ELECTRO_COUP

Electrification of heating and mobility: Socioeconomic impacts of non-ETS policies with sector coupling and sectoral linkages

WORKING PAPER 2

ELECTRO_COUP scenarios

Draft: Do not cite without permission from the authors

Authors: Andrea Frank-Stocker, Kurt Kratena, Andreas Müller

Vienna, September 2022

ELECTRO_COUP

Duration: 1st October 2021 – 31st March 2023

Lead: Centre of Economic Scenario Analysis and Research (CESAR)

Partner: Westfälische Wilhelms-Universität Münster (WWU) Münster, Lehrstuhl für Mikroökonomik, insbes. Energie- und Ressourcenökonomik

Kontakt: Kurt Kratena (kurt.kratena@cesarecon.at)

powered by klima+ energie fonds

This project is funded by the Austrian Climate and Energy Fund as part of the „Austrian Climate Research Programme – ACRP 13th Call“.

Content:

Introduction 3
Scenario development 5
Scenario assumptions 6
  Scenario "Renewables 2030" 6
  Scenarios "Decarbonizing 2040" 8
Scenarios for the building sector 8
  Scenario "Renewables 2030" 9
  Scenario "Decarbonizing 2040 – low system efficiency" 13
  Scenario "Decarbonizing 2040 – high system efficiency" 14
Scenarios for the transport sector 17
  Scenario "Renewables 2030" & "Decarbonization 2040 – low system efficiency" .. 17
  Scenario "Decarbonization 2040 –high system efficiency" 18
References: 22

Introduction

In this working paper we describe the scenarios developed in the project ELECTRO_COUP in order to analyse the decarbonization potential of sector coupling between electricity generation, heating, and mobility. The scenarios aim at achieving the Austrian decarbonization targets for 2030 and 2040 and reveal the consequences on energy and socio-economic indicators. The model-based analysis improves the knowledge on the decarbonization potential of sector coupling and linkages between ETS and non-ETS.

The EU climate policy architecture distinguishes sectors covered by the EU Emissions Trading Scheme (ETS) from sectors not included in the EU ETS. While the ETS comprises emissions from power plants and a range of energy intensive sectors, non-ETS sectors contain ground transportation, agriculture, waste, and buildings. These non-ETS sectors are responsible for around 55% of the EU's GHG emissions (see Eurostat[1]). In order to reduce these emissions, the Effort Sharing Decision sets national emissions targets. The individual Member States are responsible for achieving these targets. Subsequently, Austria has committed to reduce emissions in non-ETS sectors by at least 36% until 2030 compared to 2005. If the current pathway is not considerably adjusted, Austria may miss this obligation by up to 20% (EC, 2019). From the required emission reduction of 36%, only 27% will be reached until 2030. Climate-scientists claim that even a reduction of 50% will be necessary to be compatible with the Paris-goal (EEÖ, 2020).

Especially in the sectors transport and buildings, the potential for reducing CO_2 emissions is seen to be substantial. Transport is the major source of energy-related CO_2 emissions and has contributed the most to the increase in total emissions. In 2018, the sector accounted for 40% of total emissions and emitted 24.8 Mt CO_2. Heating, cooling and hot water use in buildings account for 27% of Austria's total final energy consumption and were responsible for around 16% of greenhouse gas (GHG) emissions in the non-ETS sector in 2017 (FMST and FMTIT, 2018).

Contrary to the reduction goal of GHG emissions for non-ETS sectors, the objectives for renewable energy and energy efficiency must be fixed independently by the Member States. In its national Climate and Energy Strategy (#mission2030) Austria has set ambitious targets to expand the share of renewable energy to 45-50% by 2030, with 100% of the total electricity consumption being covered by renewables[2]. Added to the challenge of 100% electricity generation from renewable energy by 2030, Austria is committed to achieving net zero emissions from GHG by 2040. Energy efficiency represents another important pillar of the energy transition. Primary energy intensity should fall by 25-30% by 2030 compared to 2015 (FMST, 2019).

These objectives for decarbonization will require far-reaching transformations in the energy services heating and mobility, not only with respect to generation and consumption, but also with respect to distribution and storage. Furthermore, they constitute central challenges for the Austrian electricity industry, as a decarbonised power system serves as the basis to substantially reduce CO_2 emissions in other sectors through electrification and sector coupling (IEA, 2020).

Electricity consumption in Austria has been steadily growing. In 2018, Austria consumed over 65 TWh of electricity (a 6% growth in a decade), with 50 TWh stemming from renewable electricity generation. Renewable energies accounted for 77% of total electricity generation (including waste), with hydropower responsible for most of this generation. Due to the required additional sustainable electrification of the energy system, the role of electricity in Austria's energy mix will increase significantly by 2030. Electricity consumption is expected to reach 80-85 TWh in 2030 (an increase of around 19-23% compared to 2017) and around 108 TWh in 2050 (FMST, 2019; IEA, 2020). E-mobility will account for a large share of future electricity demand, as will heating and cooling (FMST and FTIT, 2018; FMST, 2019). However, this also implies passing on some of the burden of decarbonization from the non-ETS sectors transportation and building to the ETS sector electricity.

---

[1] See https://ec.europa.eu/eurostat/de/data/database

[2] The 2030 renewable electricity target is set at 100% of the national balance, defined as total generation plus electricity exports minus electricity imports.

Assumptions vary considerably regarding the amount of additional power from renewables needed to boost the heating and transport sector operating mainly on electricity. Since electricity from renewable energy sources is not in infinite supply, it is expected that sector coupling would only contribute to climate protection if the final energy demand of the sectors could be decreased by 40 to 60% (Deutsche Umwelthilfe, 2017; Brauner 2019).

The Austrian government assumes that reaching the 100% renewable electricity goal will require 22-27 TWh of additional annual renewable generation across all technologies in 2030 (FMST, 2019), while other studies estimate that the needed additional generation could be in the range of 28 to 34 TWh (Haas et al., 2017). A large part of this increase will have to come from variable renewable energy (PV and wind), as hydropower resources are largely exploited and generation from biomass is not expected to grow substantially (IEA, 2020). In any case, achieving the 100% renewable electricity target by itself will not be sufficient to meet the 2030 target for 46-50% renewables in gross final consumption and the goal of net zero emissions by 2040. Significant additional renewable deployment needs to take place in other sectors, notably in the two non-ETS sectors transport and buildings, which are currently dominated by fossil fuels (IEA, 2020).

To achieve the required deep emission reductions in the Austrian heating and transport sector, stronger cross-sectoral linkages among the different energy uses and energy carriers are needed. This approach is commonly referred to as "**sector coupling**". The term implies to integrate electricity, gas, heating/cooling, mobility systems and markets to benefit from new energy sources and technology solutions (EC, 2018). Such cross-sectoral linkages are recognized as a cost-effective decarbonisation strategy that provides significant flexibility to the system (Pavičević et al. 2020). However, it has to be noted, that despite the decarbonisation potential of coupling the electricity, heat and transport sectors, the proposed climate protection goals would only be achieved with a substantial reduction in consumption, combined with higher shares of renewable energies.

Impact assessment carried out by the EU Commission and its services of long-run (2050) roadmaps and strategies of decarbonization designed a scenario of electrification of end-use energy purposes accompanied by expanding electricity supply from renewables, nuclear and fossil fuels with carbon capture technologies. That comprises shifting the burden of decarbonization to the electricity sector that belongs to the ETS.

Several studies have already highlighted the potential overlapping in EU climate policy and the problems arising from that (Böhringer et al., 2008, and Böhringer, 2014). In the worst case, large part of carbon reduced in one part of the energy system reappears in another part (Eichner and Pethig, 2018), a phenomenon known as **sectoral leakage**. The term refers to a situation where a policy such as emission trading may apply only to one sector (e.g. electricity), which increases its price and shifts demand to other goods. This domestic leakage may in turn offset some of the regulated sector's carbon reduction (Baylis et al., 2014).

This is a further reason why the analysis must focus on the linkages between different sectors and must cover sector coupling. In the proposed project, we understand sector coupling as combining electricity production, distribution, and storage on the one hand with other energy sources (heat, gas) on the other hand. The decarbonization path designed in the proposed project combines fuel-shifts and efficiency increases in the non-ETS with support measures for renewable electricity and heat generation, including storage. A major part of the non-ETS changes is driven by electrification, which additionally allows for new efficient technology diffusion. The results of such an analysis also reveal, to what extent leakage and shifting of fossil energy use from end-use to carbon-intensive electricity generation is only a threat (Bloomberg Finance L.P. et al., 2020) or a relevant issue.

Scenario development

In the scenarios, we distinguish different degrees of electrification and show the associated challenges for electricity generation as well as the positive effects in the energy system ("carbon efficiency") and on the Austrian economy.

The first scenario ("Renewables 2030") has the aim to cover 100% of the electricity demand by renewable resources, but with current energy transition policies: which means that a reform of the EU Emission Trading System will take place, that the building stock will develop according to the long-term Renovation Strategy, and that the trends in transport will continue (number of e-cars, slight modal shift to public transport). However, the scenario does not consider additional sector coupling.

Furthermore, we have developed two "Decarbonizing 2040" scenarios. In addition to the measures and activities in "Renewable 2030" these scenarios analyse the potential of stronger sector coupling and decarbonization policies in the non-ETS. We differentiate between high and low system efficiency to illustrate that the decarbonization can be reached in a more or less efficient and cost-efficient way. The high system efficiency scenario, in the case of heating as well as transport, assumes that (i) fossil liquid fuels and fossil gas can be almost completely substituted by electricity, and (ii) final energy demand can be reduced considerably by efficiency increases and socio-economic changes. The low system efficiency is based on trends for energy efficiency and assumes only a slow path of substitution of fossil fuel based-capital stock by electricity based-capital stock. In order to achieve decarbonization in this scenario as well, the remaining fossil energy needs to be substituted by fuels generated from electricity (e-fuels, hydrogen).

In our scenarios, we implicitly take into account policy measures, but we do not provide a discussion of detailed policy measures. The scenarios have the intention to improve the knowledge on the electrification of the transport and the building sector and sector coupling.

We derive our scenario assumptions for example for the development of CO_2 prices or investment needs from existing scenarios (Pietzcker et al. 2021) and we explicitly include aspects of sector coupling and sectoral leakages. As we do not apply a model of the electricity sector, the information on generation by technology, capacity additions and external trade of electricity for the "Renewables 2030" scenario is taken from Pietzcker et al. (2021). For the other two scenarios, existing knowledge from other scenarios, has been used for designing decarbonization pathways in heating and transport. That includes the use of bottom-up data, functions and models, which constitute the framework, within which certain assumptions drive the development of final energy by type of energy.

Our scenarios are based on EU and Austrian policy frameworks and targets. And in this respect the decarbonization scenarios generally being based on more ambitious targets.

The underlying EU targets and policy frameworks are:

- The European Green Deal which is the EU's long-term plan to make Europe climate neutral by 2050. As an intermediate step towards climate neutrality, the EU has raised its 2030 climate ambition, committing to cutting emissions by at least 55% by 2030.
- The Fit-for-55 Package, which refers to the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030. The proposed package aims to bring EU legislation in line with the 2030 goal. The Fit for 55 package is a set of proposals to revise and update EU legislation.
- REPowerEU Plan, with the aim of ensuring EU's energy security, reducing EU's dependence on Russian fossil fuels and tackling the climate crisis.

These targets and frameworks also imply a tightening of the EU Emissions Trading System (ETS) and of the EU Effort Sharing Regulation (EU ESR) targets.

Especially relevant for Austria are the following targets and policy frameworks:

Austria intends to cover 100 % of its total electricity consumption with renewable energy sources from 2030 onwards. In this context, the Renewable Energy Expansion Act (EAG) sets out the conditions for the promotion of electricity generation from renewable sources.

The Austrian Long-term renovation strategy LTRS sets out a goal of 80% reduction in building sector GHG emissions by 2050 compared to 1990. It emphasizes the phasing out of coal and oil for heating purposes and addresses building renovation.

The reformed Renewable Heating Act (EWG) will pave the way for the phase-out of fossil fuel heating systems by 2040 and the transition to renewable heating to reduce the dependency on Russian gas supplies.

And finally, Austria's mobility master plan calls for 100 percent emission-free passenger cars from 2030 onwards. A goal that seems to be achievable. In Norway, as early as 2021, over 60 % of newly registered cars were powered exclusively by electricity.

The first two mentioned goals are relevant for the scenario “Renewables 2030”, while the last two are relevant for the Decarbonization 2040 scenarios.

Scenario assumptions

Based on this political background we have derived assumptions for our scenarios, which describe possible development paths in the electricity sector as well in the building and transport sector.

The EU ETS is the key climate policy to drive the decarbonization of the EU electricity system and a tightening will have substantial implications on the investment into new technologies. So, we assume an ETS-driven decarbonization of the electricity sector. Due to the Fit-for-55 Package the new goal for ETS sectors is a reduction of 61% of GHG emissions by 2030 instead of minus 43, as foreseen currently.

The EU ETS target is considered through the provision of annual emission allowances. The number of allowances provided is calculated via the linear reduction factor (LRF). The LRF is the rate at which the EU ETS cap decreases each year. To fulfill the minus 55% goal the Linear Redction Factor would have to be raised to 4.2%. This higher LRF is used in all our scenarios.

Emissions from the building and transport sectors are currently regulated by the Effort Sharing Regulation – ESR. The ESR establishes annual, binding greenhouse gas emissions targets from 2020 to 2030 for each Member State for sectors not covered in the EU ETS. The current regulation aims to achieve an EU-wide emission reduction of 30% by 2030, compared to 2005. To achieve the net 55% emission reduction target by 2030 the EU should reduce buildings’ greenhouse gas emissions by 60%, as well as reduce energy consumption for heating and cooling by 18%. Additionally, the European Commission will set more ambitious CO_2 emission targets for cars and vans from 2030 onward and foresees to create a new (additional) emission trading system for road transport and buildings, starting in 2026. These adaptations of the ESR are relevant for the two Decarbonization 2040 scenarios.

Scenario “Renewables 2030”

The decarbonization of electricity generation in our scenarios is based on the European Green Deal and Fit-for-55; which means 100% renewable electricity by 2030. The decarbonization of electricity generation is price induced without any need for additional support measures. Our assumptions on CO_2 caps and CO_2 prices are based on a PIK-Study by Pietzcker et al. 2021. There, the impact of the tightening of the ETS by applying the Linear Reduction Factor is simulated with an electricity sector model. Figure 1 shows the assumed carbon price resulting from this tightening in the ETS sectors. It can be observed, that in such a scenario carbon prices more than triple, increasing to 129 EUR/tCO2 in 2030 and 213 EUR/tCO2 in 2040.

Fig. 1. ETS carbon prices 2023 - 2040 (€ 2015/t) in the "Renewables 2030" scenario

	Eur2015/t CO_2
2023	60
2024	81
2025	101
2026	106
2027	112
2028	118
2029	124
2030	129
2031	137
2032	144
2033	151
2034	159
2035	166
2036	176
2037	185
2038	194
2039	204
2040	213

Source: Pietzcker, et al. (2021), Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector

Figure 2 illustrates the output shares of electricity generation in the "Renewables 2030" scenario. Fossil fuels can be substituted by renewable energies to a very high degree. Natural gas has a high share in 2020, which can be reduced to 3% in 2030 and 1% in 2040. Regarding the different renewable energy sources, it can be seen that the shares of wind and PV will rise sharply until 2040, while hydro power counts for 47% in 2030 but reduces to 31% in 2040. Biomass is becoming less important for electricity generation.

Fig. 2. Electricity generation: Output shares

	2017	**2020**	**2025**	**2030**	**2040**
Coal	6.1%	3.2%	2.5%	2.1%	1.4%
Oil products	2.4%	1.8%	1.4%	0.0%	0.0%
Natural gas	20.7%	39.9%	14.1%	2.9%	1.0%
Hydro Power	46.7%	30.7%	38.7%	47.4%	31.5%
Wind/PV	9.6%	11.3%	30.6%	36.8%	59.0%
Biomass	14.7%	13.1%	12.8%	10.7%	7.1%
	100.0%	100.0%	100.0%	100.0%	100.0%

Source: Pietzcker, et al. (2021), Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector

In the **Non-ETS sectors** heating & transport the current trends will continue, i.e. no additional policy and no adaptation of the ESR are assumed.

Scenarios “Decarbonizing 2040”

In the scenario “Decarbonizing 2040” we differentiate between low system efficiency and high system efficiency.

In the scenarios of **low system efficiency**, in the non-ETS sector fossil energy carriers will be substituted by power-to-X energy carriers. This is due to two factors: low efficiency increases in final energy efficiency and slow substitution between fossil fuels and electricity. Both factors are driven by slow embedded technological changes in capital stock. More use of the power-to-X energy technology has the advantage that power surpluses from renewable energy sources can be stored, but has the disadvantage that high converting losses emerge. Thus, an increase in electricity demand can be expected. In the electricity sector, high additions to capacity and costly transformation processes are the consequence, which leads to the question of feasibility of such a scenario.

In the decarbonization scenario with **high system efficiency** we assume efficiency improvements and socio-economic changes that considerably dampen final energy demand. For heating that implies thermal refurbishment and electrification (heat pumps). For private transport we develop a socio-economic pathway that leads to ‘peak car’ - the point at which car ownership (stock) and car use start to decline together with electrification. An increase of electricity demand can be expected from higher electrification and sector coupling.

Sector coupling is expected to play a key role in deep decarbonization pathways, mostly via direct electrification of the transport and heating sectors, but potentially also through the production of e-fuels. This would also lead to an increasing electricity demand and thus augment the decarbonization pressure within the EU ETS, as the direct emissions from transport and heating are regulated in the EU ESR and thus outside the EU ETS. We expect reasonable capacity additions in the electricity generation. The increase of electricity demand leads to an absolute increase of investments in RES. But at the same time, the higher electricity demand creates an incentive to keep more fossil-based generation in the mix.

Scenarios for the building sector

The aim of the scenarios for the building stock is to evaluate the impact of different decarbonization strategies for the building sector with a special focus on the system efficiency. The first scenario, the “Renewables 2030” scenario is an implementation of the existing “Long Term Renovation Strategy 2020” (OIB-330.6-022/19-093) and represents a view of the Austrian Federal states, along with the OIB, on how the decarbonization of the sector is envisioned. This scenario is characterized by very moderate efficiency gains. The final energy consumption for heating and domestic hot water preparation remains constant. Efficiency gains achieved through thermal refurbishment activities are counterweighted by high growth of heated floor area and increasing comfort expectations, expressed in increasing average indoor temperatures of users. The growing heated floor area is not only caused by an increasing population, but also by a strongly increasing floor area per capita. While related GHG-emissions decrease in this scenario, it is far from being climate neutral by 2050. The second scenario, the “Decarbonizing 2040 – low system efficiency” scenario, builds on the “Renewables 2030” scenario, but achieves a full decarbonisation by replacing the fossil energy carriers by their carbon-neutral equivalents. In the scenario, natural gas is replaced by methane produced through the power-to-gas route, the required electricity as well as the delivered district heating energy need to be produced from carbon-neutral energy sources. The third scenario, the “Decarbonizing 2040 – high system efficiency” scenario, tackles the transition by addressing energy efficiency as well as replacing the energy carrier by carbon neutral options. This scenario is characterized by more ambitious refurbishment activities, a lower increase in the heated floor area per capita as well as switching to more efficient heating supply systems.

In this project, we utilized the Invert model to calculate the transformation scenarios for the built environment. The Invert model is a bottom-up model to analyse space heating, hot water generation and space cooling in the building stock. It is designed to quantitatively evaluate the effects of different framework conditions on total energy demand, energy carrier and technology mix, CO_2 emissions and costs and is based on a highly disaggregated description of the building stocks in the different analysis regions. This includes the type of a building, age, state of renovation, existing heating systems, user structure as well as regional aspects such as availability of energy infrastructure for gas or district heating. In the analyses usually, both residential and tertiary buildings, are covered. Furthermore, different structures of housing provisions and household-income classes are represented in the model.

In the model Investor-Agents choose from different refurbishment options (measures related to energy needs as well as energy supply), once building components reached their lifetime. With respect to heating technologies and efficiency measures, the model uses a technology database containing technical and economic characteristics of available options. On the one hand this integrates currently applied and potential future technologies for the supply of space heating, hot water and space cooling, including on-site solar thermal and PV generation as well as the heat distribution systems in the building. On the other hand, a large set of options for building shell refurbishment and heat recovery systems is considered for decreasing energy needs in the buildings.

The model includes a dedicated energy calculation module that endogenously derives the energy needs, final energy demand and delivered energy for space heating, hot water generation and space cooling. The module applies a quasi-steady state monthly energy balance approach based on the ÖNORM B8110, which is an Austrian calculation norm, similar the European EN13790. In addition to these standards, the calculation algorithm is adjusted to take into account the observed differences between calculated and measured energy demand using a disaggregated service factor approach.

The Invert model has three different approaches to calculate the solutions of investment decisions:

- Least-cost optimization (Invert/Opt)
- Agent-specific cost-benefits (utility) driven discrete choice (Invert/EE-Lab)
- Exogenously defined scenario development (renovation rates, chosen refurbishment packages, chosen heating systems) (Invert/Accounting)

In this project, we apply a middle-ground between the investor agent driven EE-Lab approach and the accounting approach. For this, we define the overall renovation activities (related to energy needs) exogenously and set policy and energy costs-related parameters so that we achieve a predefined scenario development. It is important to note that the scenarios need to be seen as "what-if" scenarios, as we do not explicitly implement all current and proposed policy measures. Furthermore, we do not explicitly let the investor agents optimize their decisions with respect to implemented energy prices.

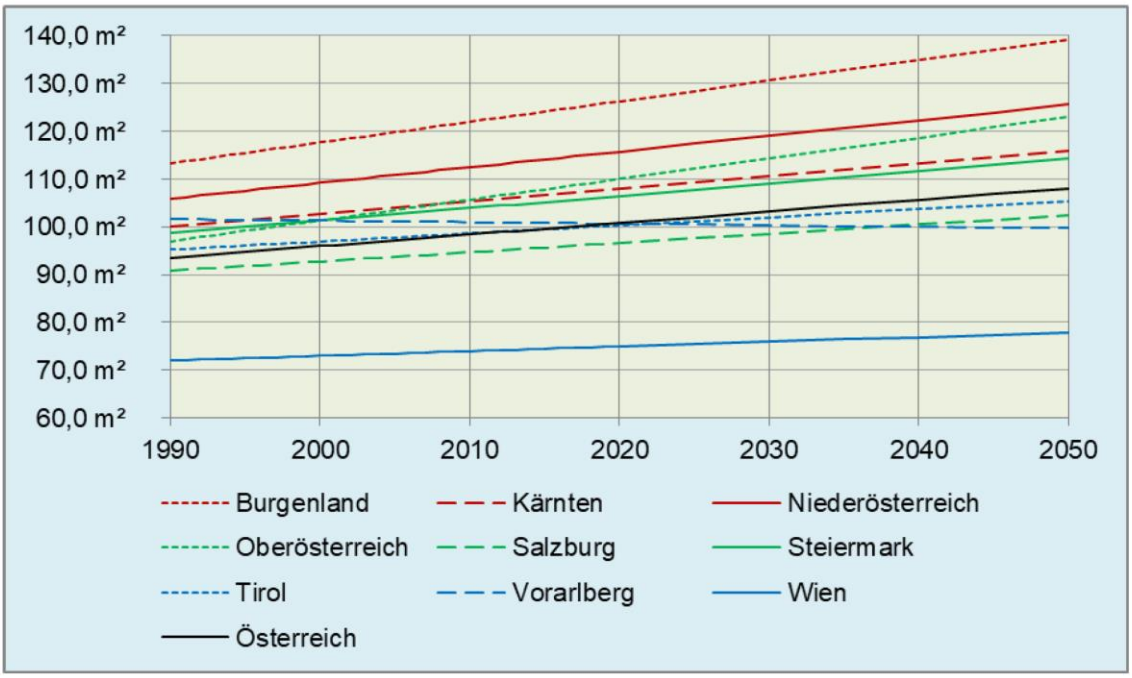
Scenario "Renewables 2030"

As said above, this scenario is our implementation of the latest Austrian Long Term Renovation Strategy. The main characteristics of the Austrian LTRS are a high growth of the heated (residential) building stock area, Moderate energy savings, and the phase out of heating oil as well as a rather constant demand for natural gas until 2040.

High growth of the heated (residential) building stock area

A high growth of the heated building area is part of the LTRS. The growth of the total area stems from three different underlying assumptions. First, the Austrian population is expected to increase, based on data provided by Statistic Austrian, starting from 8.8 million in 2017 to 9.73 million in 2050 (+10.6%). Second, the average floor area per apartment increases from 99.6 m²/dwelling in 2017 to 108.0 m²/dwelling in 2050 (+8.4%, Fig. 3). Finally, the average occupation rate of households is expected to decrease and the number of apartments without residence registration is increasing, leading to a further increase in the demand heated area per capita by 10.9% until 2050.

Fig. 3. Development of the average apartment size in the "Renewable 2030" scenario, based on the Austrian Long Term Renovation Strategy (LTRS)



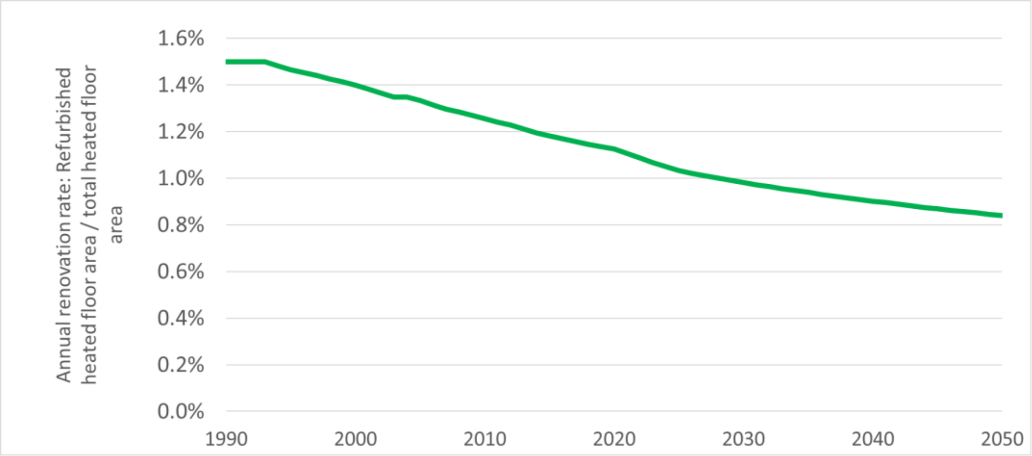
Source: OIB (2020) Langfristige Renovierungsstrategie OIB-330.6-022/19-093

In total, this leads to an increase of heated floor area by 33% until 2050, of which about two thirds are driven by increasing floor area per capita.

Moderate energy savings: Moderate target, large rebound effect

Another characteristic of the scenario are moderate efficiency gains. The underlying annual refurbishment rate is defined as 1.5% of the heated area of buildings constructed until 1993. Due to an increasing building stock, this means a decreasing refurbishment rate, if the more common definition of using the total building stock as denominator. According to this definition, the effective refurbishment rate decrease from 1.5%p.a. in the early 1990ies to about 1.1%p.a. in 2020 and further to about 0.8% in 2050 (Fig. 4).

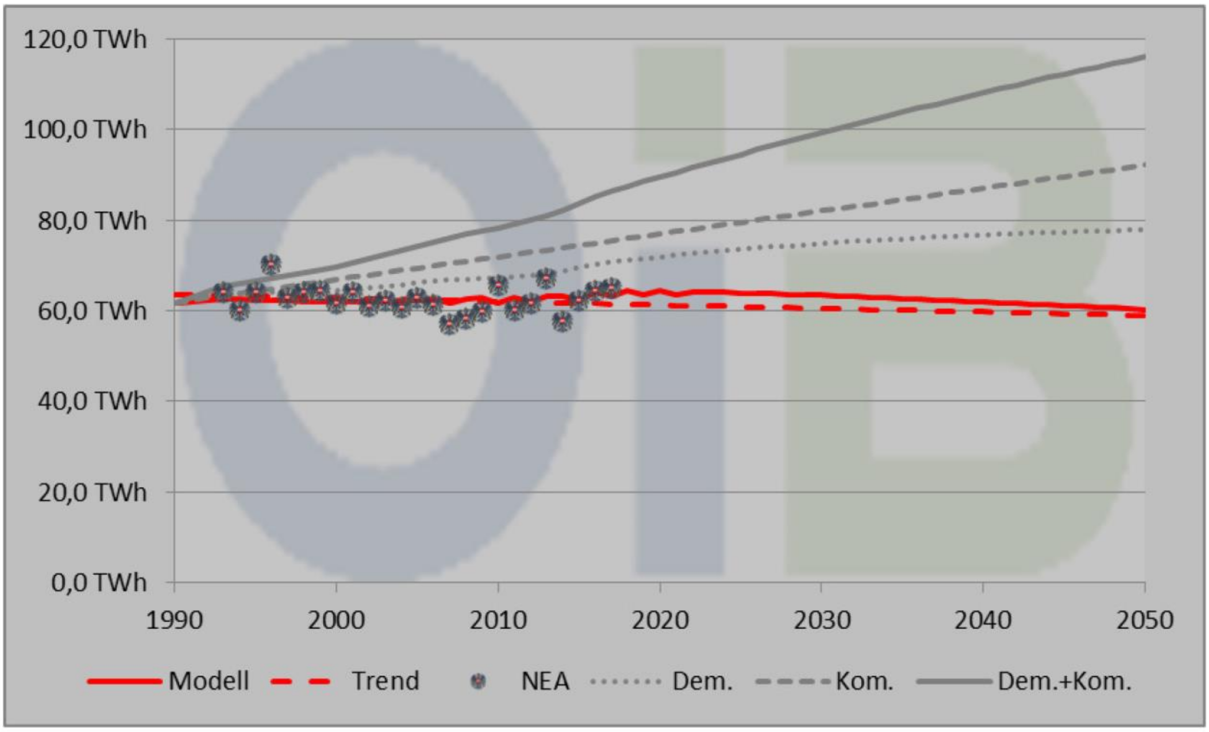
Fig. 4. Development of the annual refurbishment rate in the "Renewable 2030" scenario, based on the Austrian Long Term Renovation Strategy (LTRS)



Source: OIB (2020) Langfristige Renovierungsstrategie OIB-330.6-022/19-093

Furthermore, the scenario considers increasing set point temperature level triggered by additional comfort expectations, which offset a significant part the energy savings. In total, this scenario leads to an almost constant final energy consumption for the total (residential) building stock, which settles around 60 TWh in the year 2050.

Fig. 5. Final energy consumption for the residential space heating and domestic hot water preparation according to the Austrian Long Term Renovation Strategy (LTRS)



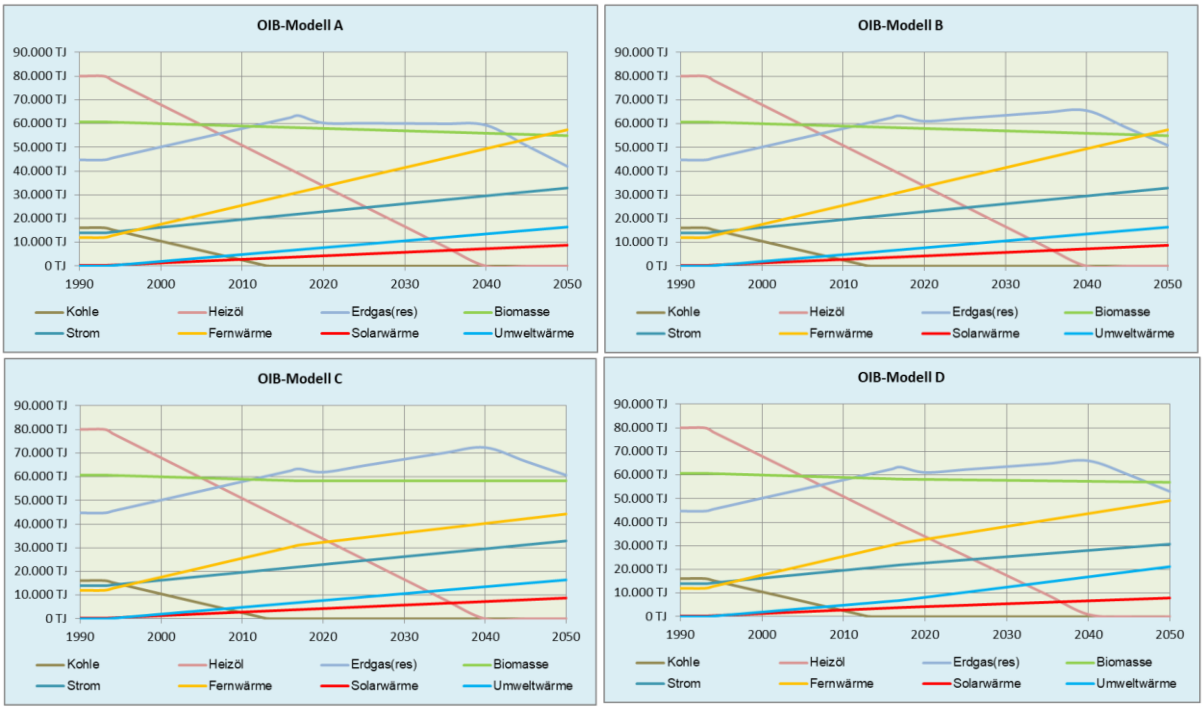
Source: OIB (2020) Langfristige Renovierungsstrategie OIB-330.6-022/19-093

Phase out of heating oil, rather constant demand for natural gas until 2040

The Austrian LTRS presents four scenarios for the development of the different energy carriers. While they vary in their exploitation of heat pumps and district heating to some degree, they all share some common features (0):

- Heating oil is going to face out until 2040.
- Biomass will slightly decrease (remain constant in one scenario)
- Natural gas consumption will remain (more or less) at the current level until 2040.
- Solar thermal heating and ambient / geothermal heat utilized by heat pumps will increase within the next decades but will play a modest role only.

Fig. 6. Development of final energy consumption per energy carrier, 4 different scenarios: A-D



Source: OIB (2020) Langfristige Renovierungsstrategie OIB-330.6-022/19-093

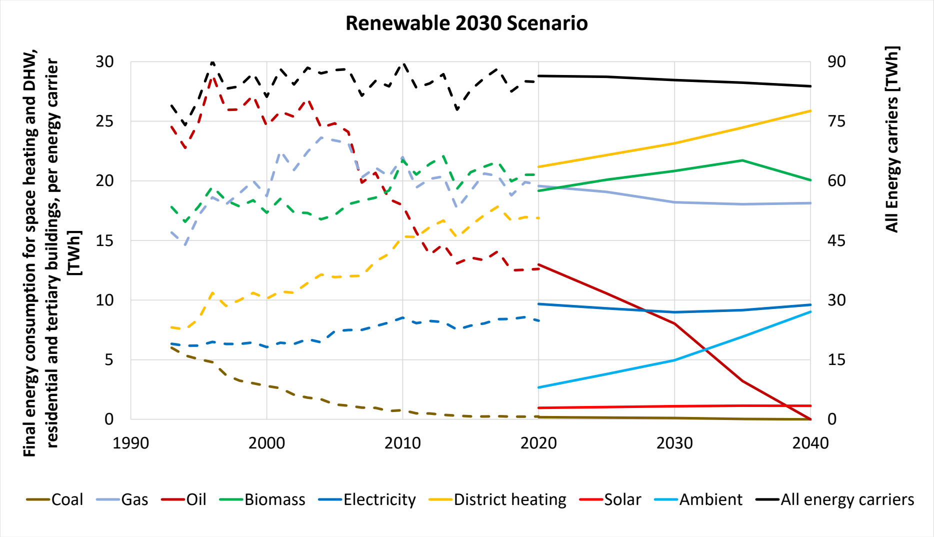
Our Invert implementation of the Renewables 2030 Scenario shares the main characteristics of the underlying Austrian LTRS scenario:

- constant final energy consumption at a level of about 85 TWh;
- phase-out of oil until 2040;
- biomass and natural gas consumption remain at the same level as they are in 2020;
- solar thermal energy remains low.

For electricity, ambient/(geothermal) heat and district heating our scenario points in similar directions, but we get larger deviations:

- The increase in district heating is less ambitious as in the LTRS scenarios.
- While the development of the sum of ambient heat (harvested by heat pumps) and total electricity consumption is similar to that in the LTRS, we see a different development for each of the two energy carriers. In contrast to the LTRS scenario, the total electricity consumption remains constant in our scenario, while we get much stronger increase in the ambient heat. In our model, this is triggered by the increasing diffusion of heat pumps along with a reduction of direct electric resistance heating systems, which are the dominant source for the electricity demand in this field as of today.

Fig. 7. Development of final energy consumption per energy carrier in the "Renewables 2030 Scenario"



Source: own calculation based on an implementation of the OIB (2020) Langfristige Renovierungsstrategie OIB-330.6-022/19-093 scenario in the Invert modelling environment.

Scenario "Decarbonizing 2040 – low system efficiency"

The Scenario "Decarbonizing 2040 – low system efficiency" builds on the first scenario but achieves GHG neutrality by substituting fossil energy carriers by their corresponding carbon neutral variant. Since oil and coal are already phased-out in the scenario, what natural gas is what remains to substituted. In this study, we consider that methane, produced via the power-to-gas route along with methane from biogenic sources, is used to replace natural gas.

For the possible share of biomethane, we apply data from a recent Austrian study on renewable gas (Baumann et al., 2021). Their estimates on the expected gas demand in 2040 in the sectors: industry, district heating and electricity production as well as transport amounts to 89-137 TWh, the biomass-based methane potential is estimated to around 20 TWh. Including the demand in buildings, as derived in our study, the gas demand increases to 108-157 TWh, the biogenic gas potential is then in the order of around 15% of that demand. Subsequently, the following analysis uses a split between e-methane and bio-methane of 85% to 15 %.

Generally speaking, the production of methane by using electricity can be split-up into three parts:

- Production of hydrogen via electrolysis
- Provision of CO_2
- Synthesis of methane (CH_4) from H_2 and CO_2

Each of these steps involves some efficiency losses and the total system efficiencies of power-to-methane pathways are currently a widely debated field and depend on multiple parameters such as:

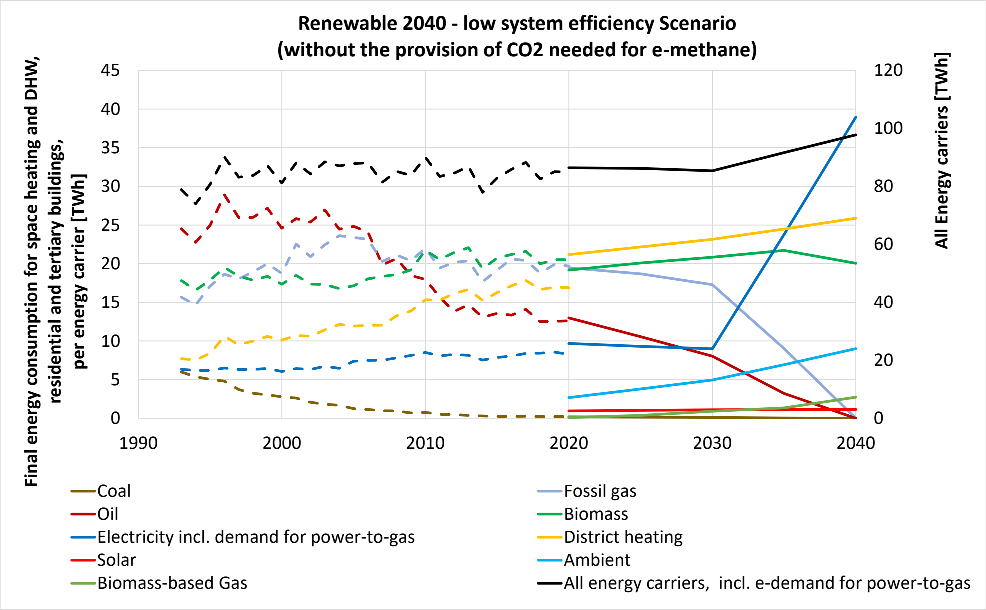
- Technologies used
- Possibility to utilize heat released by processes
- Availability waste heat needed by processes
- Availability of CO_2

According to Kumar and Himadinu, the efficiency of the hydrogen production lies in the range of 60-80%. Biswas et al. (2021) reviewed several processes for synthesizing methane and derived theoretical efficiencies (not accounting all losses occurring in real processes) between 67%-89%. The energy demand for the provision of CO_2 largely depends on the concentration of CO_2 of the CO_2 source. If the process is close by a large CO_2-emitting point source, the energy demand is going to be lower than if CO_2 needs to be extracted from a low-concentration source such as direct-air capture systems. Similar numbers are presented by Blanco et al. (2018), who report an efficiency range for hydrogen production via electrolysis of 65-75% and 75% for the hydrogen to methane route.

In our analysis, we consider a system efficiency for hydrogen production of 70% and for the synthesis of methane of 75%, leading to an overall system efficiency of 52.5%. It is important to keep in mind, that we do not account for the provision of CO_2 in these assumptions, which would lead to another drop in efficiency. If direct air capture needs to be used, according to Terlouw et al. (2021) the energy demand for the CO_2-required for one kg of methane, containing ~11 kWh of chemical energy, amounts to 5.5 kWh[3], meaning that around half of the energy that is stored in methane needs to be provided for capturing the CO_2 only. Under this assumption, the total system efficiency drops to 41%, still not considering the energy demand for transporting and storing the gases.

The impact on the final energy demand of the sector is shown in the following figure. In this scenario, energy consumption (including the electricity demand for the production of e-methane) increases to 98 TWh, stemming from a step increase of the electricity demand, which raises from around 10 TWh in 2020 to 40 TWh in 2040.

Fig. 8. Final energy consumption for space heating and DHW in the Scenario Decarbonization 2040 – low system efficiency



Source: own calculation.

Scenario “Decarbonizing 2040 – high system efficiency”

The final Scenario “Decarbonizing 2040 – high system efficiency” implements more ambitious energy efficiency measures to reduce the energy needs as well as delivered energy. The

---

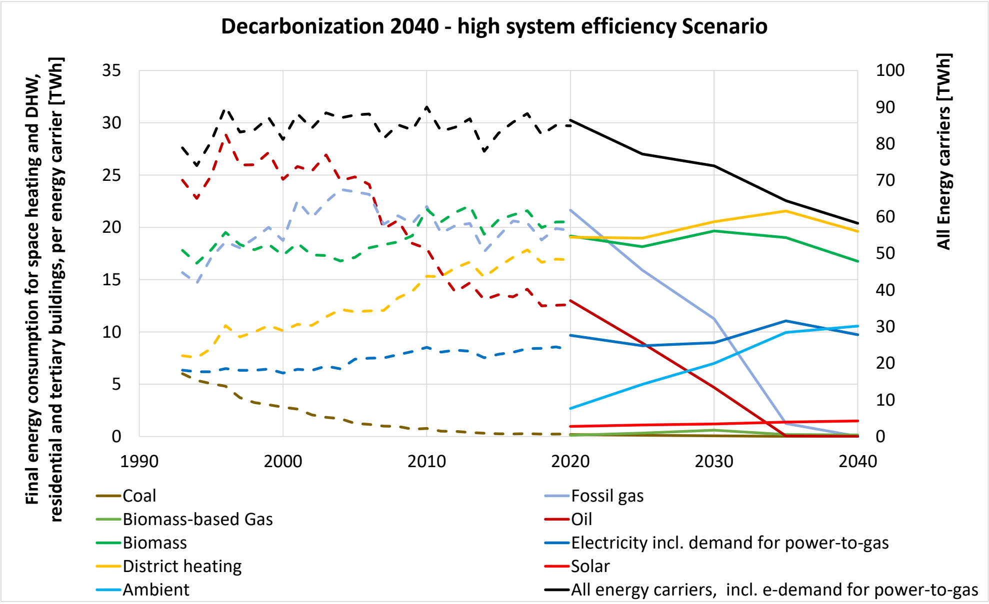
[3] For 1 kg methane (CH4), 2,75 kg of CO_2 are required. Terlouw et al. specifies the energy demand to capture 1 kg of CO2 as 500 kWh of electricity and 1500 kWh heat at around 100°C.

measures in this scenario are our take on an ambitious implemented energy efficiency and climate mitigation policies currently discussed in Austria, expressed in a draft version of the Renewable Energy Act (Erneuerbare-Wärme-Gesetz (EWG), BG (2022)). Among other measures, the acts foresees that all oil and coal fired boilers need to be replaced by renewable energy-based heating systems until 2035. Gas-fired boilers must switch to alternative until 2040; only in special cases carbon-neutral gas are allowed to be used. In addition, if buildings which do not surpass a certain energy performance, need to be refurbished. This policy is an implementation of the current draft version of the European buildings directive, in which minimum energy performance standards (MIPS) are expressed. The requirements are set in way, that the annual refurbishment rate exceeds 3% in the early 2030, a goal that is currently also expressed the Austrian government and the Federal Ministry of Austria for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK). The energy performances of refurbished and newly constructed buildings are set as such that buildings slightly exceed current legislation (in line with current discussions for new standards), however without using the less ambitious certification rule using the fGEE ("Gesamtenergie-Effizienzfaktor").

For the possible role of biomass-based energy carriers we decided to apply a future in which solid biomass plays a similar important role as it does today and thus plays an important role as a renewable energy source for those buildings which need to switch from a currently fossil energy carrier-based heating system towards a renewable based system. The biomass potential we consider in this study are based on ENSPRESO – Biomass project (EC, 2019) including the use of round-wood.

Fig. 9 presents the final energy consumption for space heating and domestic hot water preparation in the "Decarbonization 2040 – high system efficiency" scenario. In this scenario, the total final energy demand decreases by about one third until 2040. While the delivered energy of district heating, biomass and electricity remains at a similar level as it is today, oil and gas is being phased out. Energy-wise, the increasing role of heat pumps can be seen by the rising energy coming from ambient heat, which increases from about 2.5 TWh in 2020 to 10 TWh in 2040.

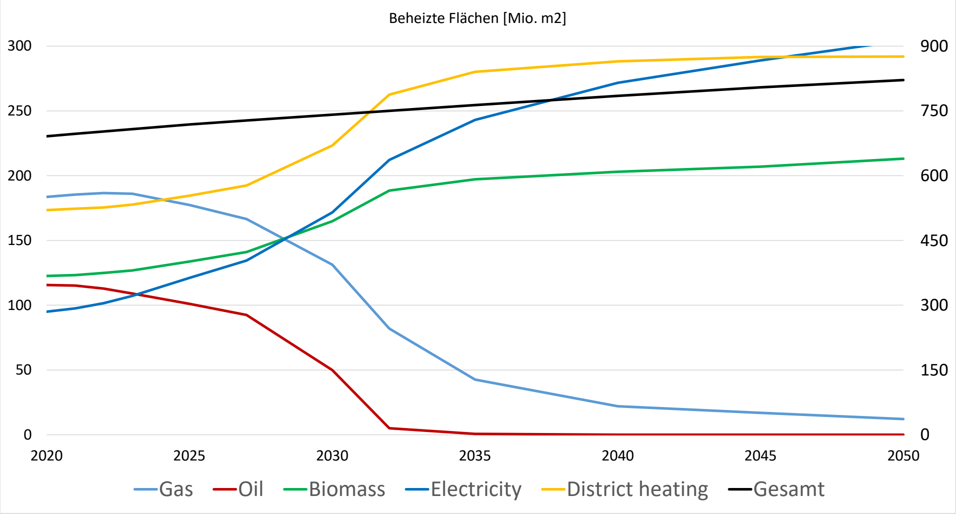
Fig. 9. Final energy consumption for space heating and DHW in the Scenario Decarbonizing 2040 – high system efficiency



Source: own calculation.

The heated floor area by energy carrier groups is shown in Fig. 10. In this scenario, the total floor area increases from 730 to 780 mio. m² in 2040. The largest shifts between energy carrier groups occur in the next 10-15 years, when oil and gas-based heating systems are being (partially) phased-out. Subsequently, the alternative system: district heating, biomass-based boilers and heat pumps gain large market shares. Once that shift has finished, biomass and district heating supplied areas stagnate in this scenario on a high level, while the heat pump technology keeps growing.

Fig. 10. Heated floor area by energy carrier for heating in the Scenario Decarbonizing 2040 – high system efficiency



Source: own calculation.

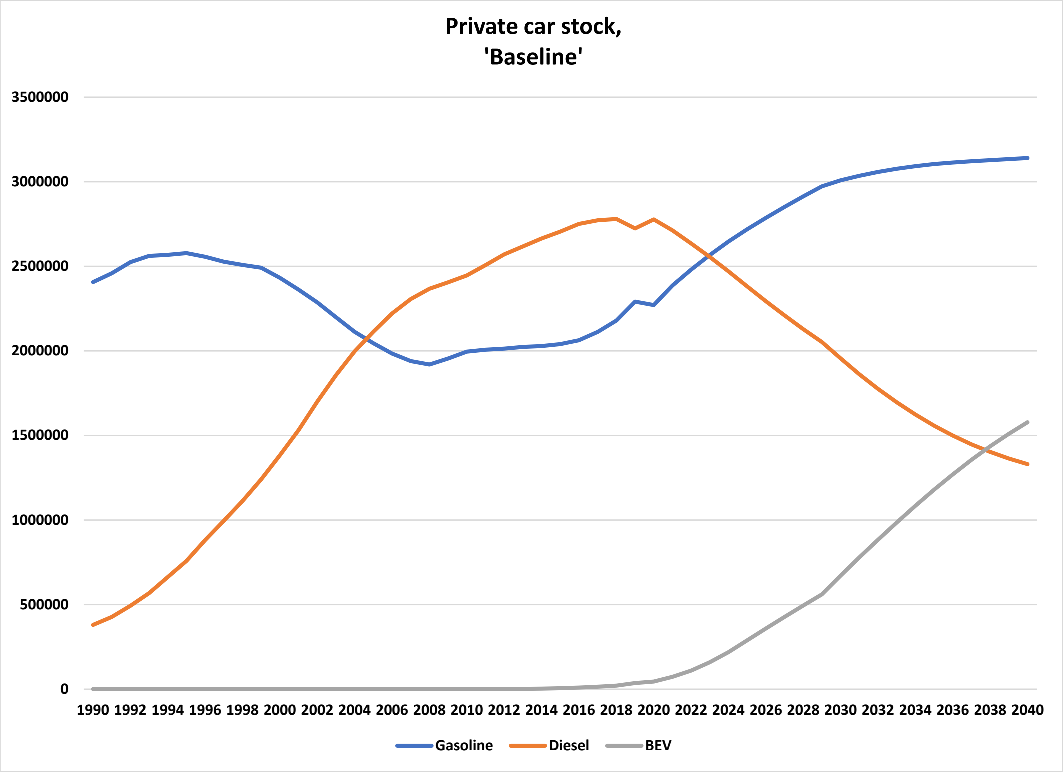
Scenarios for the transport sector

Scenario “Renewables 2030” & “Decarbonization 2040 – low system efficiency”

The objective of all scenarios for private transport is to derive pathways of energy demand by fuel *f* (*f*: gasoline, diesel, electricity). The “Renewables 2030” scenario corresponds to what is usually labeled as a ‘baseline’ scenario, i. e. a continuation of trends. The dataset for the scenarios is taken from output of the NEMO model (transport bottom-up model) for different energy scenarios in Austria. The continuation of trends is defined by the ‘baseline’ assumptions of a With Existing Measures (‘*WEM*’) scenario and the NEMO output for the “Renewables 2030” scenario can therefore be taken directly from the NEMO output for this ‘WEM’ scenario.

The core variables that define the scenario are the vehicle stock by drive (*f*) and energy demand by energy carrier. Decarbonization – that also takes place in ‘baselines’ – is generally driven by the structural change in the capital stock. In the “Renewables 2030” scenario, the share of BEV (battery electric vehicles) in the total vehicle stock rises to 12% in 2030 and 26% in 2040. The share that BEV represent in annual investment in vehicles is 33% in 2030 and 36% in 2040 in this scenario.

Fig. 11. Private car stock, 1990 – 2040, “Renewable 2030” scenario

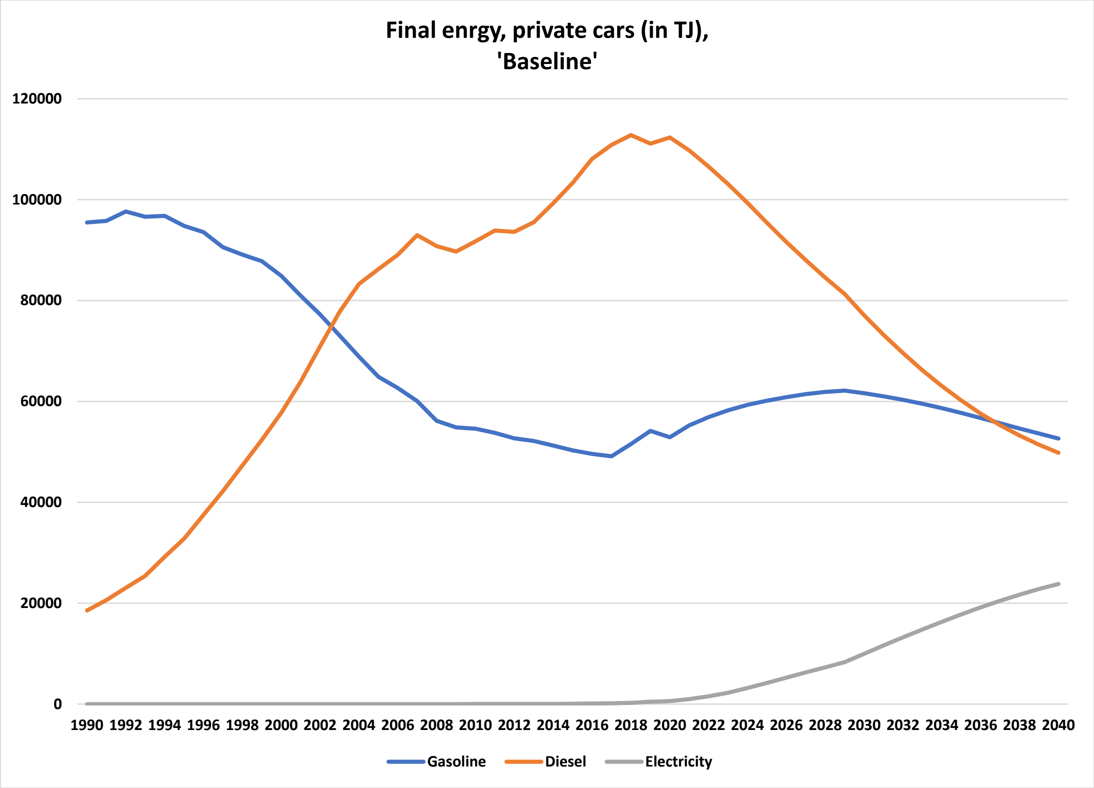


Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

As Figure 8 shows, that implies an important decline in diesel demand, but gasoline demand almost stays constant in the long-run. Both fuels still sum up to 100 PJ in 2040.

This scenario might at the same time be seen as a decarbonization scenario with low system efficiency. No acceleration of existing decarbonization trends is realized and no developments that additionally dampen energy demand (like efficiency and socio-economic change) take place. Therefore, decarbonization in 2040 could in this scenario only be reached by providing 100 PJ (28 TWh) of biofuels or e-fuels. That, in turn, would lead to extremely high renewable primary energy demand and/or high additional renewable electricity generation (sector coupling).

Fig. 12. Final energy (TJ), private cars, 1990 – 2040, "Renewable 2030" scenario



Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt).

Scenario "Decarbonization 2040 –high system efficiency"

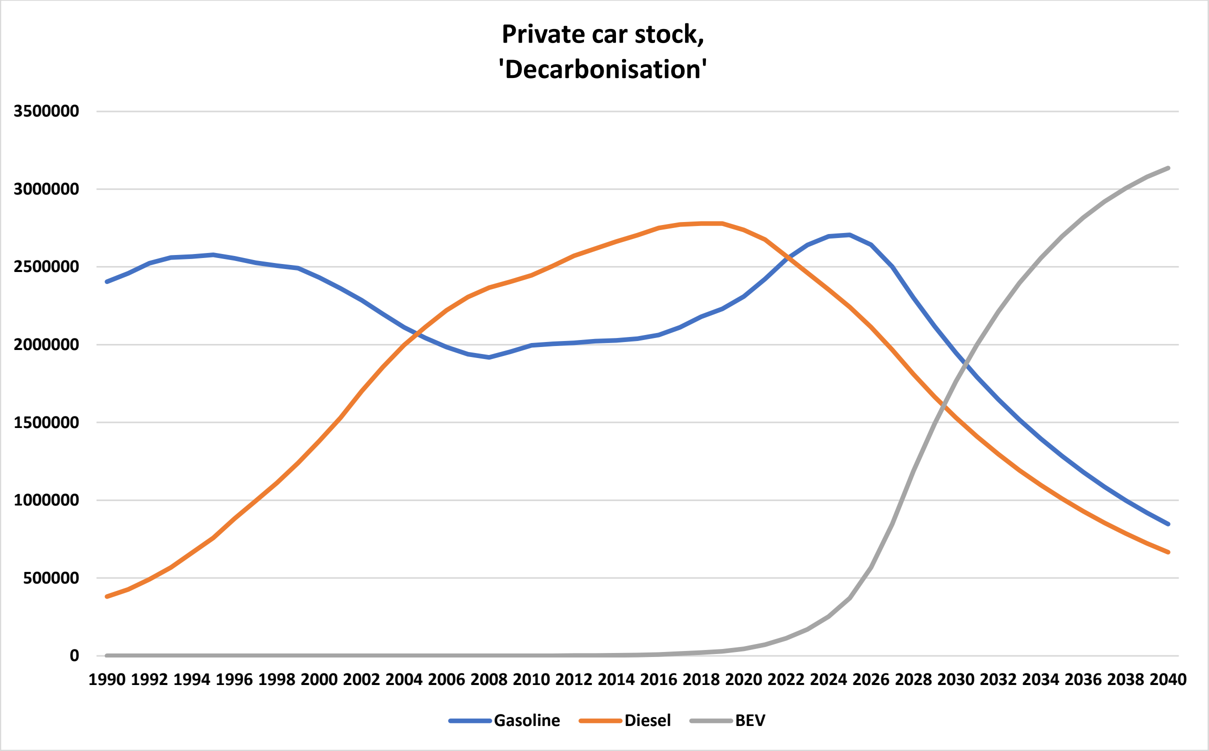
The main difference compared to the others in this scenario are several trends that increase energy efficiency and decrease the demand (km driven) for private vehicle transport. These trends are incorporated in functions of private vehicle demand, derived from historical data in the NEMO dataset and from the existing literature.

Purchases of private vehicles have in the past been dependent on population, real household income and a negative trend. The latter comprises long-run socio-economic changes like less driving licenses per head of population, more public transport infrastructure and use, etc. The "Decarbonization 2040 – high system efficiency"-scenario assumes that these changes will be reinforced until 2040 and that population growth and real income will not be significant drivers anymore for vehicle purchases. Instead, only a negative trend is effective, smaller than the trend that was derived from the function adjusted to historical data.

For the share of BEV, a function with vehicle prices, fuel and electricity prices as well as a positive trend has been calibrated for 2017. The parameters for this function have been derived from a study based on a large cross-section dataset for Norway (Fridstrøm and Østli, 2021). The vehicle price development in the "Decarbonization 2040 – high system efficiency"-scenario is the same as in the "Renewable 2030 scenario", as these developments are driven by technology development and existing policies (rebates for BEV purchases). The fuel prices (gasoline, diesel) comprise the same CO_2 prices as have been assumed for the ETS (Figure 1).

As a result of these two calibrated functions together with the assumptions about trends, the private car stock shows a peak ('peak car') in 2026 with 5.32 mill. Of cars, descending to the value of the 2013-stock in the year 2040. The BEV-share (in the stock) reaches 34.5% in 2030 and 67.9% in 2040, with a share of BEV in yearly investment (purchases) of 100% from 2031 on.

Fig. 13. Private car stock in the scenario "Decarbonization 2040"

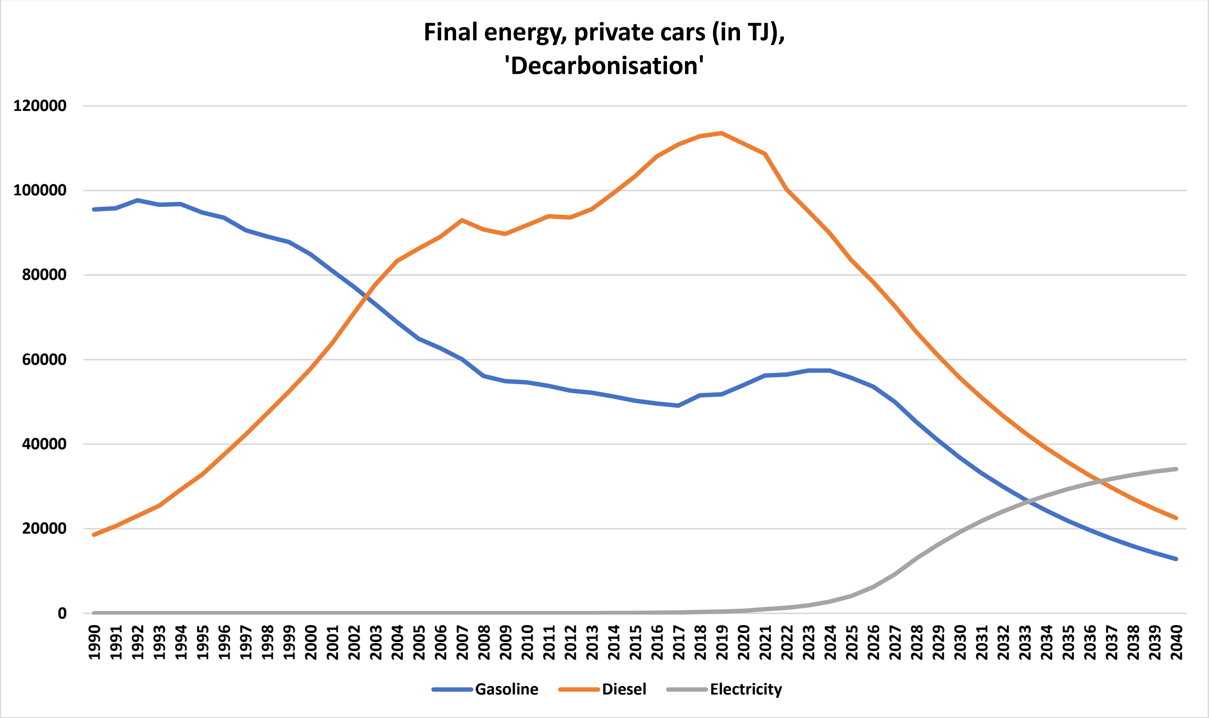


Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

In this scenario, almost full decarbonization of private transport is achieved in 2040: that amounts to a decrease of 78% (- 35.8 TWh) of gasoline and diesel demand between 2020 and 2040. This is substituted yb electricity demand, but given that the electric vehicle is much more energy efficient, the increase of electricity only corresponds to 26% of the reduction in gasoline/diesel demand. Electricity demand increases by 9.3 TWh between 2020 and 2040, and this additional demand is passed on to the electricity generation sector (sector coupling).

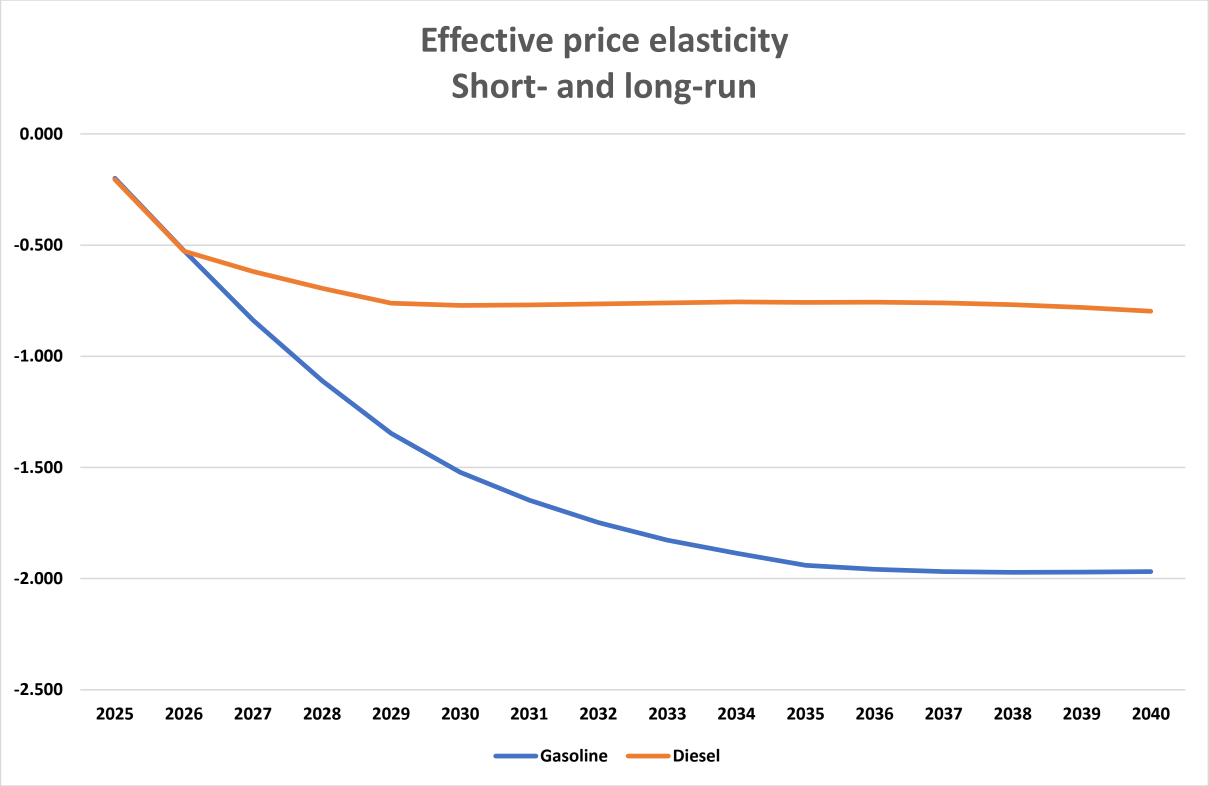
The impact of fuel prices on diesel and gasoline demand can be isolated, using the functions for vehicle purchases and isolating the other factors, i.e. no 'peak car' taking place, and no negative trends and vehicle price effect being active. Figure 11 clearly reveals that the impact of the fuel prices on energy demand increases over time due to accumulation effects in the stock of BEV. That means that the observed short-run price elasticity of -0.2 of fuel price increases on energy demand rises to a long-run elasticity of -2 for gasoline and -0.8 for diesel. The concept of short- and long-run price elasticity is in this scenario not measured by econometric methods as in large part of the literature, but explicitly described by embodied technical change that is driven by prices (induced technical change).

Fig. 14. Final energy, private cars in the scenario "Decarbonization 2040"



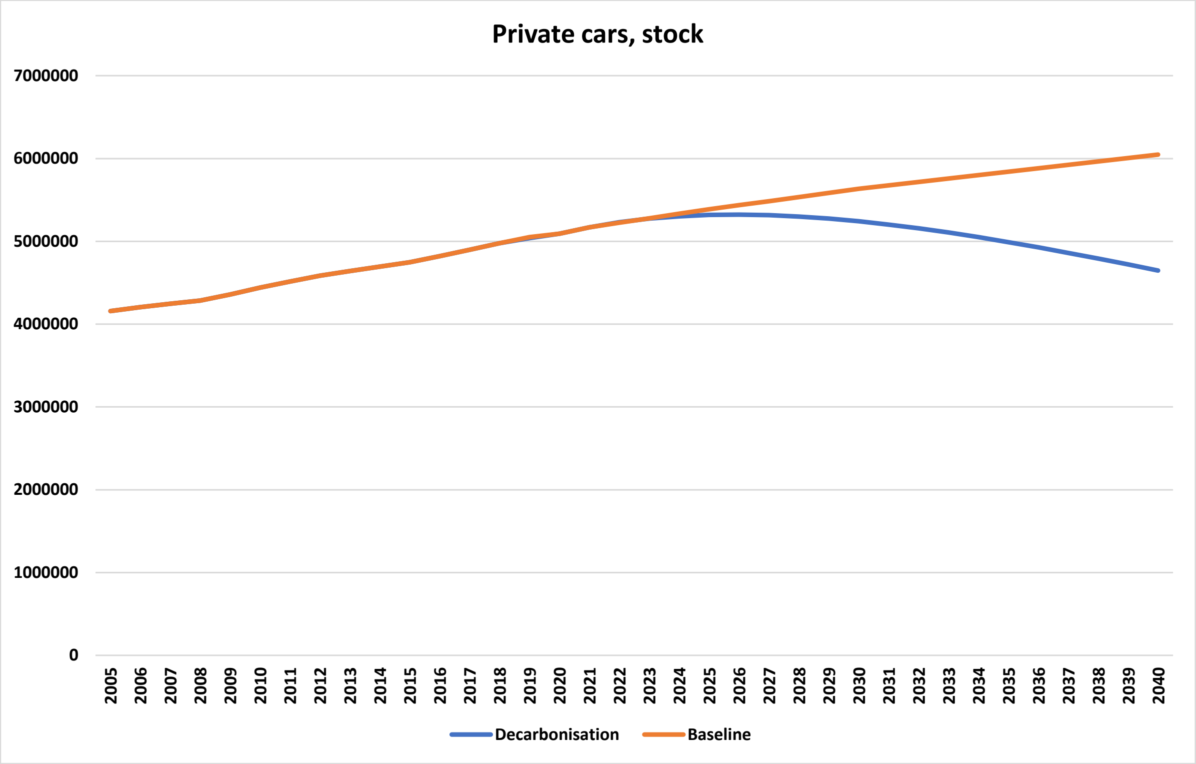
Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

Fig. 15. Effective price elasticity, short- and long-run in the scenario "Decarbonization 2040"



Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

Fig. 16. Peak Car in 2026, implicit modal shift (Person-km share of cars: -16.5%points)



Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

The ‘peak car’ phenomenon (Figure 12) in this scenario is directly driven by structural breaks in the function for vehicle purchases that translates into a different development of the stock than in the other scenarios. That implies that, if the mobility demand by unit of the stock is the same as in the other scenarios, i. e. the same amount of km is driven per car and year, the total number of km driven by vehicles will be reduced. If total transport demand (total person-km) stays the same, that, in turn, implies a significant modal shift. In this scenario, the development of the modal split therefore is not acting as a driver of vehicle demand, but *vice versa*. The implicit shift in the modal split amounts to -16.5 percentage points in the share of cars in total person-km.

References:

Baumann et al. Erneuerbares Gas in Österreich 2040, Austrian Energy Agency, study for the Federal Ministry of Austria for Climate Action, Environment, Energy, Mobility, Innovation and Technology. 2021.

Baylis, K., Fullerton, D., and Karney, D. H. (2014). Negative leakage. Journal of the Association of Environmental and Re-source Economists, 1(1-2):51–73.

Bergmann, M. et al. (2005) Quality Criteria for Transdisciplinary Research A Guide for the Formative Evaluation of Research Projects.

Bernath, Ch., Deac, G., Sensfuß, F. (2020). Impact of sector coupling on the market value of renewable energies – A model-based scenario analysis. Applied Energy 281 (2021) 115985. https://doi.org/10.1016/j.apenergy.2020.115985.

BG. Bundesgesetz zum Ausstieg aus der fossil betriebenen Wärmebereitstellung (Erneuerbare-Wärme–Gesetz - EWG), 212/ME XXVII. GP - Ministerialentwurf - Gesetzestext 12/ME XXVII. GP - Ministerialentwurf – Gesetzestext, 2022.

Biswas S, Kulkarni AP, Giddey S and Bhattacharya S (2020) A Review on Synthesis of Methane as a Pathway for Renewable Energy Storage With a Focus on Solid Oxide Electrolytic Cell-Based Processes. Front. Energy Res. 8:570112. doi: 10.3389/fenrg.2020.570112

Blanco, Herib, Wouter Nijs, Johannes Ruf, André Faaij. Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization, Applied Energy, Volume 232, 2018, Pages 323-340.

Bloess, A., Schill, W.P., Zerrahn, A. (2018). Power-to-heat for renewable energy integration: A review of technologies, 22 modelling approaches, and flexibility potentials, Applied Energy, Volume 212, 2018, Pages 1611-1626, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2017.12.073.

Bloomberg Finance L.P. (2020). Sector Coupling in Europe: Powering Decarbonization. Potential and Policy Implications of Electrifying the Economy. BloombergNEF, Eaton, Statkraft, 22odellin 2020. https://data.bloomberglp.com/professional/sites/24/BNEF-Sector-Coupling-Report-Feb-2020.pdf

Böhringer, C. (2014). Two decades of European climate policy: A critical appraisal. Review of Environmental Economics and Policy, 8(1):1– 17.

Böhringer, C., Koschel, H., and Moslener, U. (2008). Efficiency losses from overlapping regulation of EU carbon emissions. Journal of Regulatory Economics, 33(3):299–317.

Brauner, G. (2019). Systemeffizienz bei regenerativer Stromerzeugung, Strategien für effiziente Energieversorgung bis 2050. Springer Verlag.

Büscher, Ch., Scheer, D. Nabitz, L. (2020). Future converging infrastructures. Assessing the consequences of increasing sector coupling and integration. TATuP – Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis / Journal for Technology Assessment in Theory and Practice, 29 (2020) 2. https://doi.org/10.14512/tatup.29.2.17

Deutsche Umwelthilfe (2017). Sector coupling: Using electricity for heating and transport to protect the climate. Background paper.

Connolly, D.; Lund, H.; Mathiesen, B.V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew. Sustain. Energy Rev. 2016, 60, 1634–1653.

EC – European Commission (2019). Summary of the Commission Assessment of the Draft National Energy and Climate Plan 2021-2030: Austria, EC, Brussels, https://ec.europa.eu/energy/sites/ener/files/documents/necp_factsheet_at_final.pdf.

EC – European Commission (2018). A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.

Eckstein, J.; Kurdziel, M.-J.; Castro, L. Nascimento; Ordonez, J. Antonio (2020). Decreasing costs of renewables: Insights on energy sector planning and climate policy from three country case studies, Working Paper Sustainability and Innovation, No. S17/2020, Fraunhofer ISI, Karlsruhe.

EEG – Energy Economics Group (2017), Stromzukunft Österreich 2030. TU Wien, Vienna, https://static1.squarespace.com/static/5b978be0697a98a663136c47/t/5bddc29dc2241b8f6c2a08ac/1541259970635/Endbericht%2BStromzukunft%2Bsterreich%2B2030.pdf.

EEÖ – Erneuerbare Energie Österreich (2020). Analyse des Nationalen Klima- und Energieplans (NEKP) von Österreich. https://static1.squarespace.com/static/5b978be0697a98a663136c47/t/5ed79c61c8932671841ad4ea/1591188583642/EEOe_NECP_Visegrad-final.pdf

Eichner, T. and Pethig, R. (2018) EU-type carbon regulation and the waterbed effect of green energy promotion. Working paper, FernUniversität in Hagen

Eurelectric (2018). Decarbonisation pathways European Economy – EU electrification and decarbonization scenario modelling.

European Commission, Joint Research Centre (JRC) (2019): ENSPRESO - BIOMASS. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f

Federal Ministry of Sustainability and Tourism, 2019. Integrated National Energy and Climate Plan for Austria 2021-2030; pursuant to Regulation (EU) 2018/1999 of the European Parliament and of the Council on the Governance of the Energy Union and Climate Action.

FMST (Federal Ministry for Sustainability and Tourism) and FMTIT (Federal Ministry for Transport, Innovation and Technology) (2018). Austrian Climate and Energy Strategy, FMST and FMTIT, Vienna.

Fortes, A. Alvarenga, J. Seixas, S. Rodrigues (2015). Long-term energy scenarios: bridging the gap between socio-economic storylines and energy 23 Modelling, Technol. Forecast. Soc. Chang. 91 (2015) 161–178.

Fridgen, G., Keller, R. Körner, M. F., Schöpf, M. (2020). A holistic view on sector coupling, Energy Policy, Volume 147, 2020, 111913, ISSN 0301-4215, .

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. EEG der TU Wien im Auftrag der IG Windkraft. https://www.igwindkraft.at/mmedia/download/2017.07.10/1499698755049626.pdf

Hansen, K., Breyer, C., Lund, H., (2019a). Status and perspectives on 100% renewable energy systems. Energy 175, 471–480. https://doi.org/10.1016/j.energy.2019.03.092.

Hansen, K., Mathiesen, B.V., Skov, I.R., (2019b). Full energy system transition towards 100% renewable energy in Germany in 2050. Renew. Sustain. Energy Rev. 102, 1–13. https://doi.org/10.1016/J.RSER.2018.11.038.

Henning, H.-M.; Palzer, A. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part I: Methodology. Renew. Sustain. Energy Rev. 2014, 30, 1003–1018.

IEA – International Energy Agency – IEA (2020). Austria 2020. Energy Policy Review. https://www.iea.org/reports/austria-2020

Jarke, J. and Perino, G. (2017). Do renewable energy policies reduce carbon emissions? On caps and inter-industry leakage. Journal of Environmental Economics and Management, 84:102–124.

Jarke-Neuert, J. and Perino, G. (2019). Understanding Sector Coupling: The General Equilibrium Emissions Effects of Electro-Technology and Renewables Deployment (January 17, 2019). Available at SSRN: https://ssrn.com/abstract=3326407 or http://dx.doi.org/10.2139/ssrn.3326407

Junne, T., Xiao, M., Xu, L., Wang, Z., Jochem, P., Pregger, Th. (2019). How to assess the quality and transparency of energy scenarios: Results of a case study, Energy Strategy Reviews, Volume 26, 2019, 100380, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2019.100380.

Kratena, K. and A. Scharner (2020) MIO-ES: A Macroeconomic Input-Output Model with Integrated Energy System, Centre of Economic Scenario Analysis and Research (CESAR), Vienna 2020, available at: https://www.cesarecon.at/wp-content/uploads/2020/10/MIOES_Manual_Public_FINAL.pdf

Kumar, Shiva S., V. Himabindu, Hydrogen production by PEM water electrolysis – A review, Materials Science for Energy Technologies, Volume 2, Issue 3, 2019, Pages 442-454.

Landis, F., Marcucci, A., Rausch, S. et al. (2019). Multi-model comparison of Swiss decarbonization scenarios. Swiss J Economics Statistics 155, 12 (2019). https://doi.org/10.1186/s41937-019-0040-8

Lund, H., Möller, B., Mathiesen, B.V., Dyrelund, A. (2010). The role of district heating in future renewable energy systems. Energy 35 (3).

Lund, H., Østergaard, P.A., Connolly, D., Mathiesen, B.V. (2017). Smart energy and smart energy systems. Energy 137.

Lund, H., Østergaard, P.A., Connolly, D., Ridjan, I., Mathiesen, B.V., Hvelplund, F., Thellufsen, J.Z., Sorknæs, P. (2016). Energy Storage and Smart Energy Systems. Int. J.Sustain. Energy Plann. Manag. 11, 3–14. https://doi.org/10.5278/ijsepm.2016.11.2.

Maruf, M..N.I. Sector Coupling in the North Sea Region—A Review on the Energy System Modelling Perspective. Energies 2019, 12, 4298. https://doi.org/10.3390/en12224298

Mason, I.; Page, S.; Williamson, A. A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. Energy Policy 2010, 38, 3973–3984.

Mathiesen, B.V.; Lund, H.; Karlsson, K. 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy 2011, 88, 488–501.

Mathiesen, B.V.; Lund, H.; Connolly, D.; Wenzel, H.; Østergaard, P.A.; Möller, B.; Nielsen, S.; Ridjan, I.; Karnøe, P.; Sperling, K. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy 2015, 145, 139–154.

Nastasi, B.; Lo Basso, G. (2016). Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 2016, 110, 5–22.

OIB, Langfristige Renovierungsstrategie, OIB-330.6-022/19-093. Vienna, 2020.

Oei, Pao-Yu; Burandt, Thorsten; Hainsch, Karlo; Löffler, Konstantin; Kemfert, Claudia (2020): Lessons from Modeling 100% Renewable Scenarios Using GENeSYS-MOD, The Energy Journal, ISSN 2160-5882, IAEE, Cleveland, Vol. 9, Iss. 1, pp. 103-120, http://dx.doi.org/10.5547/2160-5890.9.1.poei.

Pavičević, Mm., Mangipinto, A., Wouter, N., Lombardi, F., Kavvadias, K., Navarro, J.P.J., Colombo, E., Quoilin, S. (2020). The potential of sector coupling in future European energy systems: Soft linking between the Dispa-SET and JRC-EU-TIMES models, Applied Energy, Volume 267, 2020, 115100, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.115100.

Perino, G., Jarke, J. (2015). Do Renewable Energy Policies Reduce Carbon Emissions? On Caps and Intra-Jurisdictional Leakage, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2015: Ökonomische Entwicklung – Theorie und Politik – Session: Environmental Economics IV, No. D13-V1, ZBW – Deutsche Zentralbibliothek für Wirtschaftswissenschaften, Leibniz-Informationszentrum Wirtschaft.

Ram, M., Bogdanov, D., Aghahosseini, A., Mensah, Th., Schmela, M., Rossi, R., Beauvais, A., Clark-Memler, L., Thoring, K. (2020). 100% Renewable Europe: How To Make Europe’s Energy System Climate-Neutral Before 2050.

Robinius, M.; Otto, A.; Heuser, P.; Welder, L.; Syranidis, K.; Ryberg, D.S.; Grube, T.; Markewitz, P.; Peters, R.; Stolten, D. Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling. Energies 2017, 10, 956. https://doi.org/10.3390/en10070956

Rogge, M.; Wollny, S.; Sauer, D. Fast Charging Battery Buses for the Electrification of Urban Public Transport—A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements. Energies 2015, 8, 4587–4606.

Samsatli, S.; Staffell, I.; Samsatli, N.J. Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in Great Britain. Int. J. Hydrog. Energy 2016, 41, 447–475.

Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., Stolten, D., 2015. Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany. Int. J. Hydrogen Energy 40 (12), 4285–4294. https://doi.org/10.1016/j.ijhydene.2015.01.123.

Teng, F.; Aunedi, M.; Strbac, G. Benefits of flexibility from smart electrified transportation and heating in the future UK electricity system. Appl. Energy 2016, 167, 420–431.

Tom, Karin Treyer, Christian Bauer, Marco Mazzotti, Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources, Environ. Sci. Technol. 2021, 55, 16, 11397–11411

Umweltbundesamt (2017): Energie- und Treibhausgasszenarien im Hinblick auf 2030 und 2050, Wien. https://www.umweltbundesamt.at/aktuell/publikationen/publikationssuche/publikationsdetail/?pub_id=2250

Van Nuffel, L., Gorenstein Dedecca, J., Smit, T., Rademaekers, K. (2018). Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise? Study requested by the ITRE committee of the European Parliament.

Victoria, M., Zhu, K., Brown, T., Andresen, G. B., Greiner, M. (2019). The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system, Energy Conversion and Management, Volume 201, 2019, 111977, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2019.111977.

Welder, L., Ryberg, D.S., Kotzur, L., Grube, T., Robinius, M., Stolten, D., (2018). Spatiotemporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy 158, 1130–1149. https://doi.org/10.1016/j.energy.2018.05.059.