capital expenditures (CAPEX) connected to the BF-BOF and H_2-DR-EAF routes. We compare the whole process of primary iron and steel making including the reduction of oxygen in iron ore (BF and H_2-DR) and the subsequent processing to crude steel (BOF and EAF). Electricity costs for the H_2-route includes hydrogen production using the polymer electrolyte membrane (PEM) electrolysis technology resulting in overall 4,375 kWh electricity per ton of crude steel for the whole process. In terms of OPEX, the H_2-based technology is currently around 50% costlier and this can go up to 80% (Buergler, 2018). On top, CAPEX of the H_2-based process includes new facilities (electrolyser, and the DRI and EAF plants) and not only re-investment as for the BF-BOF further increasing the cost differential in terms of unit-costs of crude steel during the investment cycle. These cost and emission factors are implemented in the macroeconomic model.

Table E.1 Iron and steel (cost) parameterization based on (Mayer et al., 2019)

	BF-BOF	H_2-DR-EAF
OPEX [EUR/t steel]	415	624
Most relevant cost components:		
- Coke	84	0
- Electricity	0	219
(Re-)Investment cost [EUR/t steel]	371	1,11
CAPEX [EUR/t steel]	29	87
Length of transition time and loan term [y]	15	15
Interest rate [%]	2	2
Emission factor [t CO_2/t steel]	1.5	0[#]

Notes: BF-BOF … blast-furnace basic-oxygen furnace, H_2 … hydrogen, DRI … Direct reduction of iron ore, EAF … electric arc furnace; [#]Short- to medium term, this process involves a negligible amount of GHG emissions (< 0.1 kgCO_2 /t steel).

A depreciation period of 15 years is applied, while Mayer et al. (2019) translated total upfront investment (at identical level) to a use period of 12 years.

New processes are often subject to substantial learning lowering the costs of production. This applies for each of the individual processes of the H_2-DRI-EAF production route, for which we derive a an overall learning rate of >1% per year over the next decade (see Table E.2; -1.2% = $(554/624)^{(1/10)}$-1). We chose a learning rate of exactly 1% p.a., which is put on top of the unit-cost of H_2-DR-EAF production. Hence, it is implemented as a conservative cost digression in the macroeconomic model assessment.

Table E.2. Learning in H2-DR-EAF production

Process	Current	Potential	Unit
H_2 via PEM	4.2	3.8 [a]	kWh/Nm^3
	750.0	562.5[b]	Nm^3/t
	3,150.0	2,137.5	kWh/t
DRI	800.0	690.0 [c]	kWh/t
EAF	425.0	350.0 [c]	kWh/t
Total electricity demand	4,375.0	3,177.5	kWh/t
Electricity price	0.05	0.05	EUR/kWh
Electricity unit-cost	218.8	158.9	EUR/t
Iron pellets unit-cost	84.0	73.5 [d]	EUR/t
Other inputs* (e.g. labor)	321.3	321.3	EUR/t
OPEX per t crude steel	624.0	553.6	EUR/t

Notes: [a] (Shiva Kumar and Himabindu, 2019); [b] 25% scrap share reduces H2 demand; [c] Lower bounds taken from http://www.iipinetwork.org/; [d] Increased scrap share of 25% reduces iron pellets intake, difference of scrap and iron pellets prices relevant, assumption 12.5% lower iron pellets cost; * (Mayer et al., 2019).

Outlook and challenges for a decarbonization scenario in steel industry

Achievement of the climate goals until 2030 (and further until 2050) seems unattainable with the currently dominating BF-BOF route, which is already operating close to its thermodynamic limit. The European steel industry committed to contribute to the Commission's CO_2 reduction target and has set its own CO_2 reduction goal of 50% (emission reduction from steel production) until 2030 (ESTEP, 2020). The maximum CO_2 reduction potential attainable with the actual production routes (considering the decrease of CO_2 intensity in the power sector as well as the increase in scrap availability) is predicted to be about 15% until 2050 (EUROFER, 2019). This enables a too low CO_2 abatement potential as required to reach the CO_2 emission target.

To reach the goal of a decarbonized steel industry, the DRI process using a shaft furnace as the central iron ore reduction aggregate with natural gas is state of the art and is operated in fully industrial scale. In the optimum future scenario, the DRI process is operated with 100% hydrogen to produce DRI. Followed by an EAF for melting and crude steel production, a carbon-neutral steelmaking process is realistic. On the way to the decarbonization of the steel industry, co-existence of DRI-EAF with partial and full H_2-operation and the conventional BF-BOF route must be considered as intermediate step since the transition to a fully H_2-DRI-EAF steel production requires massive CAPEX.

Before a 100% hydrogen-based DRI process can be established, the availability of renewable electric energy and the upscaling of electrolyser technology must be solved. Beside CAPEX, the transition to carbon-free steel production will also induce massive increase of OPEX as already

mentioned above. The requested CO_2 emission target is closely linked to a radical change in the energy supply. Massive amount of green electricity must be available. If the fossil-based energy system would be replaced by hydrogen technology, roughly 500 TWh would be required only by the European steel industry. Considering Germany as the most important European steel producing country, approximately 120 TWh on renewable energy would be necessary, which is half of the green electricity Germany produced in 2019. Similar situation is given in Austria, since approximately 33 TWh would be required for the transition to a renewable based energy system.

Another chance for reaching the CO_2 emission target is the further development of so-called "breakthrough technologies" in steelmaking. As mentioned at the beginning, the technological pathway CDA comprises electrical-based metallurgy beside the use of hydrogen as reducing agent. There are two types of electrolytic processes being in the focus of current R&D activities. These are the electrolysis and electrowinning whereas the projects ULCOLYSIS and ULCOWIN were mentioned as reference projects at the beginning of Appendix E. During electrolysis, iron ore is transformed into liquid steel at temperatures of ~1,500 °C using electricity as reducing agent. Electrowinning is a process, in which ground ultrafine iron ore concentrate is leached and then reduced in an electrolyser at approximately 110 °C. The resulting iron plates are fed into an EAF for crude steel production. Compared to the H2-based DR process, electrolytic iron ore reduction is several development steps behind. Currently, these processes have been proven at laboratory-scale at a Technology Readiness level (TRL) of 4-5. A long and costly development phase of 20-30 years leading to industrial-scale productivity is still required (Roland Berger, 2020). One main challenge towards CO_2-lean steel production with an electrolytic process is dedicated to the material of the anode. As the principle of iron ore electrolysis originates from aluminum production (fused salt electrolysis), graphite is used as anode material, which produces CO_2 during the plant operation. An inert anode material has not yet been developed. 3600 to 4000 kWh electric energy is required to produce 1 ton of liquid iron (crude steel). For comparison, the expected electric energy consumption for the 100 % hydrogen DR-shaft-EAF route is 3500 kWh plus 600 kWh for bio-fuels (SSAB et al., 2017). The TRL of this technology is also at the level of 4 to 5.

Coming back to developments in the H_2-based metallurgy, the hydrogen-based fluidized bed DR and the Hydrogen Plasma Smelting Reduction processes are currently investigated in pilot-scale within the frame of different Austrian and European funded research projects. A fluidized bed has one advantage that a pre-processing (pelletizing) step can be avoided leading to reduced costs and possibly lower CO_2 emission. Hydrogen Plasma Smelting Reduction uses separated hydrogen molecules (H_2 ions) for the reduction process. One main benefit of this route is that only one step is required to get from fine iron ore to crude steel. This makes it economically attractive for the future. However, it must be stated that all these routes are at a lower technological readiness level compared to the DRI shaft furnace process requiring further R&D activities to reach a development status being ready for industrial operation.

To sum up, the field of green electricity is of highest importance for the steel industry beside further technological developments on steelmaking processes. Without sufficient supply of cheap green electricity, the DRI production will not be economically feasible in low-carbon approaches.

Appendix F. Cement Retrofitting with Carbon Capture

Table F.1. Carbon capture key performance indicators based on (Gardarsdottir et al., 2019).

	Integrated plant		CC retrofit
	REF	**REF+CAP**	**CAP**
Emission factor [tCO_2/t clinker]	0.85	0.04	-
Unit invest cost [EUR/t clinker]	204	353	149
Unit OPEX [EUR/t clinker]	41	66	25
Unit CAPEX [EUR/t clinker]	19	33	14
Unit cost [EUR/t clinker]	60	99	39
Economic life [y]	25	25	25
Capacity factor	91	91	91
Loan term [y]	12	12	12
Discount rate	2%	2%	2%

Appendix G. Capacity Cost of Electricity

Table G.1. Cost assumptions per electricity technology based on (IRENA, 2019; Mayer et al., 2015; Pleßmann and Blechinger, 2017; Schröder et al., 2013)

Investment	[EUR/kW]		
	2011	2030	2050
NuclearBL	6,000	6,000	6,000
CoalBL	2,146	2,076	2,010
GasBL	799	775	752
WindBL#	2,134	1,844	1,584
HydroBL	2,500	2,500	2,500
OilBL	400	400	400
OtherBL*	3,321	2,801	2,346
GasP	799	775	752
HydroP	2,500	2,500	2,500
OilP	400	400	400
SolarP	1,479	600	425
Battery (§)	na	580	289
PtG (&)	na	1,356	522

Notes: *Remaining (biomass, waste, geothermal, …); #Mix of on-/offshore; (§) Zinc-bromide and molten salt technology; (&) Electrolysis, H2 storage and methanation unit; P … peak load; BL … base load.

Appendix H. Transport Sector Details

Phasing out of internal combustion engines

Table H.1. Legal initiatives in selected EU Member States for phase-out of internal combustion engines (ICE)

Country	Timeline	Description
France	2040	Law to gradually decrease share of vehicles with internal combustion engines (ICE) and to end the sale of new ICE by 2040. (Secretary of State for the Digital Economy (France), 2019)
Ireland	2030	Formulated target. 500,000 Electric Vehicles (Evs) on the road by 2030. No new non-zero emissions vehicles sold post-2030 (Government of Ireland, 2019)
Norway	2025	Formulated target. End sale of ICEs by 2025 (Norwegian Ministry of Climate and Environment, 2019)
Sweden	2030	Government appointed inquiry on how to implement a ban on the sale of vehicles with internal combustion engines (ICE) and when fossil fuels should be phased out. The final report is to be presented by 1 February 2021. (Ministry of the Environment, 2019)
UK	2040	Formulated target. Currently consultation on bringing forward the end to the sale if new petrol and diesel vehicles to 2035, or earlier if a faster transition appears feasible, as well as including hybrids for the first time. (Department for Transport, 2020)

Cost and penetration of motorized individual transport

The unit cost of motorized individual transport is calculated using an investment-cycle spreadsheet calculation differentiating the share of conventional (cMIT) and electrified cars (eMIT), taking into account projected person-kilometers until 2050 as well as acquisition costs, operating costs, life time and the occupation rate of vehicles. We assume that MIT rises from 80 billion person-kilometers in 2020 to 90 billion by 2030, 97 billion by 2040 and 105 billion by 2050 (based on (Capros et al., 2016)). Starting with a 1% share of eMIT in 2020, market penetration by 2030 is assumed to rise to 40%, 50%, 55% and 60% for the respective EU emission reduction targets. By 2040, full penetration of eMIT is assumed. The occupation rate is kept constant at 1.22 people per vehicle and the economic life time at 10 years ((BMVIT, 2016)). Operating expenditures (net of taxes) are 0.26 EUR/pkm for cMIT and 0.21 EUR/pkm for eMIT. Acquisition costs for a representative cMIT are EUR 22,000. For eMIT, we assume EUR 30,000 for a comparable vehicle, with expected cost reductions (due to rapid technological progress in batteries) leading to EUR 23,000 by 2030 and EUR 20,000 by 2050 ((Kreyenberg, 2016)).

Technologies and alternative fuels considered in the freight transport sector

Seven technologies and eight alternative fuels are considered in this work. Two technologies that emit CO_2 and five zero-emission technologies. The considered emitting technologies are combustion engine diesel (CE-D) with diesel as fuel and combustion engine gas (CE-G) with compressed/liquid natural gas (CNG/LNG) as fuel. The alternative zero-emission technologies are combustion engine hydrogen (CE-H2) with hydrogen as fuel, plug-in hybrid electric vehicle with diesel, biofuel, power to liquid (PtL) and electricity as fuels, battery electric vehicle (BEV) with electric as fuel, overhead catenary electric vehicle (OC-EV) with electricity as fuel and fuel-cell electric vehicle (FCEV) with hydrogen as fuel. Other alternative fuels used in CE-D are biofuel and PtL. Alternative fuels considered in CE-G are biogas and power to gas (PtG). PtL and PtG are synthetic fuels produced by electricity.

Market penetration of technologies and fuel share in technologies in 2018, 2030 and 2040 for EU40 and EU55

In the following three Tables (Table H.2-Table H.4), the market penetration of alternative technologies is shown as well as the share of fuels in certain technologies. Hereby, the information in the first seven rows show the share of each conventional and alternative fuel in the corresponding technology. These shares are the same for the EU40-baseline and the EU55-scenario. Biofuel and biogas are in the same row. The reason is that biofuel is only an input in CE-D and PHEV and biogas only an input for CE-G, which applies also for PtL and PtG.

Table H.2. Market share of technologies and fuel share in each technology in 2018.

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV
Share of fuels in percent							
Diesel fuel	*93*			*55.8*			
CNG/LNG		*100*					
Biofuel/Biogas	*7*	*0*		*4.2*			
PtL/PtG	*0*	*0*		*0*			
Electricity				*40*	*100*	*100*	
Hydrogen			*100*				*100*
Market share of technology in 2018 [%]	99.998	-	-	-	0.002	-	-

Notes:
CE-D … combustion engine diesel, CE-G … combustion engine gas, CE-H2 … combustion engine hydrogen, PHEV … plug-in hybrid electric vehicle, BEV … battery electric vehicle, OC-EV … overhead catenary electric vehicle, FCEV … Fuel-cell electric vehicle; CNG/LNG … compressed/liquid natural gas, PtL … power to liquid, PtG … power to gas

Table H.3. Market share of technologies and fuel share in each technology in 2030.

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV
Share of fuels in percent							
Diesel fuel	*65*			*39*			
CNG/LNG		*80*					
Biofuel/Biogas	*15*	*10*		*9*			
PtL/PtG	*20*	*10*		*12*			
Electricity				*40*	*100*	*100*	
Hydrogen			*100*				*100*
Market share of technology EU40 [%]	76.5	9.2	1.8	0.1	1.6	2.0	8.8
Market share of technology EU55 [%]	66.3	9.2	1.8	0.1	2.2	2.9	17.4

Table H.4. Market share of technologies and fuel share in each technology in 2040.

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV
Share of fuels in percent							
Diesel fuel	*0*			*0*			
CNG/LNG		*0*					
Biofuel/Biogas	*15*	*15*		*6*			
PtL/PtG	*85*	*85*		*34*			
Electricity				*60*	*100*	*100*	
Hydrogen			*100*				*100*
Market share of technology in 2040 [%]	24.8	13.7	6.2	0.1	9.5	11.1	34.6

Most of the technologies mentioned above are not yet in operation, a year when the technology is available on the market was defined for each technology (Table H.5). The starting years are taken from (Heid et al., 2017) for BEV, from (Jöhrens et al., 2020) for OC-EV, and from (BDI, 2019) for PtL and PtG. For CE-G, PHEV, CE-H2 and FCEV we use own assumptions. The following table shows the implemented starting years.

Table H.5. Availability of technologies on the market.

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV	PtL+PtG
Transition start [y]		2022	2025	2022	2022	2028	2025	2025

Cost assumptions in the freight transport sector

We include two aspects for the cost development in the freight transport sector. On the one hand, costs of technologies and fuels are included, on the other hand costs for the required infrastructure to allow vehicles to come into operation. Furthermore, costs are also projected into the future for which a top-down method using extensive literature research has been used. We take the costs for Diesel as a benchmark in order to consider the change in costs for other combinations of technologies and fuels (incl. a battery weight for BEVs). References for each technology and fuels are explained below. According to (Blakemore, 2018), the fuel costs make 30% of total OPEX. Only for hydrogen and synthetic fuels (PtL, PtG) cost decreases in operation costs are assumed from 2018 to 2040 where all other components of technology-specific OPEX remain at the same level. For acquisition costs, we assume only reductions for BEV, OC-EV and FCEV.

CE-D

Diesel fuel

The acquisition costs (CAPEX) for CE-D are taken from different sources such as (Blakemore, 2018) and information from manufacturers. The operation costs (OPEX) are based on (Blakemore, 2018), (IEA, 2017) and (Mareev et al., 2018). The CAPEX and OPEX for Diesel in 2040 are assumed to be as high as in 2018.

Biofuel (biomass-fuel)

According to (US Department of Energy, 2020)costs for biofuel are 1.27 times higher than costs for diesel fuel.

PtL

In 2018, synthetic fuels are assumed to be 4.29 times higher than diesel fuel. Although a price digression until 2040 can be expected, synthetic fuels will remain more expensive than diesel fuel by a factor of around 1.8 ((Perner et al., 2018)).

CE-G

CNG/LNG

The CAPEX of CE-D has been taken as a basis to calculate the CAPEX of CE-G which is based on the findings in IEA (2017). The OPEX for CNG/LNG are assumed to be 0.8 times the OPEX of Diesel (IEA (2017); (US Department of Energy, 2020)). The same costs for CAPEX and OPEX are assumed in 2040.

Biogas

Here only fuel costs are different from the OPEX of CNG/LNG. These are assumed to be 1.11 times higher than for CNG/LNG ((US Department of Energy, 2020)). The same OPEX are assumed in 2040.

PtG

Same OPEX as for PtL ((Perner et al., 2018)).

CE-H2

The CAPEX are assumed to be as high as for CE-G and OPEX are assumed to be a mixture between OPEX from diesel and FCEV. Here, the OPEX without fuel costs are taken from CE-D and the fuel costs are taken from FCEV.

FCEV

The CAPEX of FCEV vehicles are taken from (Transport and Environment, 2020), (IEA, 2017) and (Moultak et al., 2017). The operation expenditures are slightly higher than those of CE-D, which is based on (IEA, 2017). According to (Transport and Environment, 2020) the OPEX are expected to decline by 29% in 2040 whereas the hydrogen fuel costs remain at the initial level. Here, a rather conservative estimate is used if compared with the findings of (Ruf et al., 2018), who project stronger declines in the operating expenditures of FCEV.

PHEV

Here, the capital expenditures are assumed to be 1.1 times higher than Diesel and no declines of CAPEX are assumed until 2040. Operation expenditures are assumed to be the same as for other fuels.

BEV

The acquisition costs are taken from T&E (2020) and (Moultak et al., 2017), where also the battery size is considered. Operation costs are assumed to be lower than for CE-D based on (Mareev and Sauer, 2018), (Mareev et al., 2018) and (Earl et al., 2018).

OC-EV

The acquisition costs are taken from IEA (2017) and combined with the assumption that these acquisition costs are slightly lower than for FCEVs. The OPEX are taken from (Mareev and Sauer, 2018) and (Mareev et al., 2018).

We distinguish different use cases to calculate the unit costs of the road freight transport sector. In the following table cost assumptions which are used as an input are shown as an aggregate of all these use cases for 2018, 2030 and 2040.

Table H.6. Cost parameters for vehicles in the road freight transport sector (2018).

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV
OPEX [EUR/tkm]	0.085	0.068	0.104	0.076	0.063	0.059	0.088
Components:							
Diesel fuel	*0.085*			*0.085*			
CNG/LNG		*0.068*					
Biofuel/Biogas	*0.092*	*0.071*		*0.092*			
PtL/PtG	*0.17*	*0.17*		*0.17*			
Electricity				*0.063*			
CAPEX [EUR]	87,741	106,023	106,023	109,676	181,766	134,318	163,342
Interest rate [%]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Economic life [y]	6	6	6	6	6	6	6

Notes:
CE-D … combustion engine diesel, CE-G … combustion engine gas, CE-H2 … combustion engine hydrogen, PHEV … plug-in hybrid electric vehicle, BEV … battery electric vehicle, OC-EV … overhead catenary electric vehicle, FCEV … Fuel-cell electric vehicle; CNG/LNG … compressed/liquid natural gas, PtL … power to liquid, PtG … power to gas.

Table H.7. Cost parameters for vehicles in the road freight transport sector (2030).

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV
OPEX [EUR/tkm]	0.096	0.075	0.104	0.083	0.063	0.059	0.084
Components:							
Diesel fuel	*0.085*			*0.085*			
CNG/LNG		*0.068*					
Biofuel/Biogas	*0.092*	*0.071*		*0.092*			
PtL/PtG	*0.135*	*0.135*		*0.135*			
Electricity				*0.063*			
CAPEX [EUR]	87,741	106,023	106,023	102,497	142,122	119,665	127,366
Interest rate [%]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Economic life [y]	6	6	6	6	6	6	6

Table H.8. Cost parameters for vehicles in the road freight transport sector (2040).

	CE-D	CE-G	CE-H2	PHEV	BEV	OC-EV	FCEV
OPEX [EUR/tkm]			0.104	0.079	0.063	0.059	0.08
Components:							
Diesel fuel	*0.087*			*0.087*			
CNG/LNG		*0.068*					
Biofuel/Biogas	*0.093*	*0.071*		*0.093*			
PtL/PtG	*0.106*	*0.106*		*0.106*			
Electricity				*0.063*			
CAPEX [EUR]	88,423	106,849	106,849	97,266	108,560	108,249	97,932
Interest rate [%]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Economic life [y]	6	6	6	6	6	6	6

Three types of infrastructure are required for a transition in the freight transport sector on the road, which are electric charging stations, hydrogen filling stations and overhead catenary.

Charging Stations

Charging stations comprise 80% ordinary stations with 50kW and 20% superchargers with 500kW. With a higher penetration of BEVs on the road, the use per charging station increases. As in 2018 the penetration is quite low, higher costs are assumed. For 2040 the penetration of BEVs is higher and the share of infrastructure costs declines when looking at unit-cost of driving. We investigate different use cases in the road freight transport sector, which allows to differentiate infrastructure costs regarding delivery, drayage and long-haul applications based on (Hall and Lutsey, 2019).

Hydrogen Filling Stations

The differentiation between Delivery, Drayage and Long-Haul is also made here. The costs in-between are linearly interpolated. The reference for this study is again (Hall and Lutsey, 2019).

Overhead Catenary

The infrastructure costs per km are assumed to be 2.2 million euros per km according to (Wietschel et al., 2019). The needed kilometers that have to be electrified by overhead catenary system is calculated by the assumptions of (Wietschel et al., 2019) and data from (VCÖ, 2018). Other studies assume comparable lower costs for overhead catenary and a lower range needed to be electrified (e.g. (Gnann, 2018) and (Hill et al., 2019)).

The following tables summarize the cost of infrastructure for 2018, 2030 and 2040.

Table H.9. Cost assumptions for infrastructure costs in the road freight transport sector in 2018.

	Electric Charging	H2-Filling Station	OC-Infrastructure
CAPEX [€/n; €/km (for OC-EV)]	61,538	3,564,103	2,200,000
Infrastructure required [n; km (for OC-EV)]	28	0	0
Interest rate [%]	2.0	2.0	2.0
Economic life [y]	15	15	20

Table H.10. Cost assumptions for infrastructure costs in the road freight transport sector in 2030.

	Electric charging	H2-filling station	OC- infrastructure
CAPEX [€/n; €/km (for OC-EV)]	50,035	3,494,527	2,200,000
EU40 – Infrastructure required [n; km (for OC-EV)]	2,331	264	211
EU55 – Infrastructure required [n; km (for OC-EV)]	3,692	471	211
Interest rate [%]	2.0	2.0	2.0
Economic life [y]	15	15	20

Table H.11. Cost assumptions for infrastructure costs in the road freight transport sector in 2040.

	Electric Charging	H2-Filling Station	OC-Infrastructure
CAPEX [€/n; €/km (for OC-EV)]	42,556	3,831,648	2,200,000
Infrastructure required [n; km (for OC-EV)]	10,339	734	422
Interest rate [%]	2.0	2.0	2.0
Economic life [y]	15	15	20

Appendix I. Material Use of Biomass

Biomass, especially wood-based biomass, plays a crucial role for achieving more stringent EU climate goals. The Austrian bio-economy strategy underlines the importance of biomass as a raw material to substitute fossil fuels energetically and for material use, including in industry and in the building sector as a construction material (BMNT et al., 2019). This is reasonable in a number of applications, depending on the available resources and the desired product features. Moreover, it is an enabler for a circular economy, as biomass provides high potential for recycling purposes and its usage in a cascading manner.

For the use of wood-based biomass for energy production a recent Joint Research Centre (JRC) study, (Camia et al., 2021), identifies trade-offs among climate mitigation strategies but also between climate mitigation and biodiversity conservation. This study concludes that a cascade use of wood and the prioritization of wood residues for energy use has to be pursued to increase a positive climate impact of wood-based bioenergy. A study by Braun et. al. (2016) examined scenarios for an increased use of biomass as a raw material in Austria, especially in the building sector and energetically (Braun et al., 2016). It was assumed, that demand for wood will increase about 20% for both energetic use and material use, respectively, from 2010-2100. They found that the emission reduction potential is significantly higher when wood is used in a cascading manner than directly for energy production. This effect even increases when simulating a longer time period.

Therefore, biomass is not only expected to have a share in a future renewable energy mix, its importance as a material feedstock in the buildings sector and industry sector will be substantial. However, increased competition for resources and land availability, considering particularly also the global scale, should be handled with care, as highlighted e.g. by European Commission (2019c), stating for this scale that "emissions from land-use and land-use change, mostly due to deforestation, are the second biggest cause of climate change after burning fossil fuels. They account for nearly 12% of all greenhouse gas emissions, and action in this area is important to fight climate change" (p.1).

Emissions accounting of biomass materials and products

Domestic forests serve as a natural CO_2 sink. As such, forests are indispensable to curb greenhouse gas concentrations in our atmosphere. This atmospheric-concentration-reducing effect needs to be preserved when biomass is used more intensively across the energy, building and industry sectors.

In this respect, when substituting conventional materials by biomass one has to be careful when accounting for the impacts of activities of the building and industry sector on the greenhouse gas concentration in the atmosphere. The reason is, that not the wood-based (construction) material itself has a CO_2 fixing effect but the forest from where the wood came from. This means, that the CO_2-fixing effect from the forest is transferred to the building or industry sector. Hence, when accounting for the emission-fixing effect of wood-based products, various parameters such as the origin of the wood (e.g. domestic, sustainable forest management) and rotation periods of harvesting are crucial. In terms of emissions accounting of wood-based products, when looking, for example, at the building sector, static approaches have long been present. Static approaches typically adopted either ignore the CO_2 uptake or account for it by estimating the carbon content of the wood and deriving the amount of CO_2 "fixed". Recent research advocates towards a dynamic modelling, where the temporal effect of a slow, gradual uptake in the forest is taken into account, along with other important aspects such as tree rotation period, see e.g. Hoxha et. al. (2020).The static approach is found to underestimate the actual contribution of (biomass-based) building components to increase atmospheric greenhouse gas concentrations ((Hoxha et al., 2020) use a global warming score) by at least 35% and up to 200%, with the single most relevant parameter governing the deviation relying on the rotation period of the forest, which is not considered in static approaches at all as the system boundary is limited to the product stage. When restricting the analysis to the product stage, most often even a negative emission contribution (a "sink") is

indicated, even though the actual overall impact of these building components based on wood may be clearly not negative, but connected to positive net emissions.

Furthermore, when looking at a national GHG balance, one has to be careful to not double-count the emission fixing effect of wood. The reason is that the effect of forests as a CO_2 sink is usually assigned to the emission sector "Land-Use, Land-Use Change and Forestry" (LULUCF). Hence, when presenting the emission-fixing effect of wood-based materials in the building and industry sectors, one must clarify whether those emissions already have been accounted for in the LULUCF or not, and accommodate results (and time periods they refer to) accordingly.

Status quo of biomass use

In Austria, the supply of fresh wood accumulated to 20.3 mio tons (air-dried) in 2017. From these, 65% came from domestic wood production whereas 35% were imported. Almost no fresh wood is exported (0.6 mio tons). In terms of usage, 60.1% were used as saw logs in the sawmill and other industries, 20.3% as industrial wood in the paper and pulp industry and the wood-based panels industry, 10.4% as firewood and 9.2% as wood chips. From that, only 20% (firewood and wood chips) were directly used for energy whereas 80% were applied as raw material and energetically in their final use at the end of the value chain (Österreichischer Biomasseverband, 2019).

In 2013, the fresh wood supply was lower than in 2017 at 19.5 mio tons (air-dried). Moreover, the shares for wood-based industries were also slightly different. 56% of fresh wood was used as saw logs, 22% as industrial wood, 13% as firewood and 9% as wood chips. Out of the above, the paper and pulp industry in total demanded 2.7 mio tons of industrial wood and a similar amount of wood in the form of by-products from sawmills in 2013 (BMLFUW, 2014).

Future developments

Based on the yearly wood growth in Austria, and today's wood consumption, the additional – beyond current use – domestic potential of fresh wood is estimated to amount to 1.8 mio tons per anno (Moser et al., 2018).

While a range of strategies are available to reduce emissions in both the building material and industrial sectors, and mixes of these tend to be part of societal best solutions, we here review (hypothetical) maximum material demands in both sectors, for cascadic use beyond energetic use at the end of the use cycle. In reducing embodied emissions in building materials both emission reduction in the production of current building materials as well as substitute materials of various types will contribute to climate neutrality. If, hypothetically, all building constructions would be mainly based on wood and construction activities were kept at their current levels, the related demand for wood is estimated to up to 2.3 million tons per year in Austria (proHolz, 2013).

Wood-based biomass could become important for the chemical industry when bioethanol (through catalytical dehydration) or synthesis gas (gasification of biomass) is produced. In (Windsperger and Windsperger, 2020), biomass demands for different decarbonization strategies of the chemical industry were estimated for Austria. All decarbonization routes are based on intensified recycling for the main raw material supply. Building on that a maximum demand of 4.8 mio. tons of biomass was estimated when switching fully to the bioethanol route in chemical industry. In comparison, in the gasification route, a maximum demand of 5.3 mio. tons of biomass would be required. Note that this only includes wood-based biomass but also could be substituted to a certain extent by crop-based biomass or from biomass waste. The study suggests a technology mix of intensified recycling, the use of hydrogen for methanol synthesis, the biomass gasification route and bioethanol route, assuming that 2/3 of the needed biomass is wood-based and 1/3 is crop-based. Under this technology mix – i.e. relying also on recycling and hydrogen – an amount of about 1.5 mio tons of wood-based biomass is needed for chemical industry use in Austria per anno. Without enforced recycling, biomass demand would be higher.

Abbreviations

Acronym	Description
ASI	Avoid, Shift, Improve
AUT	Austria
BAT	best available technologies
BEV	battery electric vehicles
BF	blast-furnace
BOP	basic oxygen process
CAP	chilled ammonia process
CAPEX	capital expenditure
CBA	carbon border adjustment
CC	carbon capture
CCU	carbon capture and use
CE-D	combustion engine diesel
CE-G	combustion engine gas
CE-H2	combustion engine hydrogen
CGE	computable general equilibrium
CHN	China
CHP	combined heat and power
CNG/LNG	compressed/liquid natural gas
DEU	Germany
DRI	direct reduction of iron ore
EAF	electric arc furnace
ETS	Emissions trading scheme
FCEV	fuel-cell electric vehicles
GDP	gross domestic product
GFA	gross floor area
GHG	greenhouse gas
HCVs	high-capacity vehicles
HD	heating demand
HVAC	heating, ventilation and air-conditioning
ICE	internal combustion engine
IMF	International Monetary Fund
ITA	Italy
kWh	kilowatt hour
lMFH	large multi-family housing
LULUCF	Land Use, Land Use Change and Forestry
MIT	motorized individual transport
MVHR	mechanical ventilation heat recovery
NAM	North America
n.e.s.	not elsewhere specified
NFA	net floor area
nZEBs	nearly zero energy buildings
OC-EV	overhead catenary electric vehicles
OIB	Österreichisches Institut für Bautechnik
PDSP	plasma direct steel production
PEM	proton exchange membrane
PtG	power to gas
PtL	power to liquid
PV	Photovoltaics
RCA	revealed comparative advantage

RD&D	Research, design and development
RES	renewable energy supply
REU	rest of Europe
ROW	rest of the world (in the context of the report: Non-EU regions)
RST	rest of the world (in the context of CGE modelling: all other regions)
RTA	revealed technological advantage
SCMs	supplementary cementitious materials
SFH	single family housing
SITC	Standard International Trade Classification
sMFH	small multi-family housing
SSP	Shared Socioeconomic Pathway
ZEV	zero-emission vehicles

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References

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The Environment and Directed Technical Change. Am. Econ. Rev. 102, 131–166. http://dx.doi=10.1257/aer.102.1.131

Aghion, P., Dechezleprêtre, A., Martin, R., Van Reenen, J., 2016. Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. J. Polit. Econ. 124, 1–51. https://doi.org/10.1086/684581

Aghion, P., Howitt, P., 2009. The economics of growth. MIT Press, Cambridge, MA.

Aguiar, A., Narayanan, B., McDougall, R., 2016. An Overview of the GTAP 9 Data Base. J. Glob. Econ. Anal. 1, 181–208. https://doi.org/10.21642/JGEA.010103AF

Amann, M., Holland, M., Maas, R., Saveyn, B., Vandyck, T., 2017. Costs, Benefits and Economic Impacts of the EU Clean Air Strategy and their Implications on Innovation and Competitiveness. IIASA.

Amann, W., Storch, A., Schneider, W., 2020. Definition und Messung der thermischenergetischen Sanierungsrate in Österreich. Institut für Immobilien, Bauen und Wohnen und Umweltbundesamt, Wien.

Amtmann, M., Barth, T., Mitterndorfer, M., Simader, G., 2011. Kosten-Nutzen-Analyse von Energetischen Gebäudesanierungen in Österreich. Austrian Energy Agency, Vienna.

Anderl, M., Gangl, M., Haider, S., Köther, T., Kuschel, V., Lampert, C., Mandl, N., Matthews, B., Pazdernik, K., Pinterits, M., Poupa, S., Purzner, M., Schieder, W., Schmid, C., Schmidt, G., Schodl, B., Schwaiger, E., Schwarzl, B., Titz, M., Weiss, P., Wieser, M., Zechmeister, A., 2021. Austria's Annual Greenhouse Gas Inventory 1990–2019: Submission under Regulation (EU) No 525/2013 (No. REP-0751). Umweltbundesamt, Wien.

Anderl, Michael, Gangl, M., Lampert, C., Perl, D., Poupa, S., Purzner, M., Storch, A., Barbara, Schodl., Titz, M., Zechmeister, A., 2020. Emissionstrends 1990-2018. Vienna.

Anderl, M., Geiger, K., Gugele, B., Gössl, M., Haider, S., Heller, C., 2019. Klimaschutzbericht 2019. Vienna.

Anderl, M., Geiger, K., Gugele, B., Gössl, M., Haider, S., Heller, C., Köther, T., Krutzler, T., Kuschel, V., Lampert, C., Neier, H., Pazdernik, K., Perl, D., Poupa, S., Purzner, M., Rigler, E., Schieder, W., Schmidt, G., Schodl, B., Storch, A., Stranner, G., Vogel, J., Wiesenberger, H., Zechmeister, A., 2020. Klimaschutzbericht 2020 (No. REP-0738). Umweltbundesamt, Wien.

Andrijevic, M., Schleussner, C.-F., Gidden, M.J., McCollum, D.L., Rogelj, J., 2020. COVID-19 recovery funds dwarf clean energy investment needs. Science 370, 298–300. https://doi.org/10.1126/science.abc9697

Armington, P.S., 1969. A Theory of Demand for Products Distinguished by Place of Production (Une theorie de la demande de produits differencies d'apres leur origine) (Una teoria de la demanda de productos distinguiendolos segun el lugar de produccion). Staff Pap. - Int. Monet. Fund 16, 159. https://doi.org/10.2307/3866403

ASI, 2009. ÖNORM B 1801-1: Bauprojekt- und Objektmanagement - Teil 1: Objekterrichtung.

Bachner, G., Mayer, J., Steininger, K.W., 2019. Costs or benefits? Assessing the economy-wide effects of the electricity sector's low carbon transition – The role of capital costs, divergent risk perceptions and premiums. Energy Strategy Rev. 26, 100373. https://doi.org/10.1016/j.esr.2019.100373

Bachner, G., Mayer, J., Steininger, K.W., Anger-Kraavi, A., Smith, A., Barker, T.S., 2020. Uncertainties in macroeconomic assessments of low-carbon transition pathways - The case of the European iron and steel industry. Ecol. Econ. 172, 106631. https://doi.org/10.1016/j.ecolecon.2020.106631

Bachner, G., Wolkinger, B., Mayer, J., Tuerk, A., Steininger, K.W., 2018. Risk assessment of the

low-carbon transition of Austria's steel and electricity sectors. Environ. Innov. Soc. Transit. in press. https://doi.org/10.1016/j.eist.2018.12.005

Badelt, C., 2021. Interview "Im Journal zu Gast." Mittagsjournal.

Bakker, S., Zuidgeest, M., Coninck, H. de, Huizenga, C., 2014. Transport, Development and Climate Change Mitigation: Towards an Integrated Approach. Transp. Rev. 34, 335–355. https://doi.org/10.1080/01441647.2014.903531

Balassa, B., 1965. Trade liberalisation and revealed comparative advantage. Manch. Sch. Econ. Soc. Stud. 33, 99–123.

Baranzini, A., Bergh, J.C.J.M. van den, Carattini, S., Howarth, R.B., Padilla, E., Roca, J., 2017. Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. WIREs Clim. Change 8, e462. https://doi.org/10.1002/wcc.462

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., Rahbar, S., 2018. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. J. Clean. Prod. 187, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Baumgartner, J., Hyll, W., Pitlik, H., Schiman, S., 2020a. Makroökonomische Effekte des zweiten Lockdown in Österreich (Research Brief No. 17/2020). Österreichisches Institut für Wirtschaftsforschung (WIFO), Wien.

Baumgartner, J., Kaniovski, S., Glocker, C., Hyll, W., Pitlik, H., 2020b. COVID-19-Pandemie dämpft die Konjunkturaussichten: Mittelfristige Prognose 2021 bis 2025 (Monatsberichte No. 10/2002). Österreichisches Institut für Wirtschaftsforschung (WIFO), Wien.

BDI, 2019. An Industry Roadmap for the Market Introduction of Renewable and Decarbonised Gases. BDI.

Beckman, J., Hertel, T., Tyner, W., 2011. Validating energy-oriented CGE models. Energy Econ. 33, 799–806. https://doi.org/10.1016/j.eneco.2011.01.005

Bellini, E., 2020. Abu Dhabi's 1.5 GW tender draws world record low solar bid of $0.0135/kWh. PV Mag. USA.

BINE Informationsdienst, 2017. Wirtschaftlichkeit energie-optimierter Gebäude – Berechnungsmethoden und Benchmarks für Wohnungsbau und Immobilienwirtschaft.

BKI, 2018a. BKI Baukosten 2018 Neubau – Statistische Kostenkennwerte für Gebäude. Baukosteninformationszentrum.

BKI, 2018b. BKI Baukosten 2018 Neubau – Statistische Kostenkennwerte für Bauelemente. Baukosteninformationszentrum.

Blakemore, T., 2018. Truck Operating Costs Report for 2018 [WWW Document]. TheTruckExpert. URL https://www.thetruckexpert.co.uk/truck-operating-costs-report-for-2018/ (accessed 12.14.20).

Bliem, M., Friedl, B., Balabanov, T., Zielinska, I., 2011. Energie [R]evolution Österreich 2050 (Endbericht). Institut für Höhere Studien, Vienna, Austria.

BMLFUW, 2014. Industrien der Holzverarbeitung - Produktion, Verarbeitung und Verwertung von Holz in Österreich.

BMNT, BMBWF, BMVIT, 2019. Bioökonomie: Eine Strategie Für Österreich. Wien.

BMNT und BMVIT, 2018. #mission2030: Die Österreichische Klima- und Energiestrategie. Wien.

BMVIT, 2016. Österreich unterwegs 2013/2014.

Bongardt, D., Stiller, L., Swart, A., Wagner, A., 2019. Sustainable Urban Transport: Avoid-Shift-Improve (A-S-I) (No. iNUA #9), New Uban Agenda Project. GIZ.

Bowen, T., Chemyakhovskiy, I., Denholm, P., 2019. Grid-Scale Battery Storage: Frequenty Asked Questions, Grid Integration Toolkit. National Renewable Energy Laboratory.

Braun, M., Fritz, D., Weiss, P., Braschel, N., Büchsenmeister, R., Freudenschuß, A., Gschwantner,

T., Jandl, R., Ledermann, T., Neumann, M., Pölz, W., Schadauer, K., Schmid, C., Schwarzbauer, P., Stern, T., 2016. A holistic assessment of greenhouse gas dynamics from forests to the effects of wood products use in Austria. Carbon Manag. 7, 271–283.

Bruninx, K., Ovaere, M., Gillingham, K., Delarue, E., 2019. The unintended consequences of the EU ETS cancellation policy (No. 96437), MPRA Paper, MPRA Paper. University Library of Munich, Germany.

Buergler, T., 2018. Green H2 opportunities in steelmaking.

Buergler, T., Prammer, J., 2019. Hydrogen Steelmaking: Technology Options and R&D Projects. BHM Berg- Hüttenmänn. Monatshefte 164, 447–451. https://doi.org/10.1007/s00501-019-00908-8

Bundeskanzleramt Österreich, 2020. Aus Verantwortung für Österreich: Regierungsprogramm 2020-2024. Wien.

Camia, A., Giuntoli, J., Jonsson, R., Robert, N., Cazzaniga, N.E., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, J.I., Mubareka, S., 2021. The use of woody biomass for energy production in the EU (No. EUR 30548 EN). Publications Office of the European Union, Luxembourg.

Capros, P., De Vita, A., Tasios, N., Papadopoulos, D., Siskos, P., Apostolaki, E., Zampara, M., Paroussos, L., Fragiadakis, K., Kouvaritakis, N., Höglund-Isaksson, L., Winiwarter, W., Purohit, P., Böttcher, H., Frank, S., Havlìk, P., Gusti, M., Witzke, H.P., 2013. EU Energy, Transport and GHG Emissions: Trends to 2050 - Reference Scenario 2013. European Commission DG Energy, Clima, and Mobility and Transport, Brussels, Belgium.

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Paroussos, L., Fragiadakis, K., Tsani, S., Fragkos, P., Kouvaritakis, N., Höglund-Isaksson, L., Winiwarter, W., Purohit, P., Gomez-Sanabria, A., Frank, S., Forsell, N., Gusti, M., Havlìk, P., Obersteiner, M., Witzke, H.P., Kesting, M., 2016. EU Reference Scenario 2016: Energy, transport and GHG emissions - Trends to 2050. European Commission DG Energy, Climate, and Mobility and Transport, Brussels, Belgium.

Cohen, S.A., Higham, J., Gössling, S., Peeters, P., Eijgelaar, E., 2016. Finding effective pathways to sustainable mobility: bridging the science–policy gap. J. Sustain. Tour. 24, 317–334. https://doi.org/10.1080/09669582.2015.1136637

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Change 8, 260–263. https://doi.org/10.1038/s41558-018-0121-1

Dai, H.-C., Zhang, H.-B., Wang, W.-T., 2017. The impacts of U.S. withdrawal from the Paris Agreement on the carbon emission space and mitigation cost of China, EU, and Japan under the constraints of the global carbon emission space. Adv. Clim. Change Res., Including special topic on U.S. withdraw from the Paris Agreement and its impacts 8, 226–234. https://doi.org/10.1016/j.accre.2017.09.003

Dalkmann, H., Brannigan, C., 2007. Transport and Climate change. Sustainable Transport: A Sourcebook for Policy-makers in Developing Cities (No. Module 5e). GTZ.

Dasgupta, P., 2021. The Economics of Biodiversity: The Dasgupta Review. HM Treasury, London.

de Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., Ahdour, S., 2018. Environmental Prices Handbook: EU28 Version. CE Delft. https://doi.org/18.7N54.125

Department for Transport, 2020. UK: Decarbonising Transport - Setting the Challenge.

Dobler, C., 2016. Theoretische Grundlagen von Prognosemodellen für die energetische

Stadtentwicklung angewandt auf das Beispiel Innsbruck (Master thesis). Universität Innsbruck, Unit Energy Efficient Buildings, Innsbruck.

Dornmayr, H., Rechberger, M., 2020. Fachkräftebedarf/-mangel in Österreich 2020 (IBW Research Brief No. 108). IBW.

Dorr, A., Seba, T., 2020. Rethinking Energy 2020-2030 (A RethinkX Sector Disruption Report).

Doyal, L., Gough, I., 1991. A theory of human need. Macmillan, Basingstoke.

Earl, T., Mathieu, L., Cornelis, S., Kenny, S., Ambel, C.C., Nix, J., 2018. Analysis of Long Haul Battery Electric Trucks in EU: Marketplace and Technology, Economic, Environmental, and Policy Perspectives. Transport and Environment.

Ebenbicher, R., Hertl, A., Streicher, W., Fischer, D., Richtfeld, C., Mailer, M., Anton, I., Hofmann, A., Pöham, C., Oblasser, S., 2018. Ressourcen- und Technologieeinsatz - Szenarien Tirol 2050 - Bericht. Innsbruck.

EEA, 2012. The contribution of transport to air quality. TERM 2012: transport indicators tracking progress towards environmental targets in Europe (EEA Report No. 10/2012). European Environment Agency.

ESTEP, 2020. Clean Steel Partnership roadmap. European Steel Technology Platform (ESTEP) AISBL.

EUROFER, 2019. Low Carbon Roadmap: Pathways to a CO2-neutral European steel industry. The European Steel Association.

European Commission, 2020a. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law), COM(2020) 80 final.

European Commission, 2020b. Amended proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law), COM(2020) 80 final.

European Commission, 2020c. IMPACT ASSESSMENT Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people. Brussels, European Commission SWD (2020) 176 final, COM(2020) 80 final.

European Commission, 2019a. Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011 (Text with EEA relevance.) (No. PE/6/2019/REV/1).

European Commission, 2019b. Council Regulation (EC) 2019/1242 of 20 June 2019 setting CO2-emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC.

European Commission, 2019c. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: Stepping up EU Action to Protect and Restore the World's Forests, {SWD(2019) 307 final}.

European Parliament, 2020. Amendments adopted by the European Parliament on 8 October 2020 on the proposal for a regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law).

Fairley, P., 2019. China's Ambitious Plan to Build the World's Biggest Supergrid. IEEE Spectrum.

Fankhauser, S., Bowen, A., Calel, R., Dechezleprêtre, A., Grover, D., Rydge, J., Sato, M., 2013. Who will win the green race? In search of environmental competitiveness and innovation. Glob. Environ. Change 23, 902–913. https://doi.org/10.1016/j.gloenvcha.2013.05.007

Feist, W., 2020. Passive House Planning Package (PHPP) [WWW Document]. Passive House Inst. URL https://passivehouse.com/04_phpp/04_phpp.htm (accessed 12.19.20).

GABC, 2019. 2019 global status report for buildings and construc-tion: Towards a zero-emission, efficient and resilient buildings and construction sector. Global Alliance for Buildings and Construction (GABC), International Energy Agency and the United Nations Development Programme.

Gardarsdottir, S.O., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., Pérez-Calvo, J.-F., Berstad, D., Fu, C., Anantharaman, R., Sutter, D., Gazzani, M., Mazzotti, M., Cinti, G., 2019. Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. Energies 12, 542. https://doi.org/10.3390/en12030542

Gass, V., Schmidt, J., Strauss, F., Schmid, E., 2013. Assessing the economic wind power potential in Austria. Energy Policy 53, 323–330. https://doi.org/10.1016/j.enpol.2012.10.079

Gerbert, P., Herhold, P., Burchardt, J., Schönberger, S., Rechenmacher, F., Kirchner, A., Kemmler, A., Wuensch, M., 2018. Climate Paths for Germany [WWW Document]. Boston Consult. Group Progn. Study Behalf Ger. Fed. Ind. URL https://www.bcg.com/publications/2018/climate-paths-for-germany-english (accessed 12.23.20).

Gerres, T., Chaves Ávila, J.P., Llamas, P.L., San Román, T.G., 2019. A review of cross-sector decarbonisation potentials in the European energy intensive industry. J. Clean. Prod. 210, 585–601. https://doi.org/10.1016/j.jclepro.2018.11.036

Geyer, R., Knötter, S., Diendorfer, C., Drexler-Schmid, G., 2019. IndustRiES, Energieinfrastruktur für 100% Erneuerbare Energie in der Industrie. Austrian Institute of Technology.

Givoni, M., 2014. Addressing transport policy challenges through Policy-Packaging. Transp. Res. Part Policy Pract. 60, 1–8. https://doi.org/10.1016/j.tra.2013.10.012

Gnann, T., 2018. Technologiebericht 7.2 Eloktromobilität - Hybrid-Oberleitungs-LKW (energiewirtschaftliche Aspekte). Fraunhofer.

Government of Ireland, 2019. Climate Action Plan 2019 To Tackle Climate Breakdown. Department of Communications, Climate Action and Environment.

Grossmann, W., Grossmann, I., Steininger, K.W., 2015. Solar electricity supply isolines of generation capacity and storage. Proc. Natl. Acad. Sci. 112, 3663–3668. https://doi.org/10.1073/pnas.1316781112

Grossmann, W.D., Grossmann, I., Steininger, K.W., 2014. Solar electricity generation across large geographic areas, Part II: A Pan-American energy system based on solar. Renew. Sustain. Energy Rev. 32, 983–993. https://doi.org/10.1016/j.rser.2014.01.003

Grossmann, W.D., Grossmann, I., Steininger, K.W., 2013. Distributed solar electricity generation across large geographic areas, Part I: A method to optimize site selection, generation and storage. Renew. Sustain. Energy Rev. 25, 831–843. https://doi.org/10.1016/j.rser.2012.08.018

Haas, R., Molitor, R., Ajanovic, A., Brezina, T., Hartner, M., Hirschler, P., Kalt, G., Kettner, C., Kranzl, L., Kreuzinger, N., Macoun, T., Paula, M., Resch, G., Steininger, K., Türk, A., Zech, S., 2014. Energie und Verkehr, in: Österreichischer Sachstandsbericht 2014 (AAR14). Austrian Panel on Climate Change (APCC), Verlag der Österreichischen Akademie der Wissenschaften, Vienna, Austria, pp. 857–932.

Haas, R., Redl, C., 2009. Langfristige Szenarien der gesellschaftlich optimalen Stromversorgung der Zukunft (Berichte aus Energie- und Umweltforschung No. 58/2009). Bundesministerium für Verkehr, Innovation und Technologie, Vienna, Austria.

Haas, R., Resch, G., Burgholzer, B., Totschnig, G., Lettner, G., Auer, H., Geipel, J., 2017. Stromzukunft Österreich 2030 - Analyse der Erfordernisse und Konsequenzen eines ambitionierten Ausbaus erneuerbarer Energien. Technische Universität Wien (TU Wien), Energy Economics Group, Vienna, Austria.

Habert, G., Miller, S.A., John, V.M., Provis, J.L., Favier, A., Horvath, A., Scrivener, K.L., 2020. Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat. Rev. Earth Environ. 1, 559–573. https://doi.org/10.1038/s43017-020-0093-3

Hall, D., Lutsey, N., 2019. Estimating the Infrastructure Needs and Costs for the Launch of Zero-Emission Trucks. ICCT.

Heid, B., Hensley, R., Knupfer, S., Tschiesner, A., 2017. What's Sparking Electric Vehicle Adoption in the Truck Industry. McKinsey center for future mobility.

Heinfellner, H., Ibesich, N., Lichtblau, G., Stranner, G., Svehla-Stix, S., Vogel, J., Wedler, M., Winter, R., 2018. Sachstandsbericht Mobilität und Mögliche Zielpfade zur Erreichung der Klimaziele 2050 mit dem Zwischenziel 2030 (No. REP-0667). Umweltbundesamt and BMVIT, Vienna.

Hill, N., Hilton, G., Morgan-Price, S., Weldon, P., 2019. Zero Emission HGV Infrastructure Requirements. Ricardo Energy&Environment.

Hills, T., Leeson, D., Florin, N., Fennell, P., 2016. Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting. Environ. Sci. Technol. 50, 368–377. https://doi.org/10.1021/acs.est.5b03508

Höltinger, S., Salak, B., Schauppenlehner, T., Scherhaufer, P., Schmidt, J., 2016. Austria's wind energy potential – A participatory modeling approach to assess socio-political and market acceptance. Energy Policy 98, 49–61. https://doi.org/10.1016/j.enpol.2016.08.010

Holzer, P., 2020. Nichtfossile Alternativen zu Gas-Etagenheizungen in Bestandbauten. klimaaktiv webinar.

Hoxha, E., Passer, A., Saade, M.R.M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Build. Cities 1, 504–524. https://doi.org/10.5334/bc.46

IEA, 2020. Evolution of Li-ion battery price, 1995-2019. IEA, Paris.

IEA, 2018. World Energy Outlook 2018. Inernational Energy Agency.

IEA, 2017. The Future of Trucks: Implications for energy and the environment (No. Second edition). International Energy Agency.

IHS, 2020. Prognose der österreichischen Wirtschaft 2020-2021. Institut für Höhere Studien, Wien.

International Monetary Fund, 2020. World Economic Outlook: A Long and Difficult Ascent. Washington, D.C.

IPCC, 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, in: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), . World Meteorlogical Organisation, Geneva, Switzerland.

IRENA, 2019. Renewable Power Generation Costs in 2018. (No. 978-92-9260-126–3). IRENA - International Renewable Energy Agency.

Islam, D., Ricci, S., Nelldal, B.-L., 2016. How to make modal shift from road to rail possible in the European transport market, as aspired to in the EU Transport White Paper 2011. Eur. Transp. Res. Rev. 8. https://doi.org/10.1007/s12544-016-0204-x

Jarke-Neuert, J., Perino, G., 2020. Energy efficiency promotion backfires under cap-and-trade.

Resour. Energy Econ. 62, 101189. https://doi.org/10.1016/j.reseneeco.2020.101189

Jarke-Neuert, J., Perino, G., 2019. Understanding Sector Coupling: The General Equilibrium Emissions Effects of Electro-Technology and Renewables Deployment (SSRN Scholarly Paper No. ID 3326407). Social Science Research Network, Rochester, NY. https://doi.org/10.2139/ssrn.3326407

Jöhrens, J., Helms, H., Beckers, T., Frischmuth, F., Gerhardt, N., 2020. Roadmap für die Einführung eines Oberleitungs-Lkw-Systems in Deutschland. ifeu - institut für Energie- und Umweltforschung Heidelberg.

Kalt, G., Baumann, M., Lauk, C., Kastner, T., Kranzl, L., Schipfer, F., Lexer, M., Rammer, W., Schaumberger, A., Schriefl, E., 2016. Transformation scenarios towards a low-carbon bioeconomy in Austria. Energy Strategy Rev. 13–14, 125–133. https://doi.org/10.1016/j.esr.2016.09.004

Kaltschmitt, M., Streicher, W. (Eds.), 2009. Regenerative Energien in Österreich: Grundlagen, Systemtechnik, Umweltaspekte, Kostenanalysen, Potenziale, Nutzung. Vieweg+Teubner, Wiesbaden.

Karlsson, M., Alfredsson, E., Westling, N., 2020. Climate policy co-benefits: a review. Clim. Policy 20, 292–316. https://doi.org/10.1080/14693062.2020.1724070

Kc, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Change 42, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Kemfert, C., Jacobson, M.Z., 2020. Mediocrity is the Enemy of the Solution [WWW Document]. Clean Tech. URL https://cleantechnica.com/2020/12/16/mediocrity-is-the-enemy-of-the-solution/

Kent, J., Dowling, R., Maalsen, S., 2017. Catalysts for transport transitions: Bridging the gap between disruptions and change. J. Transp. Geogr. 60, 200–207. https://doi.org/10.1016/j.jtrangeo.2017.03.013

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., Stern, N., 2018. Making carbon pricing work for citizens. Nat. Clim. Change 8, 669–677. https://doi.org/10.1038/s41558-018-0201-2

Kolbitsch, A., Stalflenhardt, M.L., Kropik, A., Prestros, L., 2008. Studie über Wirtschaftlichkeitsparameter und einen ökonomischen Planungsfaktor für geförderte Wohnbauprojekte in Wien.

Köppl, A., Kettner, C., Kletzan-Slamanig, D., Schleicher, S., Schnitzer, H., Titz, M., Damm, A., Steininger, K.W., Wolkinger, B., Lang, R., Wallner, G., Artner, H., Karner, A., 2011. EnergyTransition 2012\2020\2050: Strategies for the Transition to Low Energy and Low Emission Structures. Österreichisches Institut für Wirtschaftsforschung (WIFO).

Köppl, A., Schleicher, S., Schratzenstaller, M., Steininger, K.W., 2020. COVID-19, Klimawandel und Konjunkturpakete (Research Brief No. 1/2020). Österreichisches Institut für Wirtschaftsforschung (WIFO), Wien.

KPMG, 2020. Austria - Government and institution measures in response to COVID-19 [WWW Document]. KPMG. URL https://home.kpmg/xx/en/home/insights/2020/04/austria-government-and-institution-measures-in-response-to-covid.html (accessed 11.6.20).

Kreyenberg, D., 2016. Fahrzeugantriebe für die Elektromobilität. Springer.

Krutzler, T., Kellner, M., Gallauner, T., Gössl, M., Heller, C., Wiesenberger, H., Lichtblau, G., Schindler, I., Stoiber, H., Storch, A., Stranner, G., Winter, R., Zechmeister, A., 2015. Energiewirtschaftliche Szenarien im Hinblick auf die Klimaziele 2030 und 2050 Synthesebericht 2015. Umweltbundesamt, Wien.

Kynge, J., Hornby, L., 2018. Truly Wielding Power: How China Wants to Create the World's First Global Electricity Grid - OZY | A Modern Media Company [WWW Document]. OZY. URL https://www.ozy.com/around-the-world/truly-wielding-power-how-china-wants-to-

create-the-worlds-first-global-electricity-grid/87270/ (accessed 11.10.20).
Lamb, W.F., Steinberger, J.K., 2017. Human well-being and climate change mitigation. WIREs Clim. Change 8, e485. https://doi.org/10.1002/wcc.485
Lenz, B., Schreiber, J., Stark, T., 2010. Nachhaltige Gebäudetechnik-Grundlagen-Systeme-Konzepte.
Lofgren, H., Harris, R.L., Robinson, S., 2002. A standard computable general equilibrium (CGE) model in GAMS. International Food Policy Research Institute, Washington, D.C.
Maier, R.H., Posch, A., Proß, C., 2020. Total Social Costs of Mobility.
Maisch, M., 2020. Federal government awards major project status to Sun Cable's 10 GW solar plan. PV-Mag.
Mareev, I., Becker, J., Sauer, D.U., 2018. Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation. Energies 11.
Mareev, I., Sauer, D.U., 2018. Energy Consumption and Life Cycle Costs of Overhead Catenary Heavy-Duty Trucks for Long-Haul Transportation. Energies 11.
Matthey, A., Bünger, B., 2019. Methodenkonvention 3.0 zur Ermittlung von Umweltkosten: Kostensätze. Dessau-Roßlau.
Mauschitz, G., 2020. Emissionen aus Anlagen der österreichischen Zementindustrie Berichtsjahr 2019. Institut für Verfahrenstechnik, Umwelttechnik und Technicsche Biowissenschaften, Technische Universität Wien, Wien.
Max-Neef, M.A., Elizalde, A., Hopenhayn, M., 1991. Human Scale Development: Conception, Application and Further Reflections. Apex Press, University of California.
Mayer, J., Bachner, G., Steininger, K.W., 2019. Macroeconomic implications of switching to process-emission-free iron and steel production in Europe. J. Clean. Prod. 210, 1517–1533. https://doi.org/10.1016/j.jclepro.2018.11.118
Mayer, J.N., Philipps, S., Hussein, N.S., Schlegl, T., Senkpiel, C., 2015. Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study on behalf of Agora Energiewende. (No. 059/01-S-2015/EN). Fraunhofer ISE.
Mazengarb, M., 2019. Cannon-Brookes says $20bn solar project will be "lighthouse" to world | RenewEconomy [WWW Document]. Renew Econ. URL https://reneweconomy.com.au/cannon-brookes-says-20bn-solar-project-will-be-lighthouse-to-world-54180/ (accessed 11.10.20).
Meade, J.E., 1937. An Introduction to Economic Analysis and Policy, Second. ed. Oxford University Press, London.
Ministry for the Environment, 2018. The co-benefits of emissions reduction: An analysis. Wellington.
Ministry of the Environment, 2019. Sweden: Inquiry appointed on phasing out fossil fuels and banning sales of new petrol and diesel cars.
Moser, S., Goers, S., de Bruyn, K., Steinmüller, H., Hofmann, R., Panuschka, S., Kienberger, T., Sejkora, C., Haider, M., Werner, A., Brunner, C., Fluch, J., Grubbauer, A., 2018. Endberichtsteil 2 von 3: Diskussionspapier zum Projekt Renewables4Industry. Klima- und Energiefonds, Vienna, Austria.
Moultak, M., Lutsey, N., Hall, D., 2017. Transition to Zero-Emission Heavy-Duty Freight Vehicles. ICCT The international council on clean transportation.
Netherlands Institute for Sustainable Packaging, 2018. Chemical recycling of plastic packaging materials - Analysis and opportunities for upscaling.
Nijs, W., Castelló, P.R., González, I.H., 2018. Baseline scenario of the total energy system up to 2050: Business-as-usual reference scenarios (No. D5.2). Heat Roadmap Europe Project, Netherlands.

Norwegian Ministry of Climate and Environment, 2019. Norway's National Plan.
Nussbaum, M.C., 2000. Women and Human Development: The Capabilities Approach, The Seeley Lectures. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511841286
Ochs, F., Siegele, D., Jähnig, D., Rohringer, C., Calabrese, T., Pfluger, R., Fink, C., 2020. SaLüH! Sanierung von Mehrfamilienhäusern mit kleinen Wohnungen - Kostengünstige technische Lösungsansätze für Lüftung, Heizung und Warmwasser.
OECD, 2020. Patents in environment-related techologies. OECD Environment Statistics, (database).
OECD, 2016. Patent search strategies for the identification of selected environment-related technologies (ENV-TECH).
OECD, 2013. OECD Science, Technology and Industry Scoreboard 2013: Innovation for Growth (Text). OECD Publishing.
OIB, 2018. Kostenoptimalität der Anforderungen der OIB-RL 6 bzw. des Nationalen Plans gemäß Artikel 5 zu 2010/31/EU (No. OIB-330.6-005/18-001).
ÖKEVG 2019, 2020. Ölkesseleinbauverbotsgesetz.
OLD, R., 2020. Proposed $16B project combines world's largest PV farm, largest battery, longest undersea HVDC cable [WWW Document]. Pv Mag. URL https://pv-magazine-usa.com/2020/11/05/proposed-16b-project-combines-worlds-largest-pv-farm-largest-battery-longest-undersea-hvdc-cable/ (accessed 11.10.20).
O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004
ÖNORM, 2008. EN ISO 13790:2008 10 01 Energieeffizienz von Gebäuden - Berechnung des Energiebedarfs für Heizung und Kühlung.
Österreichischer Biomasseverband, 2019. Bioenergie - Basisdaten 2019.
Österreichischer Biomasseverband, n.d. Bioenergie in Österreich. Bedeut. Bioenergie. URL https://www.biomasseverband.at/bedeutung-der-bioenergie/ (accessed 12.3.20).
Österreichisches Institut für Bautechnik, 2019. OIB-Richtlinie 6, Energieeinsparung und Wärmeschutz (No. OIB-330.6-026/19).
Österreichisches Institut für Wirtschaftsforschung, 2008. Energieeffiziente Gebäude Potentiale und Effekte von emissionsreduzierenden Maßnahmen.
Paardekooper, S., Lund, R.S., Mathiesen, B.V., Chang, M., Peterson, U.R., Grundahl, L., David, A., Dahlbaek, J., Kapetanakis, I.A., Lund, H., Bertelsen, N., Hansen, K., Drysdale, D.W., Persson, U., 2018. Heat Roadmap Austria: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Aalbord University, Denmark.
Passive House Institute, 2020. PHPP Tool [WWW Document]. URL https://passiv.de/ (accessed 11.10.20).
Perez, C., 2016. 11. Capitalism, Technology and a Green Global Golden Age: The Role of History in Helping to Shape the Future. Polit. Q. 86, 191–217. https://doi.org/10.1111/1467-923X.12240
Perino, G., 2019. Reply: EU ETS and the waterbed effect. Nat. Clim. Change 9, 736–736. https://doi.org/10.1038/s41558-019-0580-z
Perino, G., Pioch, T., 2017. Banning incandescent light bulbs in the shadow of the EU Emissions Trading Scheme. Clim. Policy 17, 678–686. https://doi.org/10.1080/14693062.2016.1164657
Perino, G., Ritz, R., Bentham, A. v., 2020. Overlapping Climate Policies (CEPR Discussion Paper No. DP 13569).

Perner, J., Unteutsch, M., Lövenich, A., 2018. The Future Cost of Electricity-Based Synthetic Fuels. agora Energiewende, agora Verkehrswende.

Peters, J.C., 2016. The GTAP-Power Data Base: Disaggregating the Electricity Sector in the GTAP Data Base. J. Glob. Econ. Anal. 1, 209–250. https://doi.org/10.21642/JGEA.010104AF

Pfeifer, D., 2017. Entwicklung, Untersuchung und Bewertung von Berechnungsmodellen zur Erstellung von kommunalen Energiebilanzen im Gebäudebereich (PhD thesis). University of Innsbruck, Innsbruck.

Pigou, A.C., 1920. The Economics of Welfare. Macmillan, London.

Pleßmann, G., Blechinger, P., 2017. How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050. Energy Strategy Rev. 15, 19–32. https://doi.org/10.1016/j.esr.2016.11.003

Plötz, P., Gnann, T., Wietschel, M., Kluschke, P., Doll, C., Hacker, F., Blanck, R., Kühnel, S., Jöhrens, J., Helms, H., Lambrecht, U., Dünnebeil, F., 2018. Alternative Antriebe und Kraftstoffe im Strassengüterverkehr - Handlungsempfehlungen für Deutschland. Fraunhofer ISI, Karlsruhe, Berlin, Heidelberg.

Poledna, S., Rovenskaya, E., Cuaresma, J.C., Kaniovski, S., Miess, M., 2020. Recovery of the Austrian economy following the COVID-19 crisis can take up to three years (No. IIASA Policy Brief #26). International Institute for Applied Systems Analysis, Laxenburg.

proHolz, 2013. Bauen mit Holz im Ökovergleich: Klimaschutz durch Gebäude aus Holz (No. Edition 12). proHolz Austria.

Ragacs, C., Schneider, M., Vondra, K., 2020. Economic Outlook for Austria from 2020 to 2022: COVID-19-induced recession: biggest economic policy challenge for Austria in the "Second Republic." Oesterreichische Nationalbank, Wien.

Rail Freight Forward, 2019. 30 by 2030: Rail Freight strategy to modal shift. Rail Freight Forward Coalition.

Rapier, R., 2020. Proposed $16B project combines world's largest PV farm, largest battery, longest undersea HVDC cable. PV-Mag.

RenewEconomy, 2020. UK climate body lays out economy-boosting plan to reach net zero emissions. RenewEconomy. URL https://reneweconomy.com.au/uk-climate-body-lays-out-economy-boosting-plan-to-reach-net-zero-emissions-38163/ (accessed 12.11.20).

Ritchie, H., Roser, M., 2020. Austria: CO2 Country Profile [WWW Document]. URL https://ourworldindata.org/co2/country/austria?country=~AUT (accessed 11.6.20).

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S.I., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol. Soc. 14. https://doi.org/10.5751/ES-03180-140232

Roland Berger, 2020. The future of steelmaking - How the European steel industry can achieve carbon neutrality (Focus No. 05.2020).

Ruf, Y., Lange, S., Pfister, J., Droege, C., 2018. Fuel Cells and Hydrogen for Green Energy in European Cities and Regions. Roland Berger.

Scheucher, R., 2014. Wettbewerd im österreichischen Güterverkehrsmarkt: Konstellationen zwischen Straße und Schiene (No. 51), Verkehr und Infrastruktur. Kammer für Arbeiter und Angestellte für Wien, Vienna.

Schiman, S., 2021. Compensation of High Economic Losses. Economic Outlook for 2020 to 2022. Österreichisches Institut für Wirtschaftsforschung (WIFO), Wien.

Schiman, S., 2020. Economic Outlook for 2020 and 2021: Subdued Recovery After Strong Rebound (Press release). Österreichisches Institut für Wirtschaftsforschung (WIFO), Wien.

Schinko, T., Bednar-Friedl, B., Steininger, K.W., Grossmann, W.D., 2014. Switching to carbon-free production processes: Implications for carbon leakage and border carbon adjustment. Energy Policy 67, 818–831.

Schleicher, S., Köppel, A., Lienin, S., Treberspurg, M., Österreicher, R., Grünner, R., Lang, R., Mühlberger, M., Steininger, K., Hofer, C., 2018. Welche Zukunft für Energie und Klima? Folgenabschätzungen für Energie- und Klimastrategien. Die Aussagen. Österreichisches Institut für Wirtschaftsforschung (WIFO).

Schleicher, S., Steininger, K., 2018. Dekarbonisierung und Carbon Management für Österreich: Diskussionsbeiträge für Strategien (Research Brief No. 79–2018). Wegener Center Verlag, Graz, Austria.

Schleicher, S.P., Steininger, K.W., 2017. Wirtschaft stärken und Klimaziele erreichen: Wege zu einem nahezu treibhausgasemissionsfreien Österreich (Research Brief No. 73–2017). Wegener Center Verlag, Graz, Austria.

Schneider, H.W., Pöchhacker-Tröscher, G., Demirol, D., Luptácik, P., Wagner, K., 2020. Österreichische Umwelttechnik-Wirtschaft - Export, Innovation, Startups und Förderungen. Aktuelle Entwicklungen inkl. Corona-Krisenbetrachtung 2020 (Nachhaltig Wirtschaften 41/2020). Studie im Auftrag von BMK, BMDW und WKÖ.

Schneider, M., 2019. The cement industry on the way to a low-carbon future. Cem. Concr. Res. 124, 105792. https://doi.org/10.1016/j.cemconres.2019.105792

Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., von Hirschhausen, C., 2013. Current and prospective costs of electricity generation until 2050 (No. DIW Data Documentation No. 68. Research Report.).

Schumpeter, J.A., 1934. The theory of economic development, reprinted 1961. ed. Oxford University Press, London.

Secretary of State for the Digital Economy (France), 2019. LOI no 2019-1428 du 24 décembre 2019 d'orientation des mobilités (1). JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE.

Sen, A., 1999. Development as Freedom. Oxford University Press.

Shiva Kumar, S., Himabindu, V., 2019. Hydrogen production by PEM water electrolysis – A review. Mater. Sci. Energy Technol. 2, 442–454. https://doi.org/10.1016/j.mset.2019.03.002

Simoes, S., Zeyringer, M., Mayr, D., Huld, T., Nijs, W., Schmidt, J., 2017. Impact of different levels of geographical disaggregation of wind and PV electricity generation in large energy system models: A case study for Austria. Renew. Energy 105, 183–198. https://doi.org/10.1016/j.renene.2016.12.020

Smith, A., 1776. An inquiry into the Nature and Causes of the Wealth of Nations.

Smyth, J., 2020. Australia aims to become renewable energy export superpower. Financ. Times.

Sölkner, P.J., Oberhuber, A., Spaun, S., Preininger, R., Dolezal, F., Mötzl, H., Passer, A., Fischer, G., 2014. Innovative Gebäudekonzepte im ökologischen und ökonomischen Vergleich über den Lebenszyklus (No. 51/2014). Bundesministerium für Verkehr, Innovation und Technologie.

SSAB, LKAB, Vattenfall, 2021. Hybrit - Fossil-free steel [WWW Document]. Hybrit. URL https://www.hybritdevelopment.se/en/ (accessed 3.2.21).

SSAB, LKAB, Vattenfall, 2017. Summary of findings from HYBRIT Pre-Feasibility Study 2016–2017. HYBRIT - Fossil-free steel.

Statistik Austria, 2019a. Modal Split – Güterverkehr [WWW Document]. URL https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/verkehr/modal_split_gueterverkehr/107347.html (accessed 10.23.20).

Statistik Austria, 2019b. Nutzenergieanalyse für Österreich 1993-2018.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R.,

Carpenter, S.R., Vries, W. de, Wit, C.A. de, Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347. https://doi.org/10.1126/science.1259855

Steininger, K.W., Bednar-Friedl, B., Knittel, N., Kirchengast, G., Nabernegg, S., Williges, K., Mestel, R., Hutter, H.-P., Kenner, L., 2020a. Klimapolitik in Österreich: Innovationschance Coronakrise und die Kosten des Nicht-Handelns (Wegener Center Research Briefs No. 1–2020). Wegener Center Verlag, Universität Graz, Graz, Austria.

Steininger, K.W., Meyer, L.H., Schleicher, S., Riahi, K., Williges, K., Maczek, F., 2020b. Effort Sharing among EU Member States: Green Deal Emission Reduction Targets for 2030 (Research Brief No. 2–2020). Wegener Center Verlag, University of Graz, Austria, Short Version, October 2020.

Stern, N., 2015. Why are we waiting? The logic, urgency and promise of tackling climate change, Lionel Robbins Lectures. MIT Press, USA.

Streicher, W., Schnitzer, H., Titz, M., Tatzber, F., Heimrath, R., Wetz, I., Hausberger, S., Haas, R., Kalt, G., Damm, A., Steininger, K., Oblasser, S., 2010. Energieautarkie für Österreich 2050: Feasibility Study. Kommunal Kredit Public Consulting.

Sunikka-Blank, M., Galvin, R., 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. Build. Res. Inf. 40, 260–273. https://doi.org/10.1080/09613218.2012.690952

Sylvia, T., 2020. Solar-plus storage replaces coal plant in New Mexico, makes carbon-capture retrofit moot. PV Mag.

TABULA WebTool [WWW Document], 2020. URL http://webtool.building-typology.eu/#bm (accessed 11.10.20).

Teter, J., 2018. The future of trucks: Implications for energy & the environment.

Thaller, A., Posch, A., Dugan, A., Steininger, K.W., 2020. How to design policy packages for sustainable transport: balancing disruptiveness and implementability. revised resubmission upon invitation, under review.

TRAFICO, IVWL Uni Graz, IVT ETH Zürich, PANMOBILE, Joanneum Research, WIFO, 2009. Verkehrtsprognose Österreich 2025+ Endbericht: Güterverkehr Ergebnisse. Bundesministerium für Verkehr, Innovation und Technologie.

Transport and Environment, 2020. Comparison of Hydrogen and Battery Electric Trucks. Transport and Environment.

Umweltbundesamt, 2021. Umweltbundesamt: Treibhausgas-Bilanz Österreichs 2019 [WWW Document]. APA-OTS Press. URL https://www.ots.at/presseaussendung/OTS_20210119_OTS0020/umweltbundesamt-treibhausgas-bilanz-oesterreichs-2019 (accessed 3.2.21).

UNFCCC, 2015. Adoption of the Paris Agreement (No. FCCC/CP/2015/L.9/Rev. 1).

United Nations, 1994. United Nations Convention to Combat Desertification in those countries experiencing serious drought and/or desertification, particularly in Africa. Paris, France.

United Nations, 1992. United Nations Framework Convention on Climate Change, in: Conference on Environment and Development. Rio, Brazil.

United Nations General Assembly, 2015. Transforming our world: The 2030 agenda for sustainable development. New York.

US Department of Energy, 2020. Alternative Fuel Price Report [WWW Document]. Altern. Fuels Data Cent. Fuels Prices. URL https://afdc.energy.gov/fuels/prices.html (accessed 12.16.20).

van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., Brambilla, M., Fiorello, D., Fermi, F., Parolin, R., Beyrouty, K.E., 2019. Handbook on the external costs of transport: Version 2019. European Commission, Brussels. https://doi.org/10.2832/27212

VCÖ, 2018. Lkw-Verkehr auf Österreichs Autobahnen heuer massiv gestiegen [WWW Document]. VCÖ Mobil. Mit Zuk. URL https://www.vcoe.at/presse/presseaussendungen/detail/20181221-lkw-verkehr-autobahnen (accessed 12.16.20).

VFF, BF, 2011. Mehr Energie sparen mit neuen Fenstern. Verband Fenster + Fassade und dem Bundesverband Flachglas.

Vollebergh, H.R.J., van der Werf, E., Vogel, J., submitted. Designing instrument packages for the low-carbon transition: An evaluation framework with an application to the building sector in Austria.

Vorrath, S., 2020. Faster, smarter, cheaper: Batteries are beating gas peakers at their own game. Renew Economy.

Wiese, C., Cowart, R., Rosenow, J., 2020. The strategic use of auctioning revenues to foster energy efficiency: status quo and potential within the European Union Emissions Trading System. Energy Effic. https://doi.org/10.1007/s12053-020-09894-0

Wietschel, M., Gnann, T., Plötz, P., Doll, C., 2019. Electric Trolley Trucks—A Techno-Economic Assessment for Germany. World Electr. Veh. J. 10.

Windsperger, A., Schick, M., Windsperger, B., 2018. Perspektiven der Decarbonisierung für die chemische Industrie in Österreich.

Windsperger, A., Windsperger, B., 2020. Die chemische Industrie auf dem Weg zur Klimaneutralität 2040.

WKO, Industriellenvereinigung, Austrian Energy Agency, AIT, 2019. Im Wettbewerb um die Zukunft - Klimapolitische Perspektiven für den Beitrag der österreichischen Industrie zur Treibhausgasneutralität. Wien.

Wolkinger, B., Haas, W., Bachner, G., Weisz, U., Steininger, K., Hutter, H.P., Delcour, J., Griebler, R., Mittelbach, B., Maier, P., Reifeltshammer, R., 2018. Evaluating health co-benefits of climate change mitigation in urban mobility. Int. J. Environ. Res. Public. Health. https://doi.org/10.3390/ijerph15050880

Wolkinger, B., Steininger, K.W., Damm, A., Schleicher, S., Tuerk, A., Grossman, W., Tatzber, F., Steiner, D., 2012. Implementing Europe's climate targets at the regional level. Clim. Policy 12, 667–689. https://doi.org/10.1080/14693062.2012.669096

World Bank, 2020. State and Trends of Carbon Pricing 2020. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/33809 License: CC BY 3.0 IGO.

World Bank, 2019. Gross savings (% of GDP) | Data [WWW Document]. URL https://data.worldbank.org/indicator/NY.GNS.ICTR.ZS (accessed 5.29.20).

Zheng, J., Suh, S., 2019. Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Change 9, 374–378. https://doi.org/10.1038/s41558-019-0459-z

Abstract:

The European Union increased its 2030 climate ambition to at least 55% greenhouse gas emissions reduction (relative to 1990). The split up across Member States in effort sharing is still pending. The transformation task in any case is enormous. It can be solved by bringing together all the different perspectives and facts from which good and innovative solutions can emerge. While promising climate change mitigation options have become available across the board, from organizational (e.g. new business models) and institutional (e.g. green banking regulations) to technological (e.g. breakthrough technologies, new materials and applications) and behavioral (e.g. climate friendly diets), transformation to medium term climate-neutrality will not come on its own. Utmost focus of governments at each level (federal, provincial, municipal, and accommodation at the European level) as well as of all societal actors is required to scale up policy across every sector. This report spells out in detail how such a fundamental transformation could take place across all sectors, in terms of technologies, time scales, and measures, and emphasizes the necessary framework conditions and prerequisites to be set in order to enable such a transformation. It then focuses on the respective economic implications of such pathways, in particular in the economic aftermath of the Corona crisis.

Zum Inhalt:

Die Europäische Union hat ihr Klimaziel für 2030 erhöht auf mindestens 55 % Treibhausgasemissionsreduktion (bezogen auf 1990). Die Aufteilung auf die Mitgliedstaaten im sogenannten „Effort Sharing“ steht noch aus. Die Transformationsaufgabe ist in jedem Fall enorm. Sie kann gelöst werden, indem alle unterschiedlichen Perspektiven und Fakten zusammengebracht werden, aus denen gute und innovative Lösungen ableitbar sind. Während vielversprechende Optionen zur Eindämmung des Klimawandels in allen Bereichen verfügbar geworden sind, von organisatorischen (z.B. neue Geschäftsmodelle) und institutionellen (z.B. grüne Bankvorschriften) bis hin zu technologischen (z.B. bahnbrechende Technologien, neue Materialien und Anwendungen) und verhaltensbezogenen (z.B. klimafreundliche Ernährung), wird die Transformation zur mittelfristigen Klimaneutralität nicht von alleine kommen. Es bedarf der vollen Konzentration der Regierungen auf allen Ebenen (Bund, Länder, Kommunen und auf europäischer Ebene) sowie aller gesellschaftlichen Akteure, um die Politik in allen Sektoren voranzubringen. Dieser Bericht legt detailliert dar, wie eine solche grundlegende Transformation über alle Sektoren hinweg in Bezug auf Technologien, Zeitskalen und Maßnahmen erfolgen kann, und betont die notwendigen Rahmenbedingungen und Voraussetzungen, die gesetzt werden müssen, um eine solche Transformation überhaupt zu ermöglichen. Anschließend werden die jeweiligen ökonomischen Implikationen solcher Pfade beleuchtet, insbesondere im Kontext der wirtschaftlichen Nachwirkungen der Corona-Krise.

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