ELECTRO_COUP

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

WORKING PAPER 4

ELECTRO_COUP Scenario Results

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

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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)

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Content:

Abstract:

In this paper we summarize the modelling results of the ELECTRO_COUP project which has the aim to find ways to make transportation and heating in Austria cleaner and more climate friendly. The main focus is on the topics of electrification and sector coupling between electricity, heating, and mobility. The project looks at several decarbonisation scenarios to see how different measures can help reduce carbon emissions and how they will affect the economy and energy usage in the country. Through this analysis, the project aims to find the best ways to achieve Austria's climate goals for 2030 and 2040.

The scenarios were simulated using an integrated energy-economy model to see how they would affect energy use, carbon emissions, and the economy. The simulations were carried out up to the year 2040.

Overall, the study shows that policy interventions are essential for successful decarbonization, and using more electricity from renewable sources is a key part of the solution. It is found that sector coupling and replacing fossil fuels by electricity can work well. But if not done carefully, some of the pollution reduction could be lost. It is important to note that sector coupling can lead to higher electricity prices and dampen the positive economic impacts of decarbonization efforts.

The scenarios offer valuable insights into different pathways to reduce CO_2 emissions in transport and heating, emphasizing the importance of renewable energy adoption and the potential challenges posed by fossil fuel-based electricity generation or hypothetical technologies like e-fuels. Altogether, the project has significantly improved our understanding of the decarbonization potential of sector coupling.

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1 Introduction

In this working paper we describe the simulation results with the LEEM model for the scenarios developed in the project ELECTRO_COUP (see Working Paper 1; Kratena, 2022). The scenarios aim at achieving the Austrian decarbonization targets for 2030 and 2040 and are described in Working Paper 2 of the project (Frank-Stocker et al., 2022). The model-based analysis reveals the impacts of policies and energy transition paths on energy and socioeconomic indicators as well as potential sector coupling effects between ETS and non-ETS sectors. The model has been used for simulating a baseline scenario ('Base') and decarbonization scenarios, where fuel-shifts and higher efficiency in the energy system are combined.

The baseline scenario assumes full decarbonization of electricity generation due to rising ETS prices according to the reduction of the cap in the 'Fit for 55' package of the EU-Commission and fulfills several targets of the Austrian climate policy strategy (FMST and FMTIT, 2018). A major part of fuel-shifts in heating and transport accrues to electricity, so that the question of sector coupling arises (Bloomberg Finance L.P., 2020; Fridgen et al., 2020). At the EU level, 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 (in our case heating and transport) reappears in another part (Eichner and Pethig, 2018), a phenomenon known as leakage. To conduct a comprehensive analysis of the leakages, it is essential to focus on the interconnections and linkages between various sectors. These linkages must cover sector coupling in the energy system between electricity production, distribution and storage on the one hand and other energy sources (heat, gas) on the other hand (Bloomberg Finance L.P., 2020). Achieving full decarbonization of electricity generation without decarbonization in the non-ETS sector therefore is the starting point of the scenario analysis and is considered in the ELECTRO_COUP baseline scenario.

As the model applied in the scenario analysis does not endogenously determine the impact of sector coupling, decarbonization scenarios with direct electrification and energy efficiency improvement (the scenarios 'Decarb_high' = decarbonization with high system efficiency) have been simulated in two versions:

(i) no sector coupling effect, i. e. the additional electricity demand is met by generating more renewable energy and the electricity sector remains decarbonized as in the 'Base',
(ii) the 'worst case' of sector coupling, i.e. the additional electricity demand is met by additional fossil generation and a full re-switching to gas in electricity generation occurs.

It is important to emphasize that the treatment of sector coupling would be different at the EU level taking into account feedbacks from the permit market and in a model, where the choice of technology in the electricity sector is endogenous. However, in our national analysis with exogenous technologies in power generation, we address the potential impacts of sector coupling by making assumptions about two extreme scenarios (no sector coupling vs. 'worst case' of sector coupling).

The decarbonization scenarios driven by energy efficiency improvements plus direct electrification require technology shifts and investment in the corresponding non-ETS sectors (heating, private transport, road freight transport). The alternative is a scenario, where the capital stock in the non-ETS sectors is not required to change and decarbonization in the non-ETS sectors is achieved by substituting fossil fuels by e-fuels and hydrogen. In this scenario ('Decarb_low' = decarbonization with low system efficiency) no additional efficiency improvements compared to the baseline are achieved.

2 The modelling approach

The macroeconomic input-output (IO) model integrates the standard IO linkages in production, as well as the energy demand linkages between ETS and non-ETS sectors. The model therefore disaggregates the most important sectors from the perspective of climate policy: several energy intensive industries (ETS), electricity and heat generation (ETS), non-energy intensive industries (non-ETS), and services. The other main non-ETS part are households (transport and heating) and freight transport. The IO model is based on a system of supply/use tables (SUT) and covers 26 industries and 38 goods that are defined as aggregates from NACE 2-digits. The industry classification is identical with the sectors for which final energy demand is available in the energy balance (Statistik Austria, for details see Kratena, 2022). For the classification of goods, two CPA 2 digits (05-07 and 19) are split up according the energy balance classfication into coal and lignite, crude petroleum, natural gas (05 – 07) and into coke and the single petroleum products of the energy balance (19). Electricity, gas and heat & steam are directly available at the 3-digit classification (351, 352 and 353) in the IO table used for this study. This splitting up of goods yields an almost 1:1 correspondence of energy goods in the model with the types of energy in the energy balance. Exceptions are those types of energy flows that are either own inputs (such as coke oven gas and blast furnace gas) or inputs from natural sources (like biomass, ambient heat, wind/PV). These energy sources are not a result of economic transactions and, as such, do not have a monetary value attributed to them.

The philosophy for energy modelling therefore is the parallel and consistent accounting of the (monetary) IO model and of the energy system. One option for integrating is the hybrid IO model (Miller and Blair, 2022) with measuring the non-energy part in monetary units and the energy part in physical units. That also implies a correct representation of energy transformation processes (Kratena and Schleicher,1999) and is fully consistent with the energy balance concepts of 'final energy demand' and 'energy transformation (input and output)', as Guevara and Domingos (2017) has shown. On the other hand, in the model in hybrid units, at some stages all physical flows need to be converted into monetary flows using the implicit prices following from a simple division. Complete conversions are not always feasible due to conceptual differences, making it impossible to achieve a one-to-one conversion.Therefore, a model with two layers is applied, where the production system in monetary units is solved by the corresponding IO model in monetary terms (based on the SUT 2017) and the energy transformation system in physical units is solved by the corresponding IO model in physical terms (based on the Energy Balance 2017). The disaggregation of energy goods in the IO model in monetary terms as described above is a prerequisite for this two layer-methodology.

Total final energy demand is a common variable to the IO model (monetary units) and to the IO model of energy transformation (physical units). This variable is determined in physical units and then transferred to the IO model of energy transformation. The input structure of electricity generation is the other common variable to the IO model (monetary units) and to the IO model of energy transformation (physical units). This structure will be determined in the energy transformation model and changes in the input structure are proportionally transferred to the electricity sector column vector in the IO model.

The model linkage between bottom-up approaches of energy demand in the non-ETS sectors and the IO model comprises final energy for heating (buildings) and private as well as freight transport. Heating energy demand of households (physical units) stems from the Invert/EE-Lab model and is classified in the 26 types of energy k of the energy IO model. This energy demand becomes part of final energy and is converted into monetary expenditure (in the classification of energy goods in the IO model) by applying 'implicit prices'. Further results from the Invert/EE-Lab model simulation are used to determine some energy relevant expenditure for durable goods, such as dwelling area, investment in heating appliances, and investment in thermal insulation. The expenditure data (maintenance of dwellings, appliances) are directly linked to the corresponding categories of private consumption.

Private transport demand (physical units) is taken from different scenarios with the NEMO transport model, which is based on a bottom-up dataset. This dataset covers vehicle purchases and stocks by drive, technical efficiency of the stocks and 'service demand' (km driven). The variables from NEMO have been used to specify economic equations for total vehicle density with saturation effects, from which physical vehicle demand can be determined by inverting the accumulation equation. Vehicle investment in physical units, adds to the last period's stock and depreciation with fixed depreciation rate is subtracted from last period's stock. The share of drives (gasoline, diesel, electricity) in vehicle purchases is modelled in log-linear functions, where the values of price elasticity have been taken from other studies, applying models of discrete choice (Fridstrøm and Østil, 2021). From these studies own and cross price elasticities of vehicle demand have been taken to calibrate a simple log-linear function for the share of electric cars in total vehicle purchases. This equation describes the electric car-share as a function of vehicle prices (fossil (gasoline and diesel) and electric cars), fuel prices (fossil (gasoline and diesel) and electricity) and a trend parameter (Kratena and Müller, 2022).

The 'service' variable from the NEMO model, which represents the total person-kilometers traveled by households, is also considered as a given input for calculating the total expenditure on transport. To convert the energy demand for private transport (gasoline, diesel, electricity) from physical units into monetary expenditure, 'implicit prices' are applied. This specification makes the modal-split in private transport endogenous. It is determined as the residual of total transport expenditure after subtracting vehicle purchases and energy demand (i.e. the expenditure associated with car transport) from total transport expenditure. For the industries *j*, energy demand is specified in terms of energy intensity $\frac{E_{k,j}}{Q_j}$ for each type *k* of energy. These energy intensities constitute an energy intensity matrix that corresponds to the energy part of the use matrix of the IO model for those energy types (*k*) and energy goods (*en*) that exhibit a 1:1 correspondence. As explained in section 1, that excludes types of energy flows like blast furnace gas or ambient heat, to which no monetary value is applicable. Like in the case of private consumption of energy, the energy intensity matrix for all industries is linked to the matrix of technical coefficients of energy goods ($\mathbf{B}_{en} = \mathbf{B}_{en}^{d} + \mathbf{B}_{en}^{im}$) via 'implicit prices' for *k* types of energy. That ensures that together with the solution of the IO model for output $\mathbf{q}$ energy in physical units and the intermediate demand for energy goods (in monetary units) are determined simultaneously in a consistent way.

The main Kaya type equation for energy intensity of different types of energy *k* (gasoline, diesel, electricity) per unit of output in industry *j* is:

$$\frac{E_{k,j}}{Q_j} = \frac{E_{k,j}}{Q_{k,j}} \frac{Q_{k,j}}{Q_j} \qquad \text{with } Q_j = \sum_k Q_{k,j}$$

Different from private transport, where all physical stock data are available, for the non-ETS industries only total Q is known, but not the specific output (Q_k) 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, ($\frac{E_k}{Q_k}$).

The equation is modeled separately for the different scenarios, with both components serving distinct purposes. The first component captures the short-run reactions in energy intensities, whereas the second component represents the long-run shifts away from fossil fuel inputs, which play a critical role in driving decarbonization in the scenarios. This is done for the following non-ETS industries: agriculture/forestry, freight transport/road, public and private services.

The input coefficients in the two transformation processes 'Electricity plants' and 'Autoproducer electricity plants' are endogenous, the input coefficients of the other six processes are fixed. The input coefficients in electricity production are modelled in a similar way as the final energy intensities in the production sectors. The coefficients (physical units) are the product of technology (= type of energy k) specific input coefficients (for example coal input per unit of output from electricity from coal) $\frac{E_k}{Q_k}$, and the shares of these technologies in total electricty production (physical units), $\frac{Q_k}{Q}$. Again, the resulting coefficient $\frac{E_k}{Q}$ is directly converted into the corresponding technical coefficient in the electricity sector of the IO model, applying implicit prices.

This methodoology for electricity plants is not only applied to the energy and other intermediate inputs, but also to capital inputs and costs as well as labour intensity. The consistency of this method is based on calibration so that columns in the dimension of the IO model (goods and value added components) are constructed, which – multiplied by the shares of electricty production technologies, $\frac{Q_k}{Q}$, yield the total column for the electricity sector in the IO model. For the simulation period (until 2040) it is assumed, that no capacity constraints exist for additional electricity generation from gas and hydropower (due to almost constant hydropower generation), but that additional generation from wind and PV leads to capacity build-up (according to average hours of generation, taken from Austrian electricity statistics). This expansion of capacity is converted into additional investment applying capital costs by technology from IEA publications.

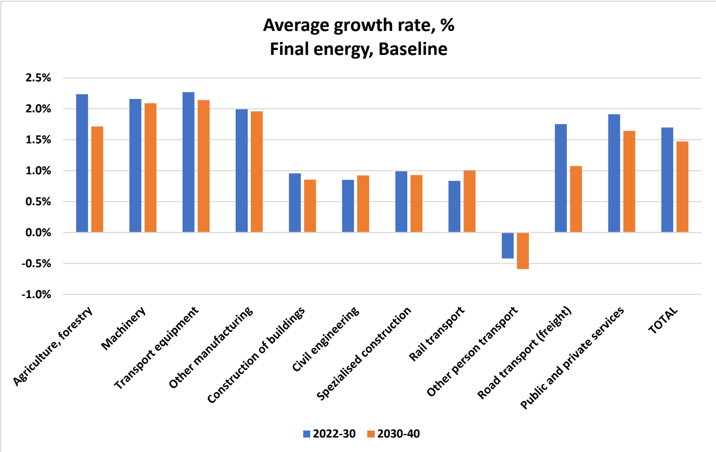
3 Scenario results

3.1 Baseline scenario (“Base”)

The baseline scenario exhibits modest aggregate GDP and gross output growth until 2040 (around 2% p.a.). The components of energy intensity by industry are extrapolated so that the outcome for energy intensity follows past trends, yielding an aggregate reduction of energy intensity (per unit of GDP) of 0.4% p.a., so that final energy growth is about 1.5% p.a. until 2040 (see Fig. 1).

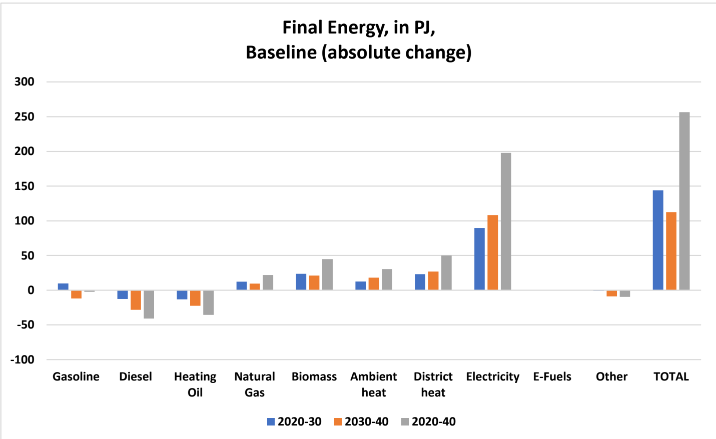
Fig. 2 shows that beyond this aggregate level, important changes in the demand for individual energy types occur during the simulation period. Even in the baseline scenario, there is a substantial reduction in the demand for some fossil fuels, specifically oil products, but not for natural gas. The fossil energy demands are primarily compensated by a significant increase in the consumption of various non-fossil energy sources, with a notable boost in electricity demand. This is largely driven by the ongoing electrification of the transport sector, which is already evident in the 'Base' scenario. Simultaneously, the high CO_2 prices within the ETS contribute to the phasing out of the only remaining fossil input in electricity generation, namely natural gas. Instead, there are modest increases in hydropower generation (not exceeding historical maximum values) and considerable expansions in wind power and PV generation (0).

Fig. 1. Final energy (growth rate, %) by selected industries, 2022 - 40 in "Base"



Source: Own representation

Fig. 2. Final energy (change in PJ) by type of energy, 2022 - 40 in "Base"



Source: Own representation

As a consequence, there is a notable decarbonization of electricity production, as illustrated in Fig. 4. This shift towards cleaner energy sources leads to small decreases in emissions within the non-ETS (non-Emissions Trading System) sector. Additionally, it results in an overall reduction of total emissions, amounting to approximately 1% per year.

Fig. 3. Electricity generation (in TJ) by main sources, 2022 - 40 in "Base"

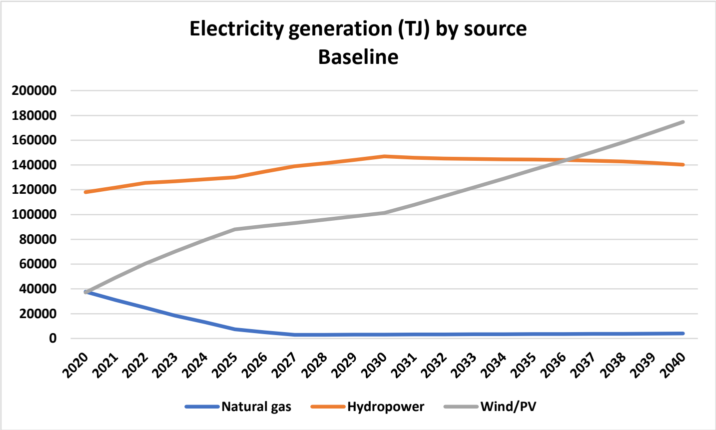


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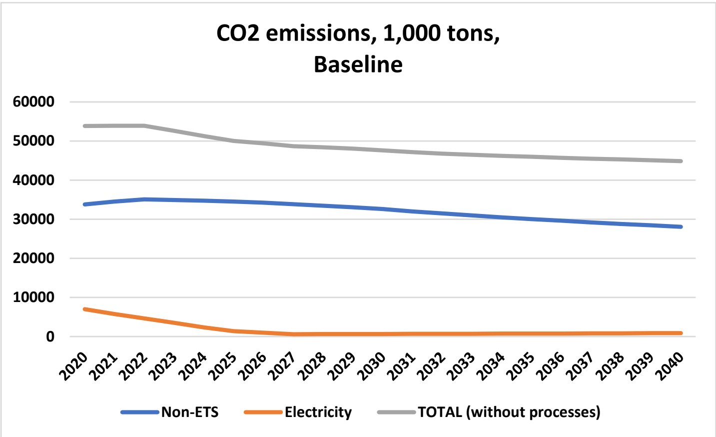
Fig. 4. CO_2 emissions (in 1,000 t), 2022 - 40 in "Base"



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3.2 "Decarbonizing 2040 – high system efficiency"

The "Decarbonizing 2040 – high system efficiency" scenario implements ambitious energy efficiency measures to reduce the energy needs as well as delivered energy as described in the ELECTRO_COUP scenario working paper (Frank-Stocker et al., 2022). The measures in this scenario are a combination of direct electrification, energy efficiency improvements and socioeconomic changes. In detail, the 'Decarb_high' scenarios implement the following decarbonization measures in the non-ETS sectors:

- Refurbishment of the dwelling stock and turnover in heating systems of households with a shift to non-fossil fuels,
- 'Peak Car' round about 2030 due to sociodemographic changes,
- Electrification of private and freight transport.

The resulting developments in the household sector (heating) are also applied to the energy use in the service sector and the resulting developments in the transport sector also impact the off-road transport in the construction sector.

Fig. 5. Household durable expenditure (in mill €, const. prices), 2022 - 40 in "Decarb_high"

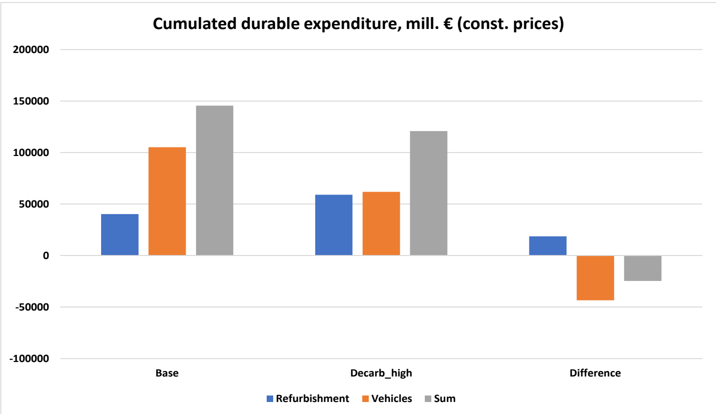

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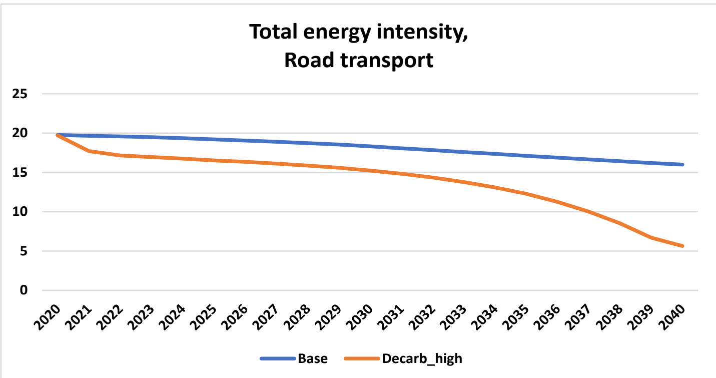
Fig. 6. Efficiency effect of road transport electrification, 2022 - 40 in "Base" and "Decarb_high"



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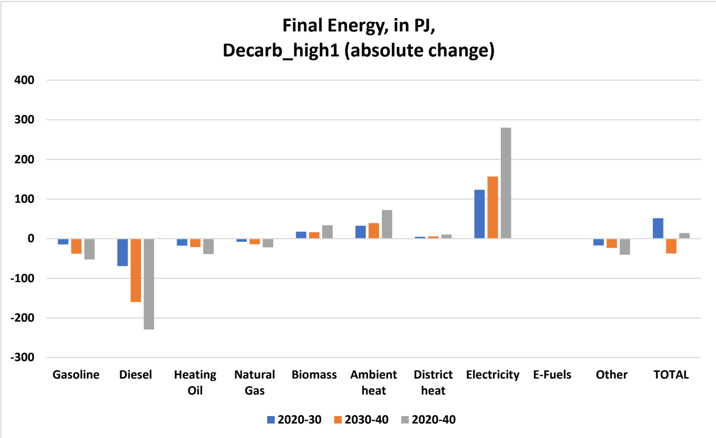
These developments trigger different potential macroeconomic mechanisms. One important channel is the change in expenditure for durable goods (refurbishment and vehicle purchases) which directly affects non-energy consumption. This holds significant macroeconomic relevance, as the share of (employment intensive) services in non-energy consumption amounts to 72%. The other channel is the large aggregate efficiency improvement in road transport when shifting from oil products to electricity drives. This productivity effect *ceteris paribus* leads to lower price dynamics and thereby to real income effects. This impact is partly compensated by a higher price per energy unit in the case of electricity compared to diesel or gasoline. Figure 7 shows that all types of fossil energy are reduced in the 'Decarb_high' scenarios, while the electricity demand is considerably accelerated compared to 'Base'.

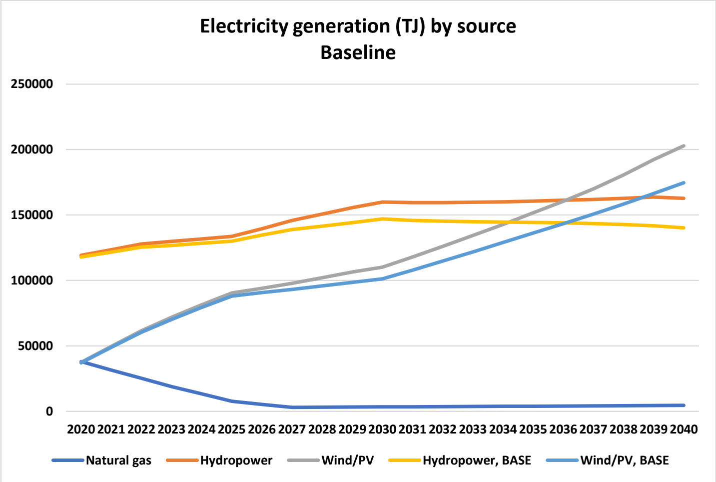
Fig. 7. Final energy (change in PJ) by type of energy, 2022 - 40 in "Decarb_high"



Source: Own representation

In the 'Decarb_high1' scenario, electricity generation from natural gas remains identical to the 'Base', preserving the decarbonization of the electricity sector. This is achieved through increased generation from hydropower (though still below historical maximum levels) and expansions in wind/PV.

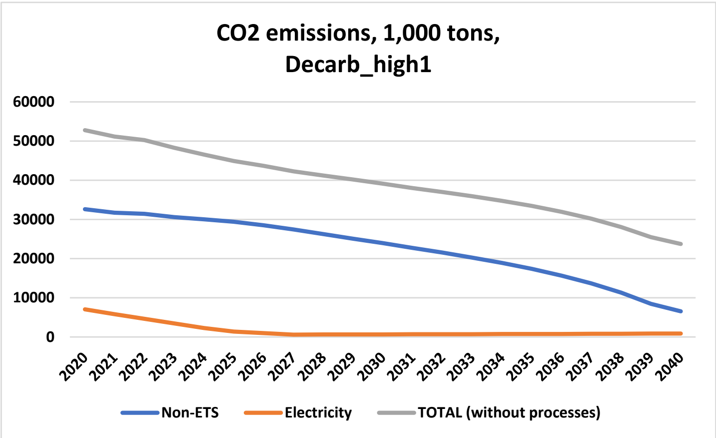
Fig. 8. Electricity generation (in TJ) by main sources, 2022 - 40 in "Base" and "Decarb_high1"



Source: Own representation

The total picture of CO_2 emissions shows simultaneous decarbonization of electricity generation (already present in 'Base') and non-ETS sector.

Fig. 9. CO_2 emissions (in 1,000 t), 2022 - 40 in "Decarb_high1"



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In the 'Decarb_high2' scenario the development in the non-ETS sector and the measures affecting decarbonization in this sector are identical to those in the 'Decarb_high1' scenario, but in the electricity sector the 'worst case' of sector coupling is assumed. The total additional electricity demand (compared to 'Base') is satisfied by additional generation from natural gas This process is referred to as 're-switching' to gas, where the electricity sector relies more heavily on natural gas to meet the increased demand. Figure 10 shows the magnitude of this sector coupling effect in comparison to the decarbonization effect of this scenario. In 2040, the resulting sector coupling effect offsets 44% of the emission reduction in the non-ETS sector.

Consequentely, the impact of sector coupling results in a reduced overall reduction in total emissions (Figure 11).

Re-switching to gas leads to an increase in the elctricity price of 19% compared to 'Base', driven by higher emission permit costs for the electricity sector. This negative income effect almost compensates the positive economic impacts of non-ETS decarbonization with respect to 'Base'. As a result, private consumption experiences a development similar to that in the 'Base'. Higher construction activity than in the 'Base' - also in a decarbonization with re-switching to gas - leads to higher aggregate investment and small positive GDP impacts. Gross output is positively affected compared to the 'Base' in construction (refurbishment) and in other personal transport (modal shift to public tranbsport).

Fig. 10. CO_2 emissions (in 1,000 t), 2022 – 40, the 're-switch' effect in "Decarb_high2"

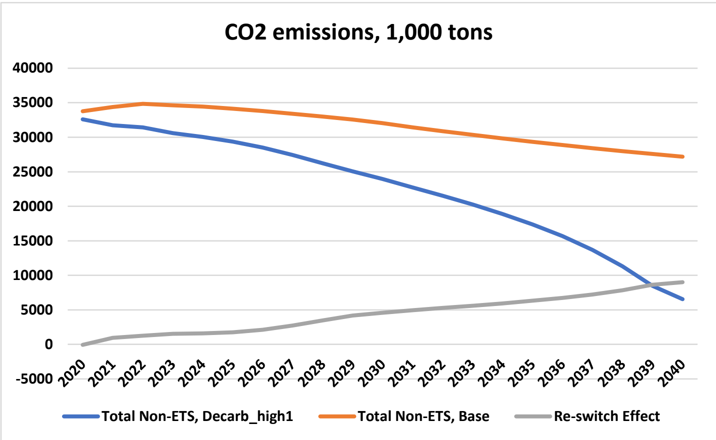

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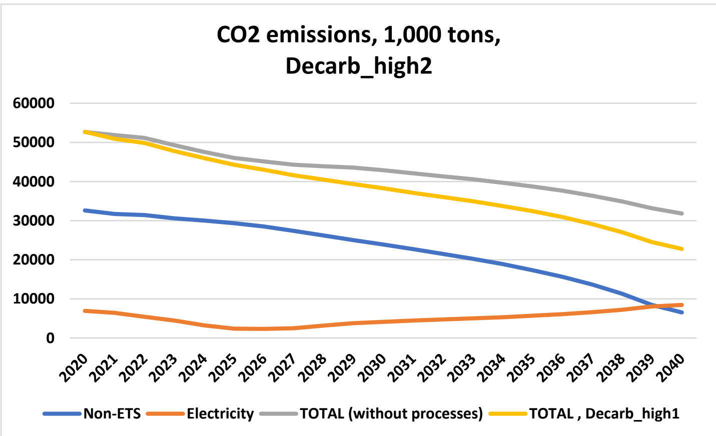
Fig. 11. Total CO_2 emissions (in 1,000 t), 2022 - 40 in "Decarb_high2"



Source: Own representation

The annual GDP growth rates of the two decarbonization scenarios with high system efficiency are only slightly higher than those of the "baseline" scenario. In the more favourable case of decarbonization with high system efficiency and a sector coupling effect for renewable electricity generation (meaning higher investment in electricity generation), the cumulative difference in 2040 is around 1%. The cumulative employment effect (compared to the "baseline" scenario) is roughly the same in both decarbonization scenarios (+58,000 full-time equivalents).

Fig. 12. Macroeconomic impact (in %), 'Decarb_high2' compared to 'Base'

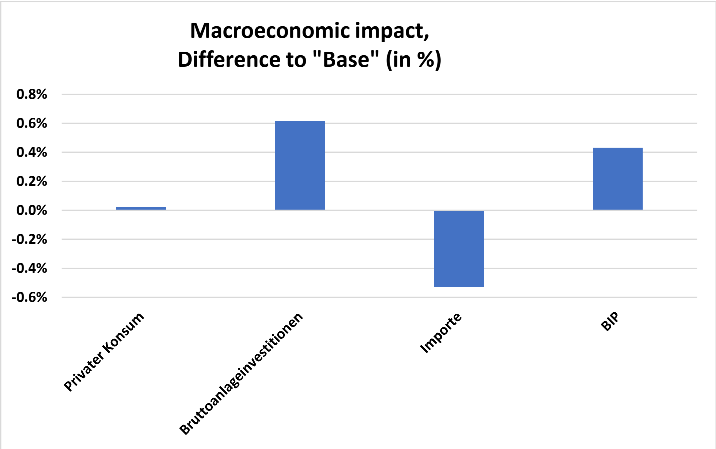


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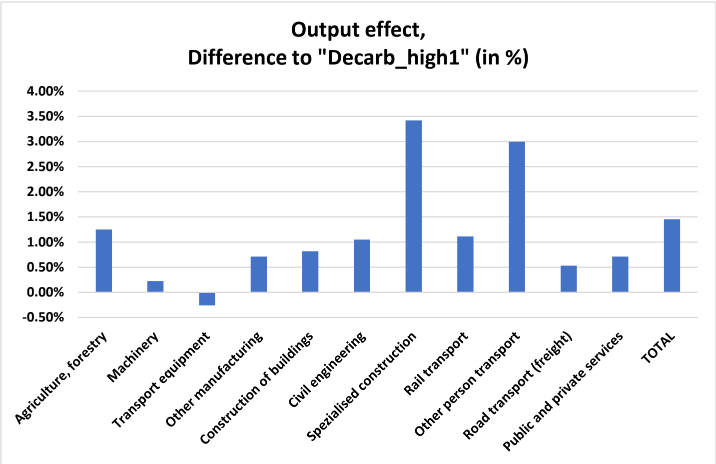
Fig. 13. Gross output impact (in %), 'Decarb_high2' compared to 'Base'



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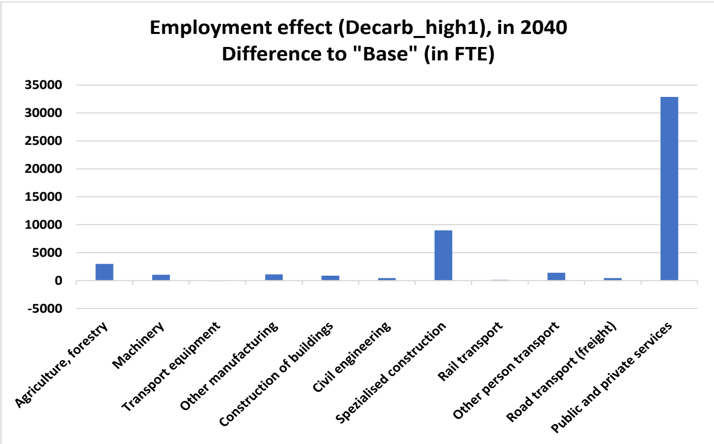
The employment effects (see following figure) are very similar in terms of amount and structure (due to the small differences in the macroeconomic effects) and are concentrated in the service sector (33,000 full-time equivalents - FTE) and the construction industry (9,000 full-time equivalents). Whether these employment effects are realized depends largely on the available labour supply in the corresponding occupations (which was not investigated as part of this project).

Fig. 14. Employment in the decarbonization scenario with high system efficiency 'Decarb_high1' in FTE compared to 'Base'



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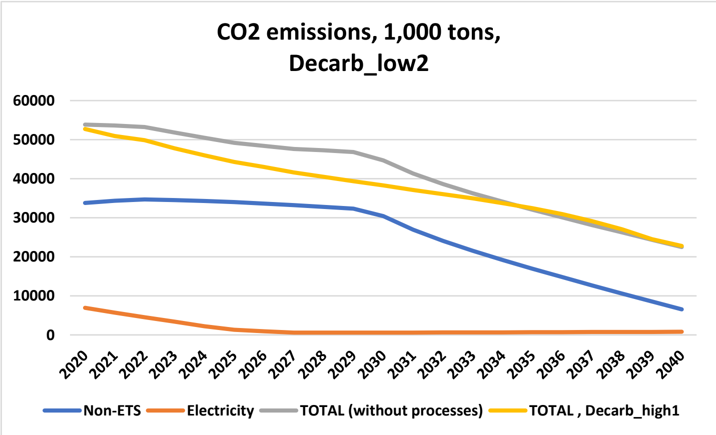
3.3 "Decarbonizing 2040 – low system efficiency"

The Scenario "Decarbonizing 2040 – low system efficiency" (Decarb_low) builds on the first scenario but achieves greenhouse gas (GHG) neutrality by substituting fossil energy carriers by their corresponding carbon free alternatives (e-fuels and hydrogen). Renewable power generation remains at the same absolute level as in the 'Base', so that capacity expansion for wind and PV and cumulated investment are also as high as in the baseline scenario. For e-fuel generation we assume that 90% of e-fuels consumed in Austria are imported and the domestic production exhibits an average efficiency of 52.5% (with input of electricity).

The macroeconomic impacts show a considerably lower average GDP growth compared to the other scenarios (1.5 % p.a. vs. 2.1 % p.a. in 'Decarb_high1' and 2.0% p.a. in 'Base'). The higher costs for e-fuels increase expenditure for energy and diminish expenditure for non-energy consumption (compared to 'Decarb_high'). The negative impact of higher costs is addressed through a two-fold effect. Firstly, decarbonization is achieved through the substitution of conventional fuels with e-fuels, which increase energy expenditure for transport compared to direct electrification ('Decarb_high' scenario). Secondly, an income-effect comes into play, with the consumption deflator being 12% higher in 2040 compared to the 'Decarb_high' scenario. This means that the increase in overall costs leads to a reduction in real income, affecting the purchasing power of consumers and influencing their consumption patterns.

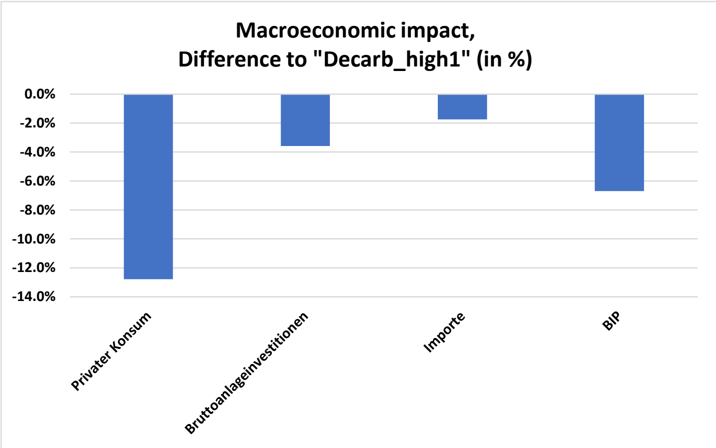
In "Decarb_low" the decarbonization is realized as well, as the same emission reduction as in the 'Decarb_high'-scenarios is achieved. That comes at a much higher cost, leading to corresponding negative impacts compared to the 'Decarb_high'-scenarios. In this scenario, the potentially positive economic impacts of a decarbonization in the non-ETS sectors are lost.

Fig. 15. Total CO_2 emissions (in 1,000 t), 2022 - 40 in "Decarb_low"



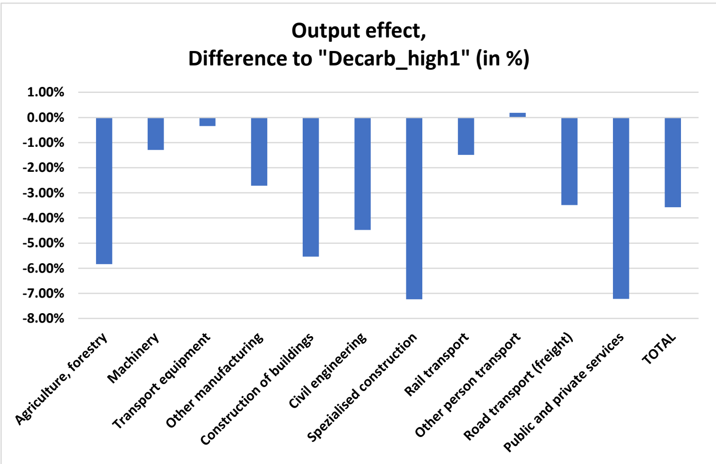
Source: Own representation

Fig. 16. Macroeconomic impact (in %), 'Decarb_low' compared to 'Decarb_high'



Source: Own representation

Fig. 17. Gross output impact (in %), 'Decarb_low' compared to 'Decarb_high'



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4 Conclusions

The results of the scenario simulations demonstrate the feasibility of decarbonization in the non-ETS sectors, with a strong reliance on carbon pricing and socioeconomic changes as driving forces. This decarbonization pathway involves a combination of energy efficiency improvements and direct electrification. An essential aspect in this context is the significant impact of electrification on aggregate energy efficiency, owing to the inherent efficiency of electricity technologies, particularly in heating (heat pumps) and transportation. The modelling approach applied in ELECTRO_COUP (macroeconomic input-output model with integrated energy system) effectively identifies income and substitution effects resulting from the implemented decarbonization policies (refurbishment, vehicle purchases, energy saving, electricity price). When assessing the economic implications of decarbonization through e-fuels, these mechanisms remain crucial: the economic performance is significantly worse in the e-fuel scenario. Due to the high costs of e-fuels the positive income and substitution effects disappear. The financial burden of e-fuels outweighs the potential benefits derived from these effects, making this particular decarbonization approach economically challenging and less favorable compared to other decarbonization strategies like direct electrification or energy efficiency improvements. It must further be noted that the decarbonization scenario with e-fuels is only hypothetically feasible but not consistent with the modelling approach for the scenarios, as with the high prices of e-fuels these technologies would not be chosen by firms and households, but instead would further trigger direct electrification.

In the worst case of sector coupling, where a full re-switching to gas is assumed, the analysis reveals that 56% of decarbonization in the non-ETS sector would still be conserved in total emissions.

These findings underscore the significance of thoughtful planning of sector coupling strategies to effectively and sustainably decarbonize the non-ETS sector.

5 References

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