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

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ELECTRO_COUP

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Introduction

In this working paper we describe the scenarios developed in the project ELECTRO_COUP 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 sectors.

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 greenhouse gas (GHG) emissions (see Eurostat[1]). To reduce these emissions, the Effort Sharing Decision sets national emissions targets. The individual Member States are responsible for achieving these targets. Subsequently, with the updated Effort Sharing Regulation (ESR) Austria has committed to reduce emissions in non-ETS sectors by at least 48% until 2030 compared to 2005. This surpasses the EU-wide reduction target of -40%. Related to 2021, this translates to a necessity for a reduction in emissions from non-ETS sectors of approximately 19 million tonnes of CO_2 equivalents, meaning a 39% reduction (Umweltbundesamt, 2023).

When evaluated against Austria's overall emissions, the overall non-ETS sector contributed 63% to the total GHG emissions in 2021 (Umweltbundesamt, 2023). 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 2021, the sector accounted for 27.8% of total emissions and emitted 21.6 million tonnes of CO_2 equivalents in 2021. Thus far, Austria has achieved a reduction in GHG emissions within the transport sector exclusively during the period 2005 to 2012. However, after this period, emissions have experienced a continuous increase, primarily driven by the expanding traffic volume. It was only in 2020, due to the pandemic, that a significant decline in emissions occurred (Umweltbundesamt, 2023).

GHG emissions from the buildings sector amounted to 9.1 million tonnes of CO_2 equivalents in 2021, representing 11.7% of total emissions. Between 1990 and 2021, emissions decreased by 3.8 million tonnes (-29.5%). The most significant reductions have been observed since 2005. These improvements can be attributed to a combination of factors, including initiatives such as thermal refurbishment, a higher share of renewable energy sources, the modernization of heating systems, and an increased utilization of district heating. However, the number of primary residential dwellings increased during this period, and there was a continuous expansion in the usable floor space per household (Umweltbundesamt, 2023).

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]. In addition to this ambitious goal, Austria has also made a commitment to attaining **net zero GHG emissions 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).

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[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.

These objectives 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.

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). The major portion of this increase must be sourced from variable renewable energy, such as photovoltaic (PV) and wind, as the hydropower resources are largely tapped, and the growth in biomass generation is not anticipated to be substantial (IEA, 2020). In any case, achieving the 100% renewable electricity target by itself will not be sufficient to meet the 2030 target for 45-50% 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 is important to highlight 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 this project, we understand sector coupling as combining electricity transport and heating. The decarbonization path designed combines fuel-shifts and efficiency increases in the non-ETS sectors with support measures for renewable electricity and heat generation. 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

Within the project ELECTRO_COUP we designed three decarbonization scenarios tailored specifically for mobility and space heating in Austria. These scenarios explore paths for electrification in both the transport and heating sector, as well as sector coupling, all with the aim of contributing to achieving full decarbonization by 2040.

The scenarios were simulated using an energy-economy model, which integrates bottom-up information about the heating and transport sector, to see how they would affect energy use, carbon emissions, and the economy. The modeling provides estimates for several indicators, including gross domestic product (GDP), CO_2 emissions, energy efficiency, value added, and employment by industry. The simulations were carried out up to the year 2040.

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 **baseline scenario** 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 three **"Decarbonizing 2040"** scenarios. In addition to the measures and activities in the baseline these scenarios analyse the potential of stronger sector coupling and decarbonization policies in the non-ETS sectors. To highlight different possibilities and levels of efficiency we differentiate between **high and low system efficiency**. This differentiation illustrates that decarbonization can be achieved through various approaches, with varying degrees of cost-effectiveness and efficiency.

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. We analyse two versions of the high system efficiency scenario with regard to the reaction of power generation to the additional electricity demand from the non-ETS. In the first version this additional demand is met by an increase in renewable power generation, so that the 100% renewable electricity-target is still achieved. In the second version, the 'worst case' of sector coupling it is assumed, that all the additional electricity demand is supplied from fossil (gas) power generation. As the analysis does not include the use of an optimization model of the electricity sector (like TIMES; MEDEAS, etc.), where prices and constraints would determine the technologies in use for power generation, this issue has to be researched in sensitivity analysis.

The **low system efficiency scenario** 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 the scenario assumptions (e.g., the development of CO_2 prices, 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 baseline scenario is taken from Pietzcker et al. (2021). 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**. In this respect the decarbonization scenarios generally are 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: ensuring EU's energy security (ending 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[3]) sets out the conditions for the promotion of electricity generation from renewable sources. The EAG introduced the instrument of the market premium, which replaced the previous fixed feed-in tariffs under the Green Electricity Act. The aim of the market premium is to compensate for the difference between the production costs of renewable electricity and the average market price for electricity. The market premium is granted as a subsidy if electricity is generated from renewable sources and fed into the public electricity grid, and if corresponding guarantees of origin are available. In the authors' view, the market premium appears to be a suitable instrument for promoting the penetration of renewable energies in the electricity sector and also for facilitating the implementation of efficient storage technologies. However, this requires a sufficiently high market premium remuneration.

In this context, the key technical challenge is to effectively coordinate irregular energy generation from fluctuating sources with consumer demand to ensure an economical and needs-based supply of electricity and heat. Energy storage systems play a decisive role, as they enable the temporal decoupling of energy generation and consumption and can therefore take on important tasks as key technologies in the future energy system. However, storage solutions should not be considered in isolation, but as part of a comprehensive solution

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[3] Bundesgesetz über den Ausbau von Energie aus erneuerbaren Quellen (Erneuerbaren-Ausbau-Gesetz – EAG)
StF: BGBl. I Nr. 150/2021 (NR: GP XXVII RV 733 AB 982 S. 115. BR: 10690 AB 10724 S. 929.)
https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20011619

that interacts closely with other measures (AIT, 2019). Pumped storage power plants are currently the most important option for grid stabilization and storage of renewable energy in Austria and will remain so in the future. AIT et al. (2022) therefore recommend increasing turbine and pump capacity. The authors of the study also emphasize the central importance of supra-regional and transnational electricity exchange via transmission grids as a key source of flexibility in the domestic electricity market. This enables the large-scale balancing of regional surpluses and deficits in electricity production.

Both techno-economic advances (such as cost reduction, service life extension, higher efficiency and safety) and the removal of economic-regulatory barriers, such as regulatory hurdles and market access problems, represent major challenges for the energy storage sector (EC 2023). For example, storage systems are currently taxed twice in Austria, once when storing energy as a consumer and a second time when withdrawing energy as a producer. This problem should be solved with the new Electricity Industry Act.

Furthermore, large-scale projects to expand the energy infrastructure are often in conflict with local interest groups, which means that long approval procedures are to be expected for these projects. The authors believe that speeding up procedures for important infrastructure projects while respecting the rights of all parties involved can make a significant contribution to the expansion of the energy storage facilities required to implement the energy transition. This aspect was included in the current amendment to the Environmental Impact Assessment Act (UVP-G) and should mean that large infrastructure projects in the field of energy storage can be implemented more quickly and easily in future.

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 goals mentioned are relevant for the baseline scenario, while the last two goals are applicable to 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.

Baseline Scenario

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/tCO_2 in 2040 (in nominal terms).

Fig. 1. ETS carbon prices 2023 - 2040 (€ 2015/t) in the baseline 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)

Figure 2 illustrates the output shares of electricity generation in the “baseline 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. Analysis of various renewable energy sources reveals a notable upward trend in the shares of wind and PV until 2040, with hydro power accounting for 47% in 2030 but declining to 31% by 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).

In the **non-ETS sectors** heating and 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. We assume an overall average efficiency of power-to-X technologies of 52.5% and an import share (for Austria) of 90%. The e-fuels are therefore produced in regions, which - despite the low efficiency of the processes – have a cost advantage for these technologies. Nevertheless, the purchaser price in Austria will be high (similar to natural gas, including the CO_2 price), 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 direct 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 direct electrification. An increase of electricity demand can be expected from higher electrification. 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.

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 baseline 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 baseline 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.

For these scenario simulations the Invert model has been used to calculate the transformation scenarios for the built environment. The Invert model is a bottom-up model for analysing 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, as well as 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 to 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.

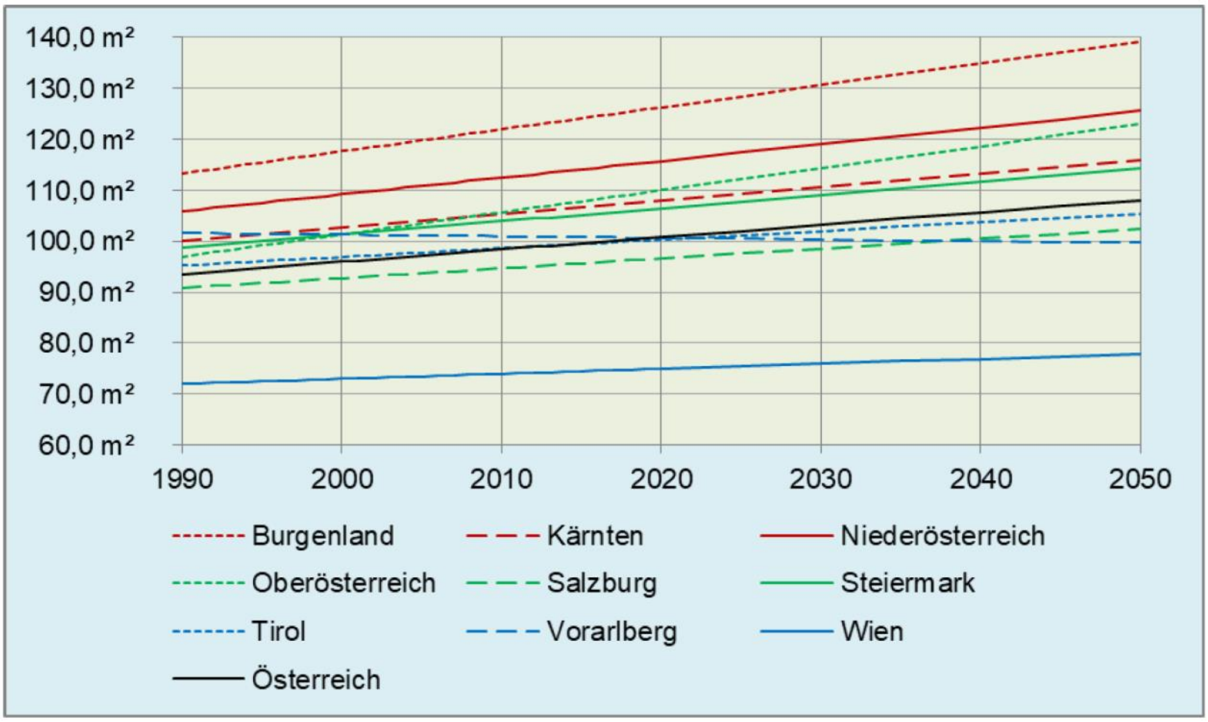
Baseline Scenario

As said above, this scenario is our implementation of the latest Austrian Long Term Renovation Strategy. The main characteristics of the Austrian LTRS are:

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 Austria, 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 baseline scenario, based on the Austrian Long Term Renovation Strategy (LTRS)



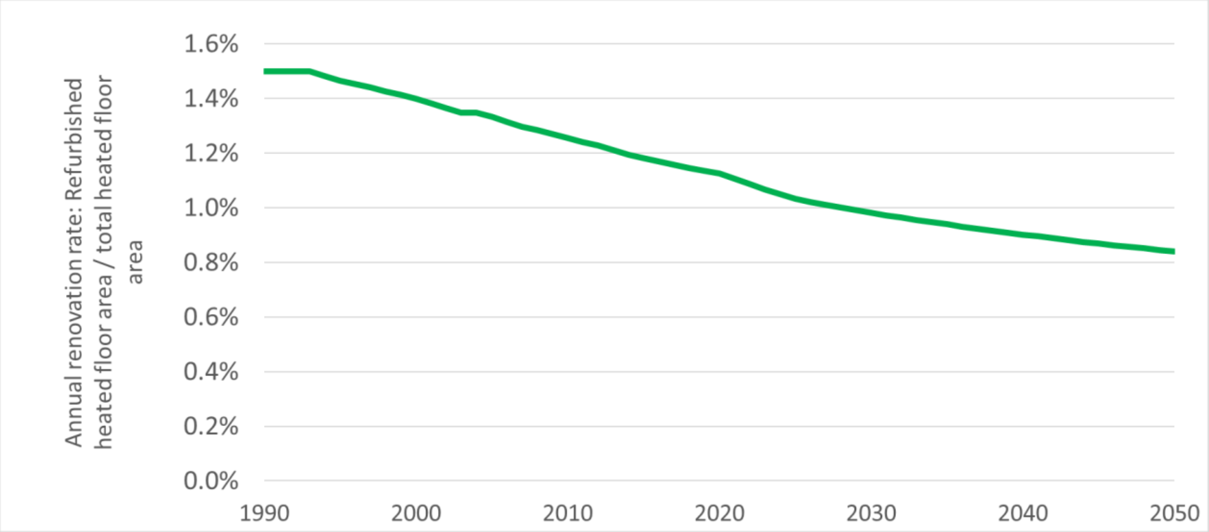
Source: OIB (2020)

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 decreases 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 (see Figure 4).

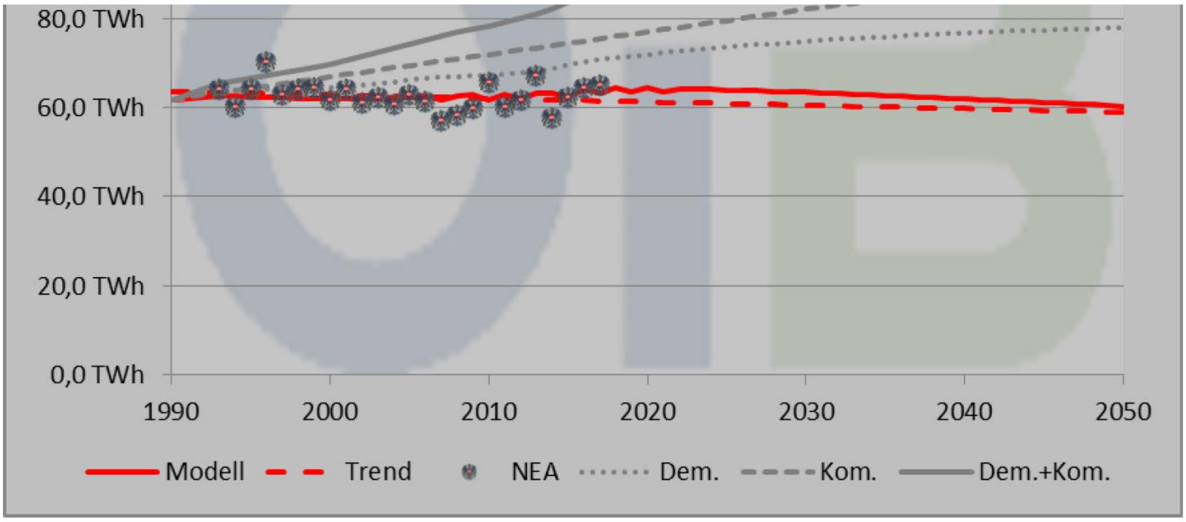
Fig. 4. Development of the annual refurbishment rate in the baseline scenario, based on the Austrian Long Term Renovation Strategy (LTRS)



Source: Own representation.

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)

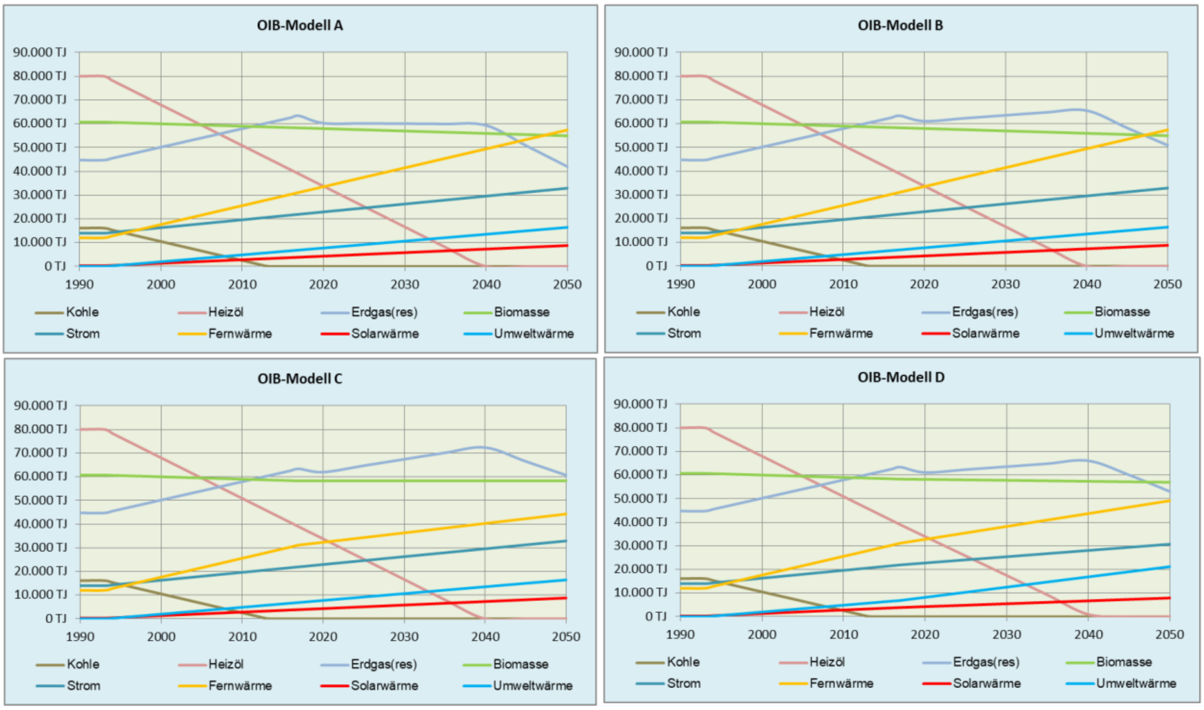
Phase out of heating oil, rather constant demand for natural gas until 2040

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 (Fig. 6):

- 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)

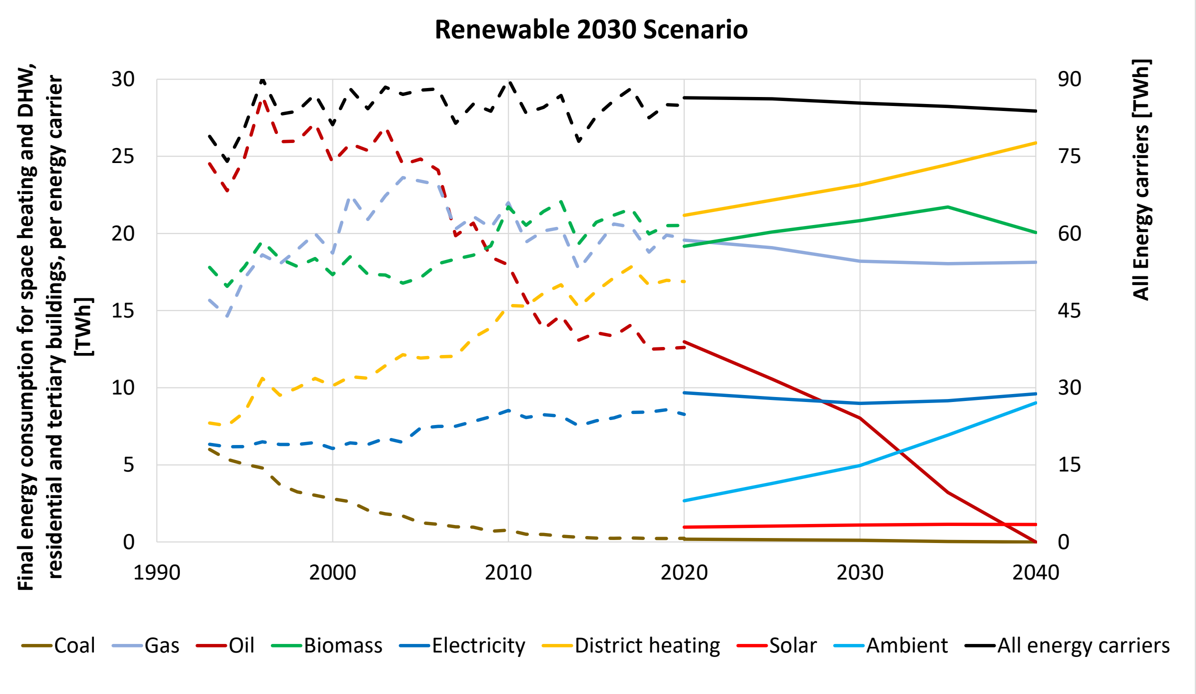
Our Invert implementation of the baseline scenario shares the main characteristics of the underlying Austrian LTRS scenario:

- 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 "Baseline 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.

"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, natural gas is what remains to be 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 15% of that demand. Subsequently, the following analysis uses a split between e-methane and bio-methane of 85% to 15 %.

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 (CH4) from H2 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:

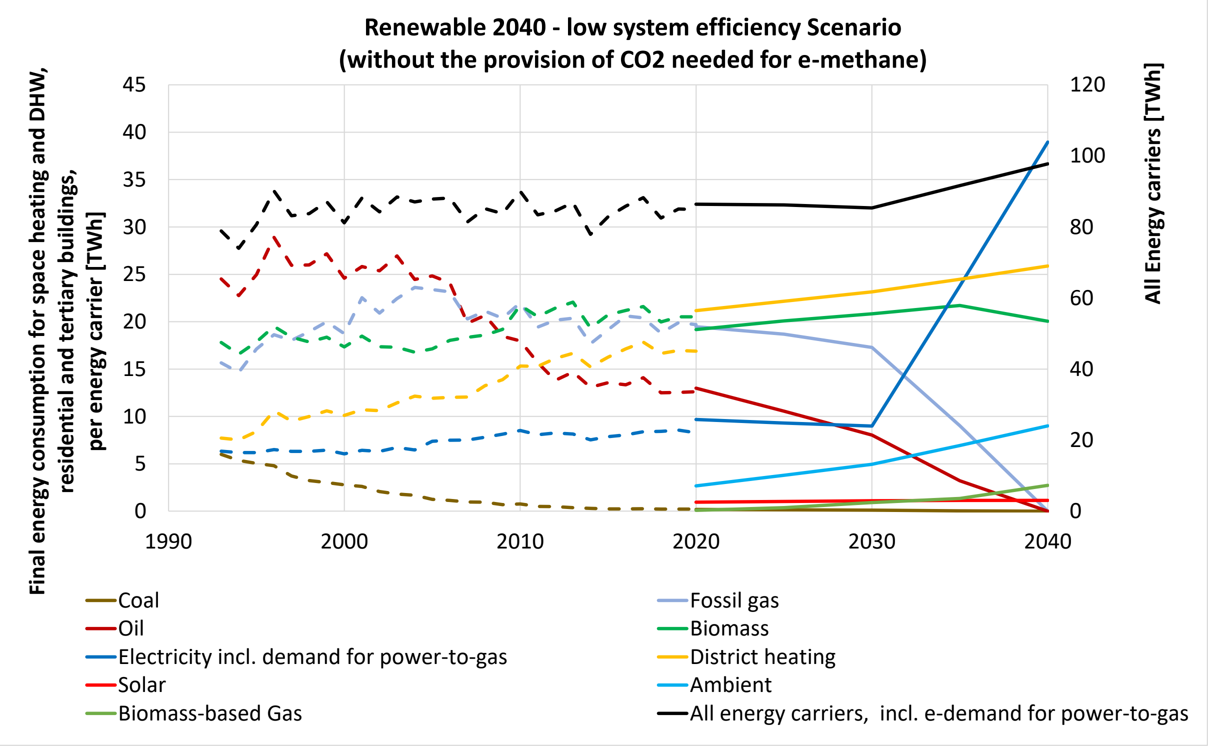
- Technologies used
- Possibility to utilize heat released by processes
- Availability waste heat needed by processes
- Availability of CO_2

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[4], 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 to produce 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.

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[4] For 1 kg methane (CH_4), 2,75 kg of CO_2 are required. Terlouw et al. specifies the energy demand to capture 1 kg of CO_2 as 500 kWh of electricity and 1500 kWh heat at around 100°C.

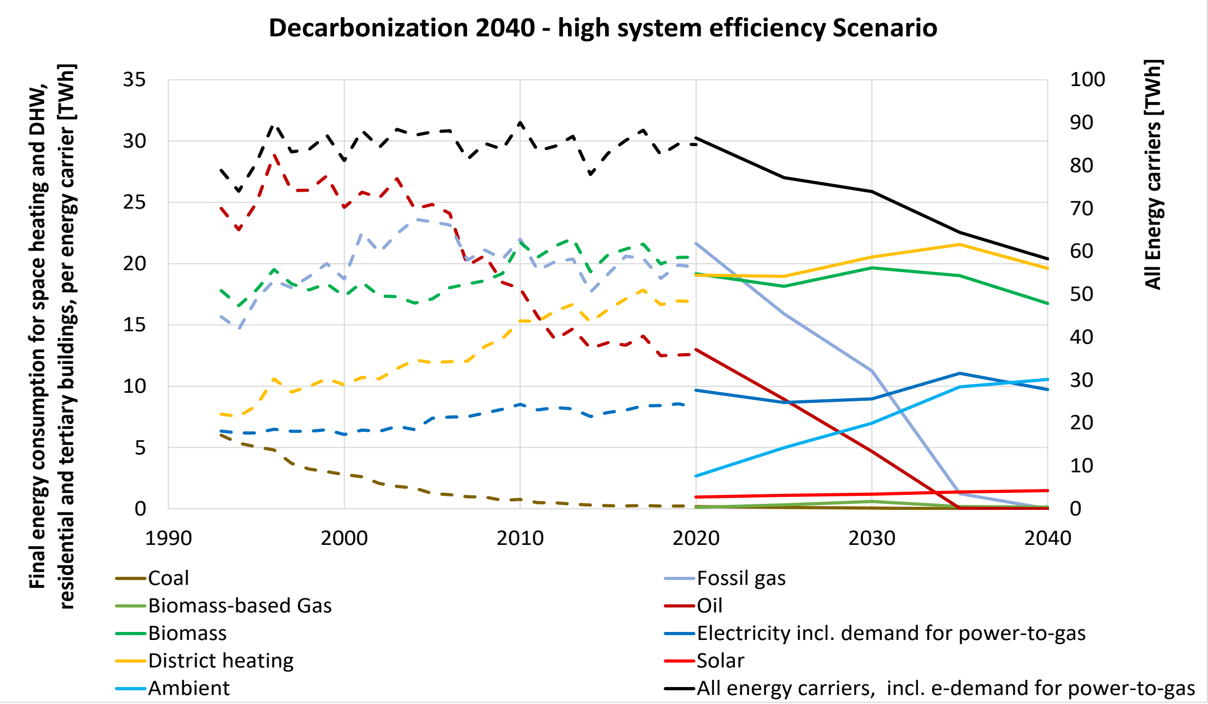
“Decarbonizing 2040 – high system efficiency”

The final scenario, "Decarbonizing 2040 – high system efficiency," incorporates a more ambitious approach to energy efficiency by implementing a range of measures to decrease energy demands and delivered energy. These measures reflect our interpretation of the ambitious energy efficiency and climate mitigation policies currently under discussion in Austria, expressed in a draft version of the Renewable Energy Act (Erneuerbare-Wärme-Gesetz - EWG, BG, 2022). Among other measures, the act foresees to replace oil and coal fired boilers by renewable energy-based heating systems until 2035. Gas-fired boilers must switch to alternative until 2040; carbon-neutral gas is permitted for use only in exceptional cases. In addition, 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, that the annual refurbishment rate exceeds 3% in the early 2030, a goal that is currently also expressed by the Austrian government and the Federal Ministry of Austria for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK). The energy performance standards for both renovated and newly constructed buildings are designed to slightly surpass current legislation, aligning with ongoing discussions for new standards, however without using the less ambitious certification rule of the fGEE (“Gesamtenergie-Effizienzfaktor”).

For the possible role of biomass-based energy carriers we decided to assume 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 in the “Decarbonizing 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 being phased out. 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.

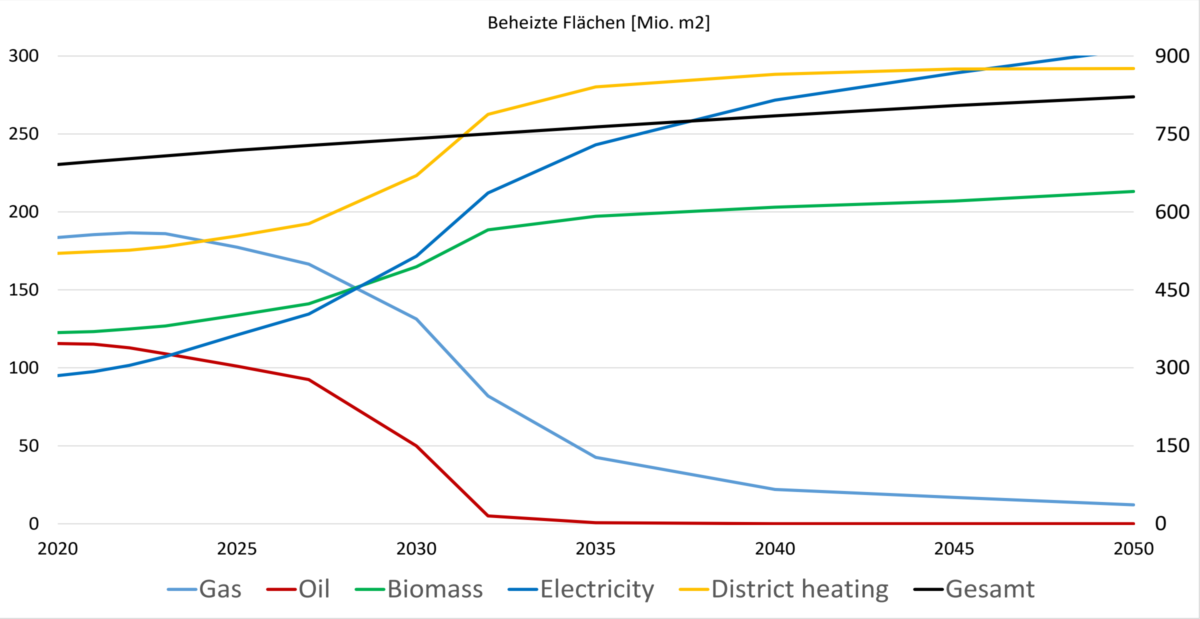
Fig. 9. Final energy consumption for space heating and DHW in the Scenario Decarbonizing 2040 – high system efficiency



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.

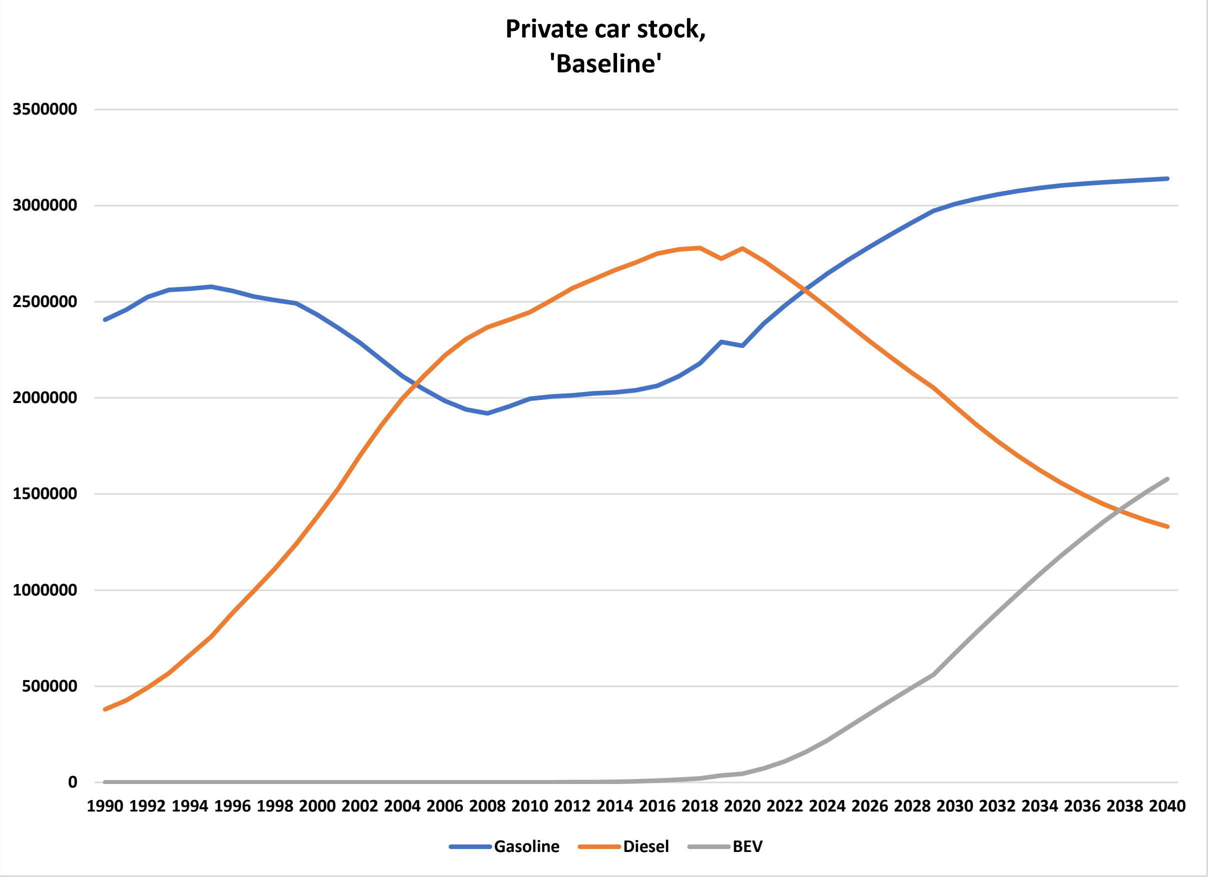
Scenarios for private transport

Baseline Scenario and “Decarbonizing 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 baseline scenario corresponds to 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 baseline 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 baseline 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, baseline scenario

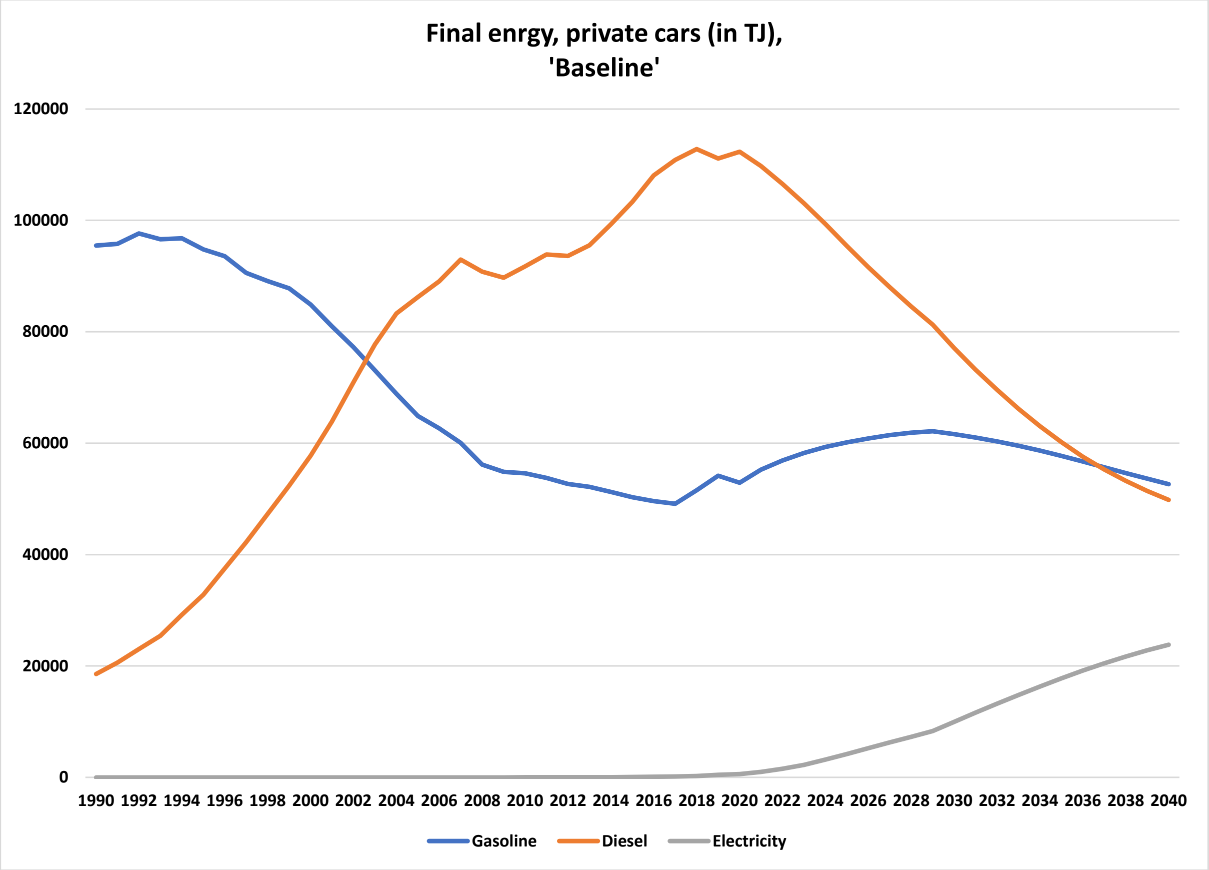


Source: Own calculation based on the NEMO model (TU Graz, Umweltbundesamt)

As Figure 12 shows, that implies an important decline in diesel demand, but gasoline demand almost stays constant in the long-run, and both fuels still sum up to 100 PJ in 2040.

At the same time, this scenario might in several aspects 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.

Fig. 12. Final energy (TJ), private cars, 1990 – 2040, baseline scenario



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

“Decarbonizing 2040 –high system efficiency”

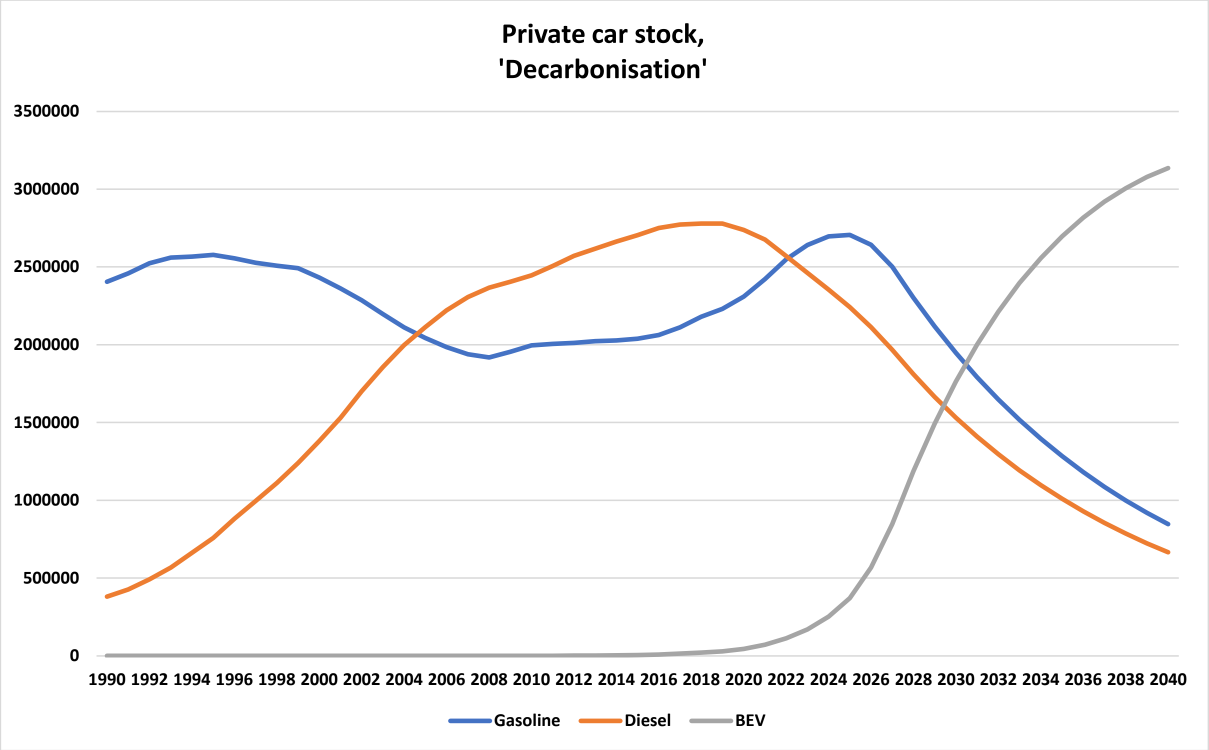
The main difference compared to the other scenarios are several trends that increase energy efficiency and decrease the demand (km driven) for private vehicle transport. These trends are incorporated in functions of private vehicle demand, derived from historical data in the NEMO dataset and from the 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, somewhat smaller than the trend that was derived from the function adjusted to historical data.

For the share of BEV, a log-linear 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 applying discrete choice models based on a large cross-section dataset for Norway (Fridstrøm and Østli, 2021). Aggregate price elasticity values are not analytically derived from the discrete choice models in Fridstrøm and Østli (2021), but from model simulations for different prices. The vehicle price development in the "Decarbonization 2040 – high system efficiency"-scenario is the same as in the "Baseline 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). The positive trend for the BEV share has been calibrated with a parameter of 0.35 which corresponds to the average growth rate of global BEV production since 2016. This is a relevant addition to the parameters from the Norwegian studies, as Norway has increased the BEV share in a period with less BEV producers and less advanced technology. The take-off of BEV production in the last decade should *ceteris paribus* (independent of prices) accelerate this shift towards BEV. This is what the positive trend parameter measures.

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 until 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"



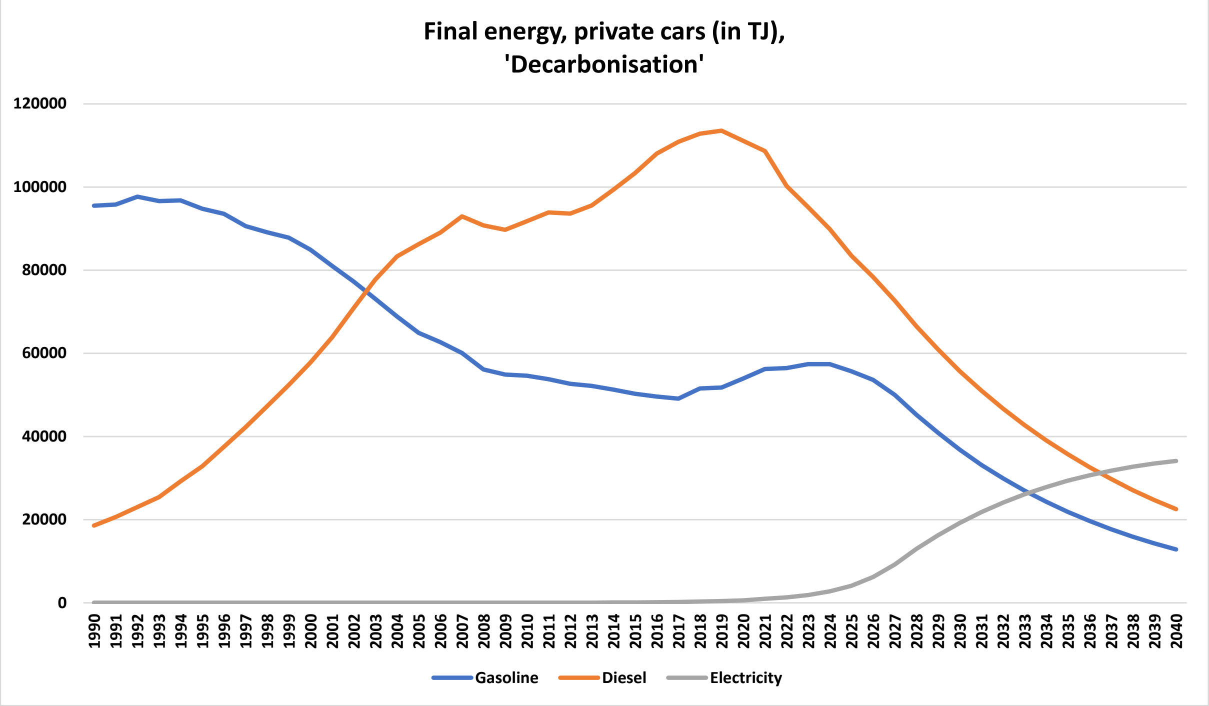
Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

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 by 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. The resulting increase in demand is then transmitted to the electricity generation sector through the sector coupling effect.

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 14 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.

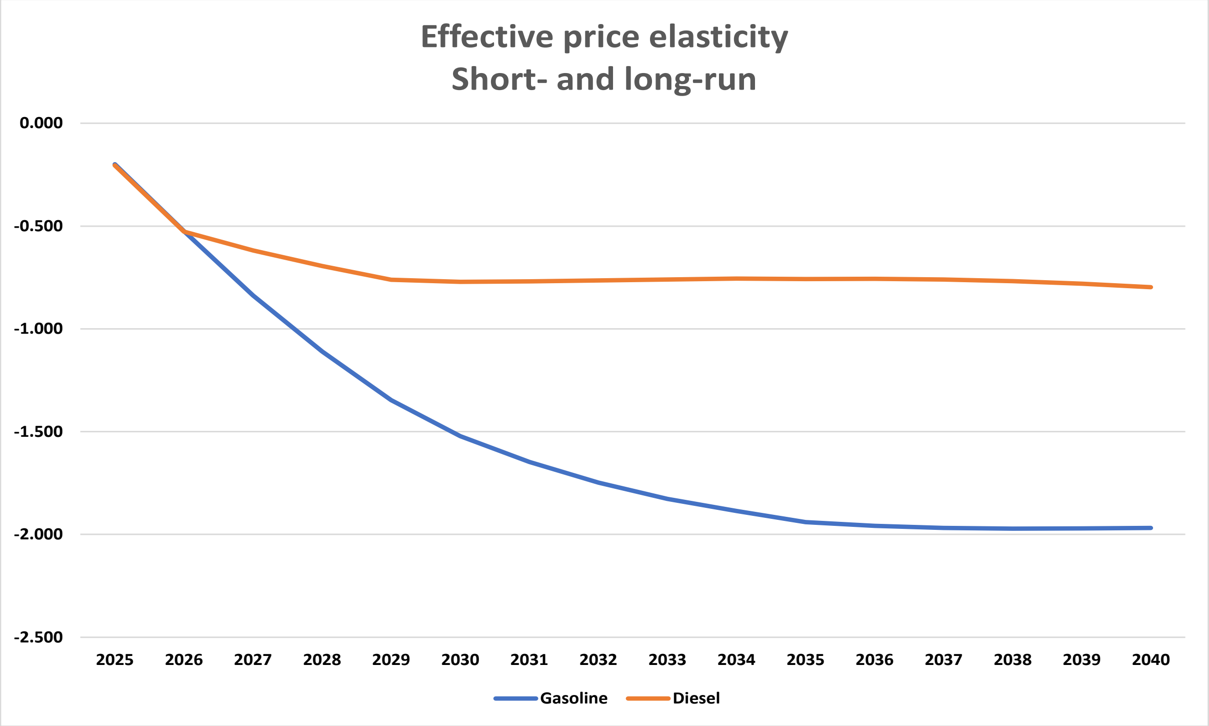
The concept of short- and long-run price elasticity is in this scenario not measured by econometric methods as in large part of the literature, but explicitly described by embodied technical change that is driven by prices (induced technical change).

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



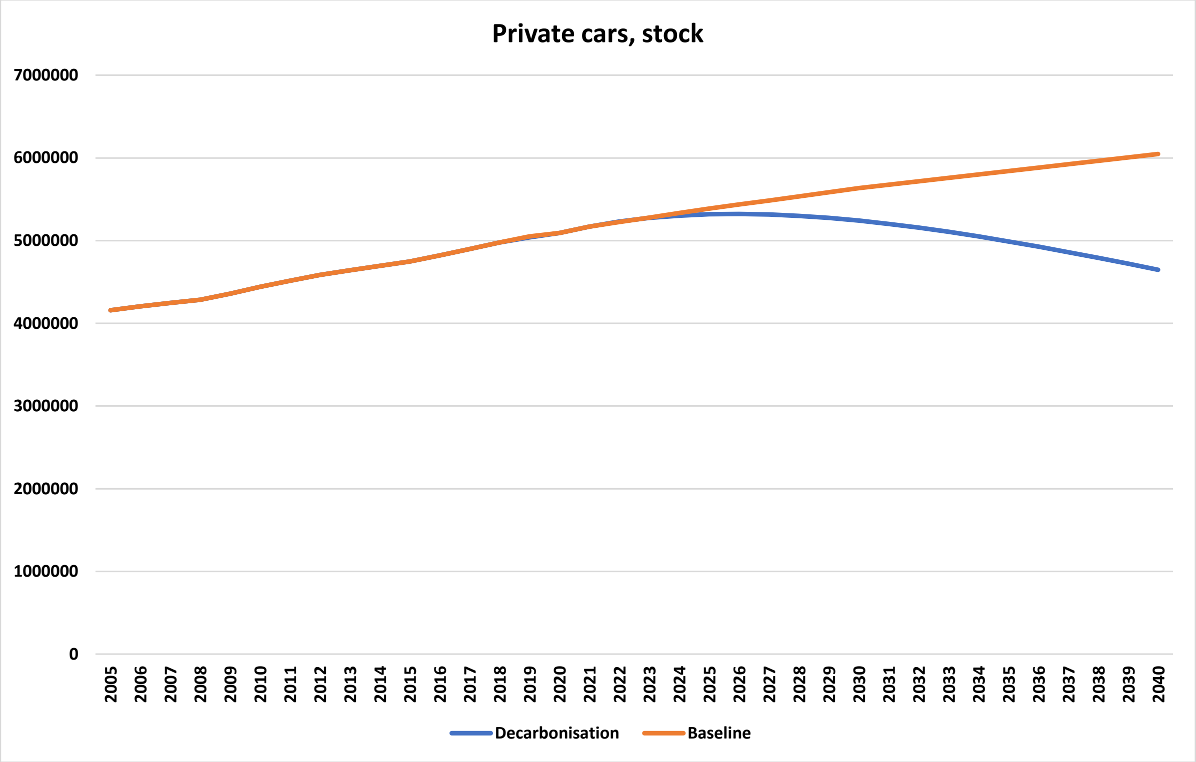
Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

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 16) 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.

Scenarios for freight transport

Baseline Scenario and "Decarbonizing 2040 – low system efficiency"

For all industries *j*, energy demand is specified in terms of energy intensity $\frac{E_{f,j}}{Q_j}$ for each type *f* of energy. The main Kaya type equation for energy intensity of different types of energy *f* (gasoline, diesel, electricity) per unit of output decomposes $\frac{E_{f,j}}{Q_j}$ into a efficiency component in each process that uses *f* ($\frac{E_{f,j}}{Q_{f,j}}$) and the output share of each process that uses *f* ($\frac{Q_{f,j}}{Q_j}$). The efficiency component can change without changes in the capital stock, whereas a shift in the structure of processes that changes output shares, requires investment in new technologies. Different from private transport, where all physical stock data are available, for the non-ETS industries only total Q_j is known, but not the specific output ($Q_{f,j}$) for fuel specific processes. This needs to be estimated and the model needs to be calibrated simultaneously, meeting plausible ranges for the relationship between efficiencies of different technologies, ($\frac{E_{f,j}}{Q_{f,j}}$). Both components are then modelled for the different scenarios, where the first component measures the short run reactions in energy intensities, whereas the second represents the long-run shifts away from fossil fuel-inputs, which is the main driver for decarbonization in the scenarios. This is done for the following non-ETS industries: agriculture/forestry, freight transport/road, public and private services.

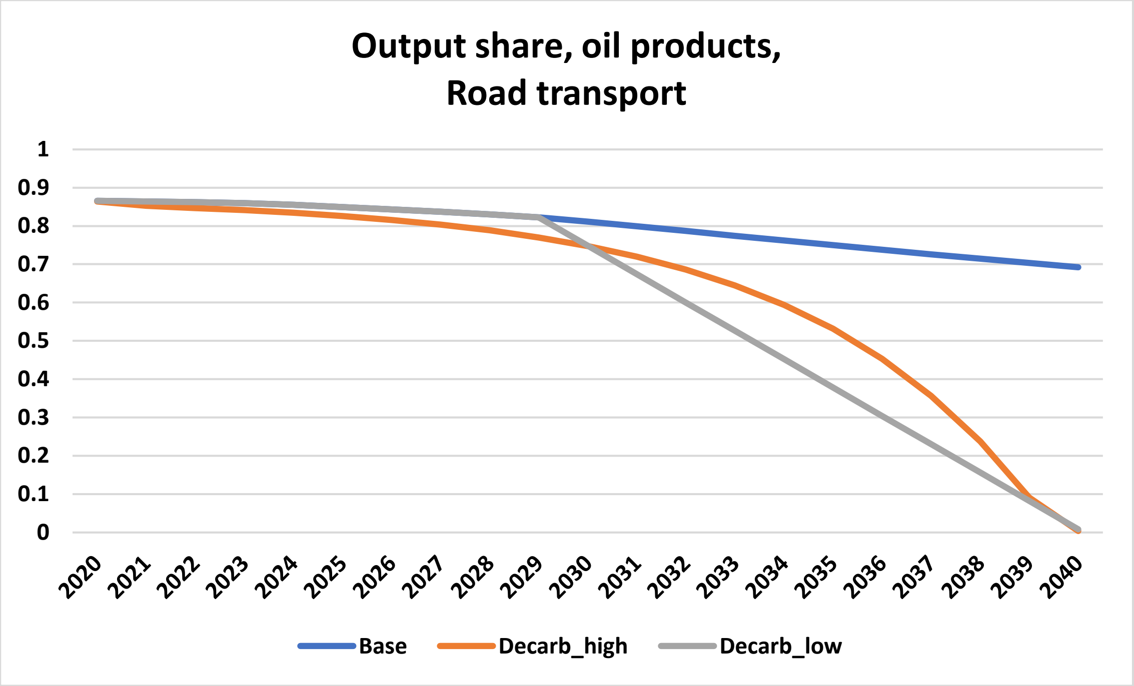
Again, as in the case of private transport, the dataset for the baseline scenario is taken from output of the NEMO model for the 'baseline' (With Existing Measures ('WEM')) scenario. These output variables are directly transformed into exogenous values for $\frac{E_{f,j}}{Q_{f,j}}$ *and* $\frac{Q_{f,j}}{Q_j}$*, and inserted into the model. In analogy to private transport, this 'baseline' development delivers at the same time the main assumptions for a decarbonization scenario with low system efficiency, in the sense of no additional decarbonization by direct electrification and no additional dampening of energy efficiency and no further socio-economic changes take place. Therefore, decarbonization with low system efficiency would in this scenario be achieved by replacing diesel (and small amounts of gasoline) demand with biofuels or e-fuels. In the specification of the model, that is represented by a continuous decrease of the output share* ($\frac{Q_{f,j}}{Q_j}$) *of oil products (Fig. 17).*

"Decarbonizing 2040 –high system efficiency"

The decarbonization with high system efficiency will result in direct electrification of road freight transport. In the specification of energy demand lined out above, that is represented by a long-run shift in output shares $\frac{Q_{f,j}}{Q_j}$ from diesel (gasoline) to electricity. The output share for electricity is specified as a log-linear function of the relative price between diesel and electricity, plus a trend parameter that resembles the trend of direct electrification already active in the baseline scenario. The price development of diesel including the rising CO_2 prices over time leads to an expansion of the share of output produced by electricity (Fig. 18) and a corresponding reduction of the output produced by oil products (Fig. 17). This reduction follows the path of the log-linear function and is not linear as it is (by assumption) in the case of e-fuel penetration ('decarbonizing – low system efficiency').

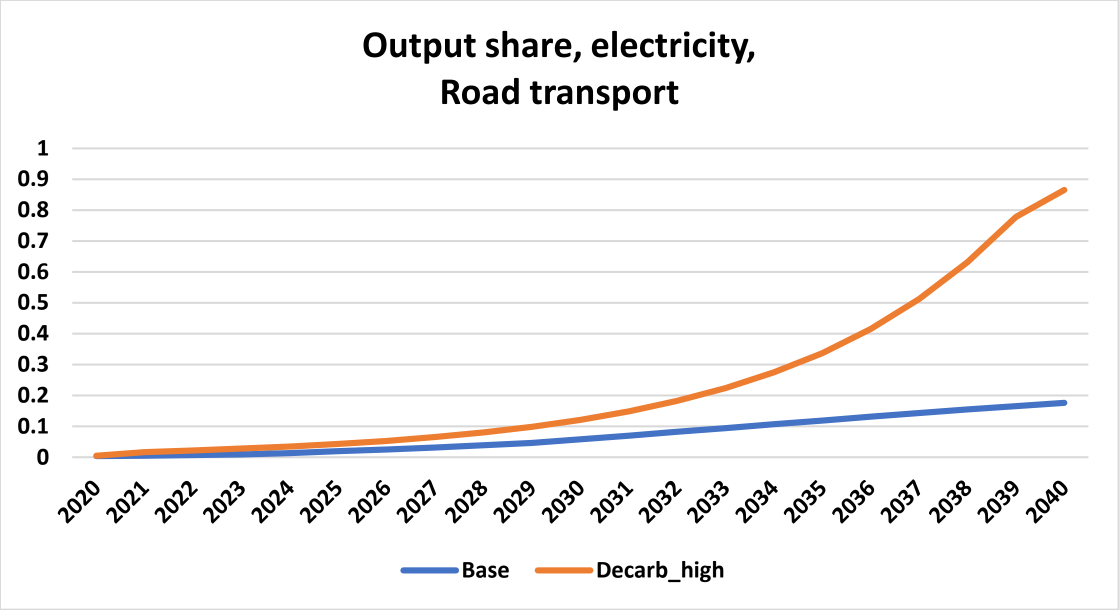
An important mechanism with direct electrification that works through all feedbacks in the macroeconomic IO model is the impact of direct electrification on aggregate energy intensity in road freight transport (Fig. 19). This is due to the lower energy intensity (in TJ/mill. t-km) of electricity driven compared to diesel driven trucks.

Fig. 17. Output shares ($\frac{Q_{f,j}}{Q_j}$) of diesel/gasoline in road freight transport, different scenarios



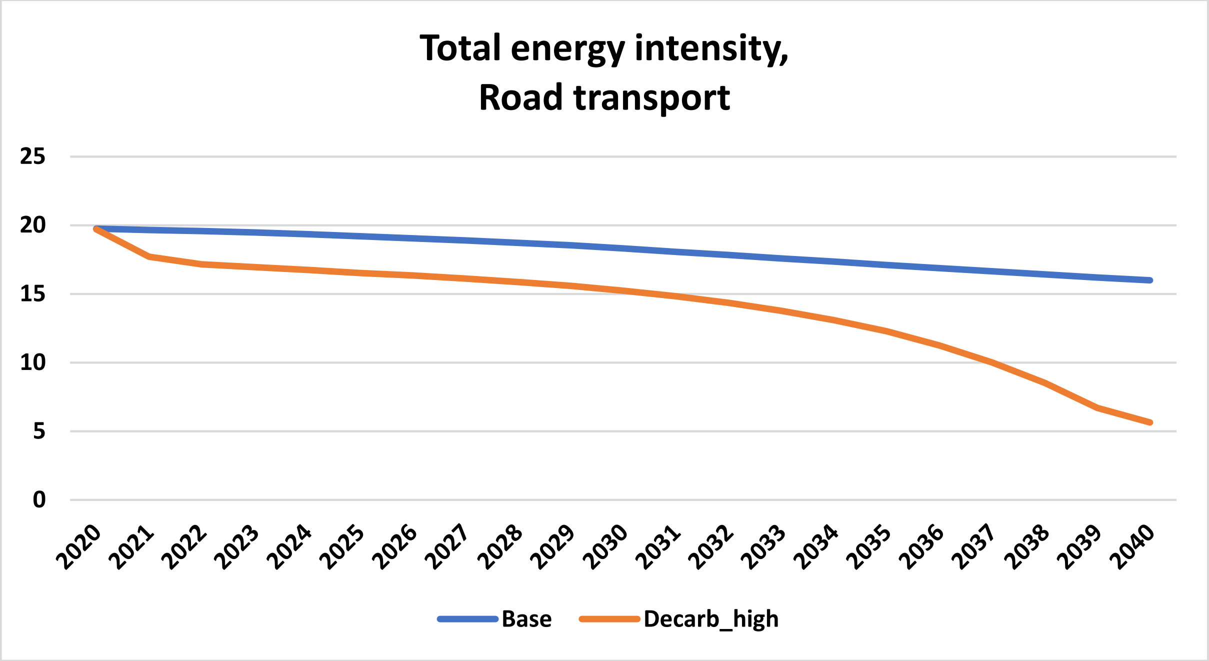
Source: Own calculation based the NEMO model (TU Graz, Umweltbundesamt.

Fig. 18. Output shares ($\frac{Q_{f,j}}{Q_j}$) of electricity in road freight transport, different scenarios



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

Fig. 19. Energy intensity impact of electrification in road freight transport



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

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