Decarbonization in the non-ETS with sector coupling via input-output linkages

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Abstract:

The main research question in this paper is to account for all feedback mechanisms between ETS and Non-ETS sectors in the energy system and in the economy in a parallel manner. In the worst case, large part of carbon reduced in one part of the energy system reappears in another part. For this purpose, the analysis must focus on the linkages between different sectors. The macroeconomic IO model applied fully integrates the energy system and explicitly deals with different types of linkages: (i) input-output (IO) linkages in production and (ii) energy demand linkages between ETS and non ETS. The model therefore disaggregates the most important sectors and goods (in a supply-use system) from the perspective of climate policy. For the non-energy intensive industries in non ETS, energy demand and technologies are also split up into heating and mobility, like in the household sector. The full integration of the energy system into a macroeconomic IO model guarantees that all changes in the energy system have a consistent impact in the economy, both at the level of quantities and of costs and prices. The IO linkages in (i) therefore comprise quantity as well as price linkages. Electricity prices are described by a formalized merit-order price model that incorporates the emission cap and permit costs. Several feedback effects from sector coupling take place, when energy demand in the non ETS shifts from fossil fuels to electricity.

Introduction

The EU climate policy architecture distinguishes non-ETS from ETS sectors and defines GHG targets for the non-ETS in the member states. Strategies of decarbonization focus on electrification of end-use energy purposes accompanied by expanding electricity supply from renewables, nuclear and fossil fuels with carbon capture technologies. That implies shifting the burden of decarbonization to the electricity sector that is covered by 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 leakage. For this purpose, the analysis must focus on the linkages between different 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). Jarke and Perino (2017, 2019) have set up an economic modelling framework that allows for integrating important feedbacks of this kind (sectoral leakage and sector coupling). Their modeling approach works on a relatively aggregate level and does not incorporate the feedback of a switch to electricity on aggregate energy efficiency.

In this paper, a modelling framework that fully integrates the energy system and explicitly deals with different types of linkages, is applied. These linkages comprise: (i) input-output (IO) linkages in production (quantities and prices) and (ii) energy demand linkages between ETS and non ETS. 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), household transport (non ETS), freight transport (non ETS), and heating of households and service industries (non ETS). The full integration of the energy system into a macroeconomic IO model guarantees that all changes in the energy system have a consistent impact in the economy, both at the level of quantities as well as at the level of costs and prices. Energy technologies are based on bottom-up datasets in the buildings and the transport sector.

The model describes the national economy of an EU country (Austria) aiming at emission targets for the non ETS using a policy mix. The permit price in the ETS is exogenous (small country assumption), but costs for permits depend on national excess permit demand and are an important component in price setting of electricity generation. Electricity prices are described by a stylized merit-order price model that incorporates the emission cap and permit costs. When energy demand in the non ETS shifts from fossil fuels to electricity, sector coupling can lead to higher renewable electricity investment or to re-switching towards fossil electricity production. In both cases, sevceral feedback mechanisms between the energy system and the economy are in place.

1. The IO Framework

The macroeconomic IO model integrates the standard input-output (IO) linkages in production, as well as the energy demand linkages between ETS and non ETS. 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 the Appendix). 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. The exception refers to those types of energy flows that are either own inputs (coke oven gas, blast furnace gas) or inputs from nature (biomass, ambient heat, wind/PV) and are not consequence of an economic transaction, so that no monetary value is applicable 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. These conversions are not always one to one, due to conceptual differences, which makes a full conversion impossible. 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.

The matrices and vectors that constitute the IO model are:

(i) the supply table (industries * goods) $\mathbf{V}$ with column sum equal to the vector of output by goods, $\mathbf{q(g)}$. The row sum of this matrix is defined as the vector of output by industries, $\mathbf{q}$,

(ii) the domestic use table for intermediates (goods * industries) $\mathbf{U^d}$ with row sum equal to the vector of output by goods, $\mathbf{q(g)}$, and

(iii) the imports use table for intermediates (goods * industries) $\mathbf{U^{im}}$ with row sum equal to the vector of intermediate imports by goods.

(iv) the matrices of final demand $\mathbf{F^d}$ and $\mathbf{F^{im}}$ (goods * final demand components), comprising domestic (d) and imported (im) goods.

Total imports im are the sum of intermediate and final imports. The supply and use tables are converted into coefficients matrices for setting up the IO model. The 'market shares matrix' $\mathbf{D}$ is derived by dividing the matrix elements of $\mathbf{V}$ through the column sum, $\mathbf{q(g)}$. This matrix links the output by industries $\mathbf{q}$ to the output by goods $\mathbf{q(g)}$: $\mathbf{q} = \mathbf{D}\ \mathbf{q(g)}$. The domestic 'technical coefficients matrix' $\mathbf{B}^d$ is derived by dividing the domestic use table Ud through the vector of total output by industries, $\mathbf{q}$. The elements xdij/qj of $\mathbf{B}^d$ define the domestic input *i* in the production of one unit of industry *j*, therefore they determine domestic intermediate demand xd as a function of output by industries **q**: $\mathbf{x}^{d} = \mathbf{B}^{d}\,\mathbf{q}$.

The two main equations of the IO model are:

$$\mathbf{q} = \mathbf{D}\,\mathbf{q}(\mathbf{g}) \tag{1}$$

$$\mathbf{q}(\mathbf{g}) = \mathbf{B}^{d}\mathbf{q} + \mathbf{cp}^{d} + \mathbf{cf}^{d} + \mathbf{f}^{*d} \tag{2}$$

In (2), the domestic part of the final demand categories that are endogenous, private consumption (**cp**) and capital formation (**cf**) are separated from the exogenous parts of final demand $\mathbf{f}^{*d}$ (public consumption, stock changes, and exports).

A similar IO model is set up for energy transformation, where final energy demand and some other components of the energy balance (transport losses, non-energy consumption, stock changes) constitute the final components. This IO model is also based on the SUT framework, where the 'industries' are the eight transformation processes *t* and the goods are the 26 types of energy *k* (for details of the classification, see the Appendix).

$$\mathbf{q} = \mathbf{D}(\mathbf{k})\,\mathbf{q}(\mathbf{k},\mathbf{T}) \tag{3}$$

$$\mathbf{x}(\mathbf{k}) = \mathbf{B}_{\mathrm{k},\tau}\mathbf{q} + \mathbf{fe} + \mathbf{ex} + \mathbf{f}^{*,\mathrm{k}} \tag{4}$$

$$\mathbf{q}(\mathbf{k}) = \mathbf{x}(\mathbf{k}) - \mathbf{im} \quad ; \qquad \mathbf{q}(\mathbf{k},\mathbf{T}) = \mathbf{T}_{\mathrm{P,T}}\,\mathbf{q}(\mathbf{k}) \tag{5}$$

Equation (3) links the output by transformation processes τ (**q**) to the output (secondary production) by types of energy *k* (**q**(**k**,**T**)) and equation (4) defines total demand (**x**(**k**)) by energy *k* as the sum of transformation input, defined by the coefficient matrix $\mathbf{B}_{\mathrm{k},\tau}$, final energy **fe**, exports **ex**, and a rest $\mathbf{f}^{*,\mathrm{k}}$ (transport losses, stock changes, non-energetic use). Total demand minus imports gives total output **q**(**k**), that contains some types of energy that are supplied directly from nature (primary production) as – for example - crude oil and natural gas, as well as others (secondary production) that stem from transformation, like steam and electricity. A matrix mostly containing one and zero elements, $\mathbf{T}_{\mathrm{P,T}}$, is applied to derive output from secondary production (**q**(**k**,**T**)) from total output **q**(**k**).

The classification in the IO model overlaps with the energy types *k* for the following types of energy goods, *en*: coal and lignite, crude petroleum, coke, gasoline, kerosine, diesel, gas oil, fuel oil, liquid gas, other oil products, refinery gas, electricity, gas and steam & heat. Final energy **fe** is the sum of the product of an energy intensity matrix (explained in section 4.1. below) with output **q** and the energy goods in $\mathbf{F}^{\mathbf{d}}$ and $\mathbf{F}^{\mathbf{im}}$. The energy part of the use matrix of the IO model ($\mathbf{B}_{\mathrm{en}} = \mathbf{B}^{\mathrm{d}}_{\mathrm{en}} + \mathbf{B}^{\mathrm{im}}_{\mathrm{en}}$) is linked to this energy intensity matrix goods via 'implicit prices' for *k* types of energy, which can be seen as conversion factors between physiscal units and units in constant prices.

2. Production and prices

The SUT framework is also applied for the price system of the economy and in analogy to output by industries (**q**) and output by goods (**q**(**g**)), in the case of prices we have domestic goods prices ($\mathbf{p}^{d\prime}$) and output prices (**p**'). Import prices ($\mathbf{p}^{im\prime}$) are exogenously given. The 'market shares matrix' transforms output prices by industry into goods prices:

$$\mathbf{p}^{\mathrm{d}\prime} = \mathbf{p}'\,\mathbf{D} \tag{6}$$

The output prices by industry are determined by mark-up pricing, combined with a unit cost function of labor, capital and intermediate inputs plus an indirect tax rate:

$$\mathbf{p}' = [(\mathbf{p}'_{\mathrm{L}}\frac{\hat{\mathbf{L}}}{\mathbf{Q}} + \mathbf{p}'_{\mathrm{K}}\frac{\hat{\mathbf{K}}}{\mathbf{Q}} + \mathbf{p}^{\mathrm{d}\prime}\mathbf{B}^{\mathrm{d}} + \mathbf{p}^{\mathrm{im}\prime}\mathbf{B}^{\mathrm{im}})(1+\ \mu)] +\ \mathbf{t}_{\mathrm{q}}{}' \tag{7}$$

Applying a CES cost function with constant returns to scale to the composite of labour (**L**) and capital (**K**), with composite price p_{LK} and nominal factor shares d_L and d_K yields the following factor demand equations for labour and capital in industry j with substitution elasticity σ_j and deterministic technology trends λ and κ:

$$s_{L,LK,j} = A^{\lambda t} d_{L,j}\left(\frac{p_{LK,j}}{p_{L,j}}\right)^{\sigma_j} \quad ; \quad s_{K,LK,j} = A^{\kappa t}\left(1 -\ d_{L,j}\right)\left(\frac{p_{LK,j}}{p_{K,j}}\right)^{\sigma_j} \tag{8}$$

The coefficients of the diagonal matrices of factor shares, $\frac{\hat{\mathbf{L}}}{\mathbf{Q}}$ and $\frac{\hat{\mathbf{K}}}{\mathbf{Q}}$, are then determined as the product of $s_{L,LK}$ and $s_{K,LK}$ with the composite input coefficient $\frac{\widehat{\mathbf{LK}}}{\mathbf{Q}}$. This composite input coefficient is the difference between the marginal cost of the base year (with prices = 1) and the intermediate input coefficient $\frac{\hat{\mathbf{M}}}{\mathbf{Q}}$ that follows a deterministic trend. The technical coefficients for non-energy goods in $\mathbf{B}^{\mathrm{d}}$ and $\mathbf{B}^{\mathrm{im}}$ are the product of $\frac{\hat{\mathbf{M}}}{\mathbf{Q}}$ and use structure matrices that represent the Leontief technology within $\frac{\hat{\mathbf{M}}}{\mathbf{Q}}$.

Once the solution for the price system, i.e. for $\mathbf{p}^{\mathrm{d}\prime}$ and $\mathbf{p}'$ is achieved, the prices of all users are determined as well. That includes the aggregate price of private consumption and the price of investment. The latter is applied for endogenously determining the price of capital p_K in each industry by applying an investment matrix $\mathbf{B}_{\mathrm{cf}}$ that links investment goods with investing industries. The loop that solves the price model (resembling the Newton-Raphson algorithm) then works over $\mathbf{p}^{\mathrm{d}\prime}$ and $\mathbf{p}_{\mathrm{K}}$.

The capital income coefficient per unit of output is derived as the difference between the output price and marginal cost, plus indirect taxes.

$$\boldsymbol{\pi}' =\ \mathbf{p}' - (\mathbf{p}'_{\mathrm{L}}\frac{\hat{\mathbf{L}}}{\mathbf{Q}} + \mathbf{p}'_{\mathrm{K}}\frac{\hat{\mathbf{K}}}{\mathbf{Q}} + \mathbf{p}^{\mathrm{d}\prime}\mathbf{B}^{\mathrm{d}} + \mathbf{p}^{\mathrm{im}\prime}\mathbf{B}^{\mathrm{im}}) -\ \mathbf{t}_{\mathrm{q}}{}' \tag{9}$$

Gross fixed capital formation by industry is not defined by optimal capital demand from the CES function (equation (8)), but by a simple equation that contains depreciation (linked to the capital stock in $t-1$) plus a constant term. Capital formation in t adds to the capital stock in $t+1$, according to the capital accumulation equation. It is then converted into the vector of capital formation by goods (**cf**), by applying an investment matrix $\mathbf{B}_{\mathrm{cf}}$ that links both dimensions and has column sum equal to one. The vector **cf** is then split up into a vector of domestic goods ($\mathbf{cf}^{\mathrm{d}}$) that feeds back to equation (2) and another vector of imported investment goods ($\mathbf{cf}^{\mathrm{im}}$).

3. Consumer Demand

The components of disposable income are determined in the production and price module. The row vector of wages (**w**’) is defined as the product of nominal labor coefficients, net of taxes [$l(1 - t_Y)$]’, where [$l(1 - t_Y)$]’ = ($l_1(1 - t_Y)$, $l_2(1 - t_Y)$, … $l_n(1 - t_Y)$), with the diagonalized matrix of output ($\hat{\mathbf{q}}$), and the row vector of profits ($\boldsymbol{\pi}$’ in equation (9)) is the product of nominal profit coefficients, net of taxes [$k(1 - t_Y)$]’ with the diagonalized matrix of output ($\hat{\mathbf{q}}$). The total sum of profits $\boldsymbol{\pi}'\mathbf{i}$ comprises non-distributed profits and profits distributed to households that are part of disposable household income. The share of total profits accruing to disposable household income is defined as s_Y. The income tax rate t_Y is defined as a net tax rate by relating the balance of public transfers to households and deductions from household income (social security contributions plus income taxes) to wage and profit income of households (**w**’ + s_Y **p**’). That yields the household vector of primary income $\mathbf{y}' = [\lambda(1 - t_Y)]'\hat{\mathbf{q}} + [s_Y\kappa(1 - t_Y)]'\hat{\mathbf{q}}$. Total disposable household income is **yd**, which besides the income generated in production (**y**) also contains the other income sources, namely profit income and net foreign transfers, Y_p.

Aggregate private consumption is therefore a function of real disposable income YD/PC, where YD is the sum of $\mathbf{y}'\mathbf{i}$ as defined above and other income, Y_p:

$$YD = \mathbf{y}'\mathbf{i} + Y_p \tag{10}$$

Aggregate real private consumption CP becomes a function of output and prices with c_Y as the average propensity of consumption:

$$CP = c_Y\left[\mathbf{y}'\mathbf{i} + Y_p\right]/PC \tag{11}$$

The consumer price PC is defined as an aggregate Divisia price index of three expenditure aggregates: (i) energy *en* (heating), (ii) personal transport *tr*, and (iii) non-energy consumption *nen*:

$$\ln(PC) = w_{en,cp}\ln\left(p_{en,cp}\right) + w_{tr,cp}\ln\left(p_{tr,cp}\right) + w_{nen,cp}\ln\left(p_{nen,cp}\right) \tag{12}$$

The budget shares $w_{en,cp}$, $w_{tr,cp}$ and $w_{nen,cp}$ are constant, implying Cobb-Douglas preferences of households and the real consumption expenditure of goods within energy and personal transport are calculated from converting the energy demand from bottom-up models and functions of households into expenditure at constant prices (applying ‘implicit prices’). The two aggregate prices $p_{en,cp}$ and $p_{tr,cp}$ are defined as simple indices with quantity shares s_i and consumption good prices, $p_{i,cp}$: S_i s_i $p_{i,cp}$. The consumption goods prices are given as weighted prices of each consumption good i (CPA): $p_{i,cp} = im_{i,cp}\, p^{im} + (1 - im_{i,cp})\, p^{d}$, where the $im_{i,cp}$ are the import shares of the good in the consumption vector.

Assuming full separability between energy and transport consumption on the one hand and non-energy consumption on the other hand, yields non-energy consumption as the difference:

$$CP_{nen} = CP - CP_{en} - CP_{tr} \tag{13}$$

This aggregate non-energy consumption comprises four durables or linked to durable consumption (that is relevant for energy consumption): maintenance of dwellings, household appliances, purchases of vehicles and transport services. These are also determined (partly in physical units, e.g.: vehicles) in the bottom-up models and functions of households. We assume Cobb-Douglas preferences for all non-durables, so that budget shares $w_{i,nen}$ are constant.

The quantity expenditure shares within non-durable non-energy consumption are derived by dividing the budget shares $w_{i,nen}$ by the consumption price for the corresponding good ($p_{i,nen}$) and multiplying with the aggregate price (($\mathbf{p}_{\mathrm{nen}}$)'$\mathbf{i}$). Consumption at constant prices of non-energy categories therefore is given with:

$$cp_{nen} = \left[(w_{i,nen} \frac{p_{i,nen}}{\mathbf{p}'_{\mathrm{nen}}\,\mathbf{i}}) Q_{nen} \right] \tag{14}$$

The vector $\mathbf{cp}_{\mathrm{nen}}$ resulting from that adds up to $\mathbf{cp}$ (including energy and durables) and can then be split up into a vector of domestic goods ($\mathbf{cp}^{\mathrm{d}}$) that enters into equation (2) and another vector of imported consumption goods ($\mathbf{cp}^{\mathrm{im}}$).

4. Energy

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.

4.1 Final energy demand

The model linkage between bottom-up approaches of energy demand in the Non-ETS 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 (for details of the classification, see the Appendix) of the energy IO model. This energy demand becomes part of final energy **fe** (equation (4)) and is converted into monetary expenditure (in the classification of energy goods in the IO model) by applying 'implicit prices'. The resulting expenditure becomes part of CP_{en} in equation (13). Other results from the Invert/EE-Lab model simulation are used for determining some energy relevant durable expenditure, for example 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:

$$K_{k,t} = (1-d)K_{k,t-1} + CF_{k,t-1} \tag{15}$$

Gross capital formation (CF), i.e. vehicle investment in physical units, adds to the last period's stock and depreciation with fixed depreciation rate d 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 which incorporates the properties of the models for Norway. 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 (Mueller and Kratena, 2022).

The 'service' variable of the NEMO model (total person-km by households) is also taken as given for determining the total expenditure on transport, CP_{tr} in equation (13). The energy demand for private transport (gasoline, diesel, electricity) in physical units is converted into monetary expenditure by applying 'implicit prices' and also forms part of category CP_{tr}. This specification makes the modal-split in private transport endogenous. It is determined as residual of total transport expenditure after subtracting vehicle purchases and energy demand (i.e. the expenditure linked to 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 ($\mathbf{B}_{\text{en}} = \mathbf{B}_{\text{en}}^{\text{d}} + \mathbf{B}_{\text{en}}^{\text{im}}$) 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:

$$\frac{E_{k,j}}{Q_j} = \frac{E_{k,j}}{Q_{k,j}} \frac{Q_{k,j}}{Q_j} \qquad \text{with } Q_j = \sum_k Q_{k,j} \tag{16}$$

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, $(\frac{E_k}{Q_k})$.

Both components of equation (16) 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.

4.2 Transformation energy demand

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 is for electricity plants 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.

5. Simulation results of sector coupling

The model has been used for simulating a baseline scenario (‘Base’) and a decarbonization scenario, where fuel-shifts and higher efficiency in the energy system are combined (‘Decarb_high’). 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. A major part of fuel-shifts in heating and transport accrues to electricity, so that the question of sector coupling arises. As the model does not endogenously determine the impact of sector coupling, the scenario ‘Decarb_high’ has been simulated in two versions: (i) no sector coupling effect, i. e. the additional electricity demand is met by additional renewable generation and the electricity sector stays decarbonized as in the ‘Base’, and (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.

The ‘Base’-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 (Figure 1).

Figure 2 shows that beyond this aggregate level, important changes in demand of single energy types takes place in the simulation period. Already in a baseline scenario, the demand for some fossil fuels is massively reduced. That refers to oil products, but not to natural gas. These fossil energy demands are mainly substituted by all non-fossil energy types with high increases in electricity demand. This is also driven by electrification of the transport sector that already takes place in the ‘Base’-scenario. Simultaneously, the high CO_2 prices in the ETS lead to fading out of the only fossil input still present in electricity generation (natural gas), modest increases of generation from hydropower (not exceeding maximum historical values) and considerable increases of generation from wind/PV (Figure 3).

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

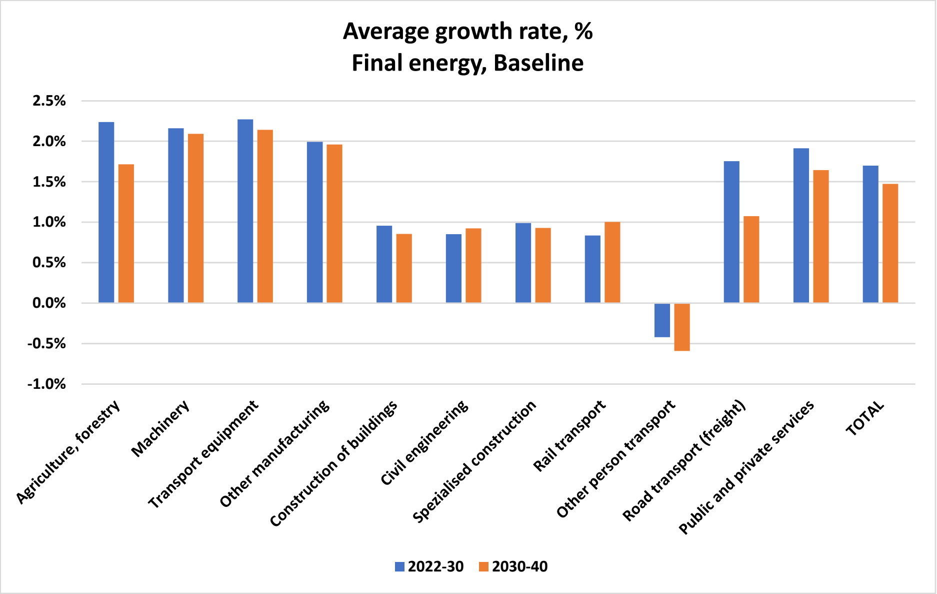
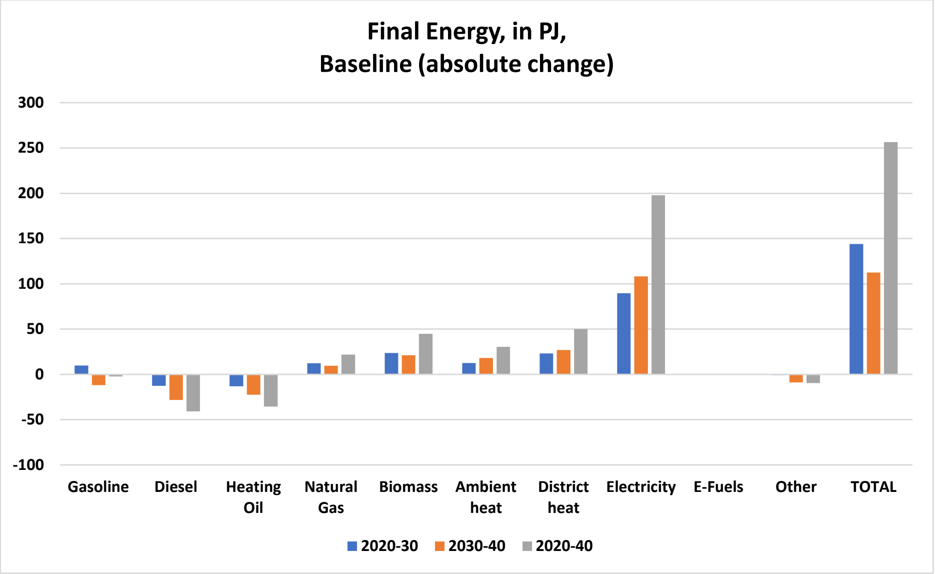


Figure 2: Final energy (change in PJ) by type of energy, 2022 - 40 in "Base"



That, in turn, leads to decarbonization of electricity production (Figure 4) and small decreases in emissions of the Non-ETS sector as well as of total emissions of around 1% p.a. .

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

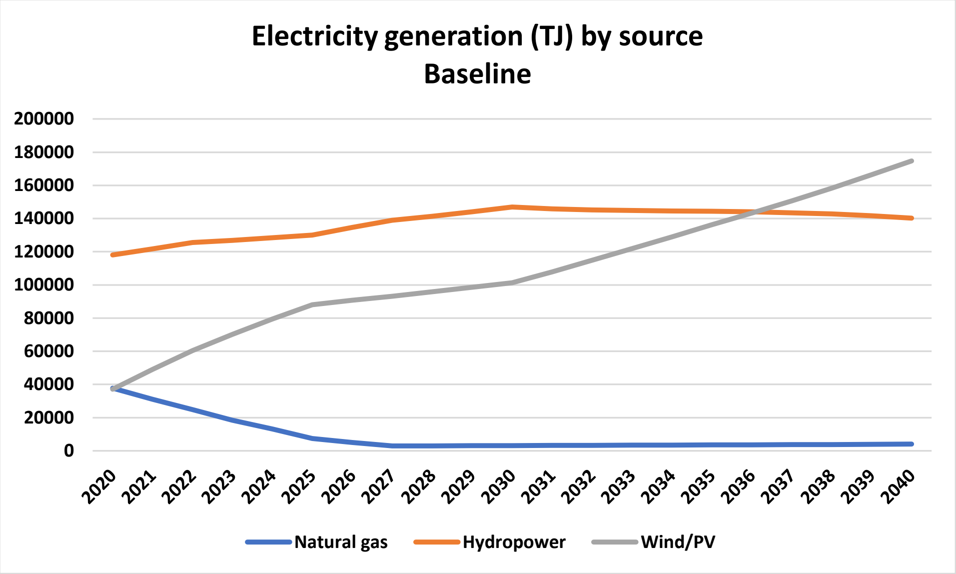
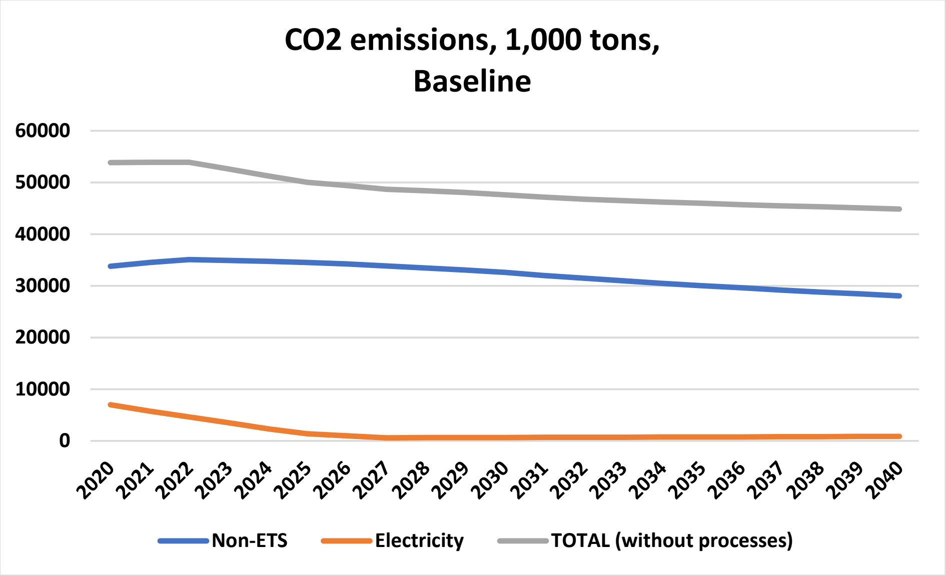


Figure 4: CO_2 emissions (in 1,000 t), 2022 - 40 in "Base"



The 'Decarb_high'-scenarios implement the following measures for decarbonization in the Non-ETS:

-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 development in the household sector (heating) is also applied to the energy use in the service sector and the development in the transport sector is also applied to the construction sector (off-road transport).

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

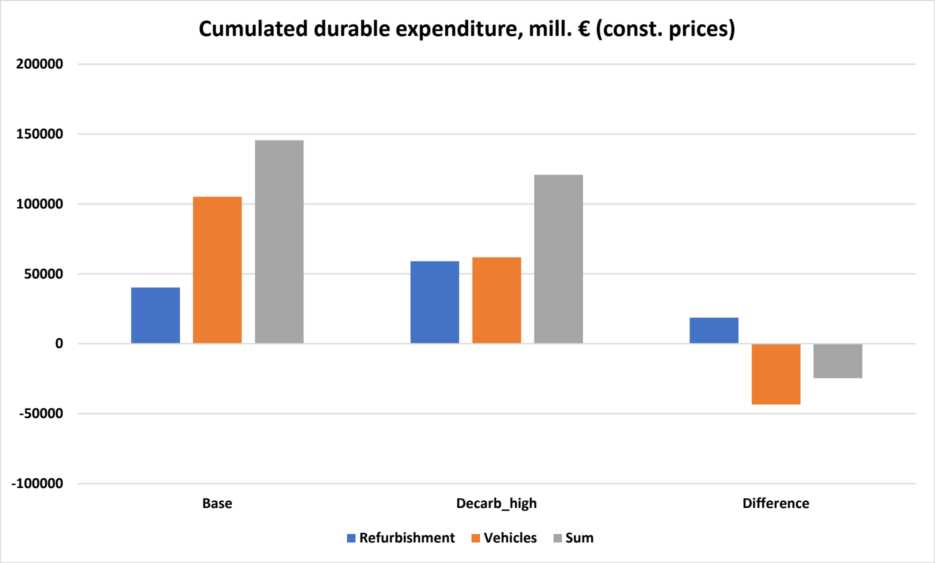
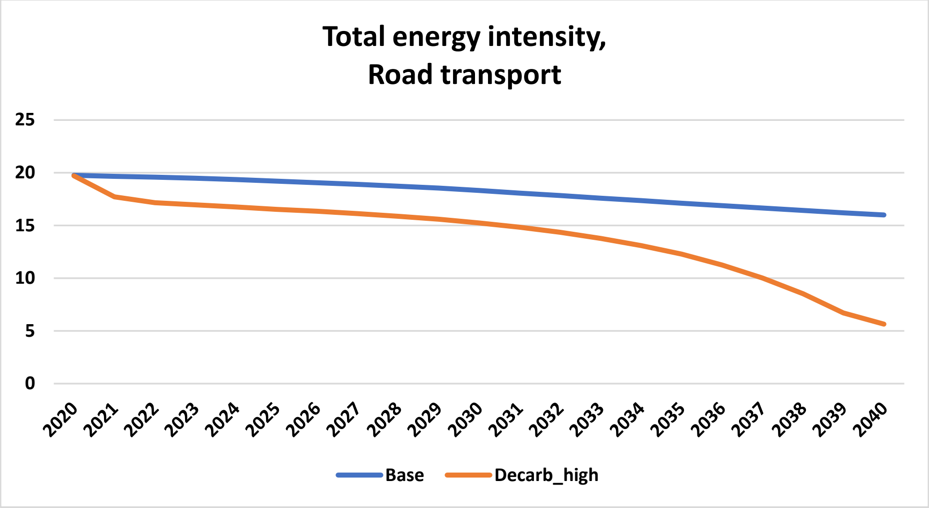
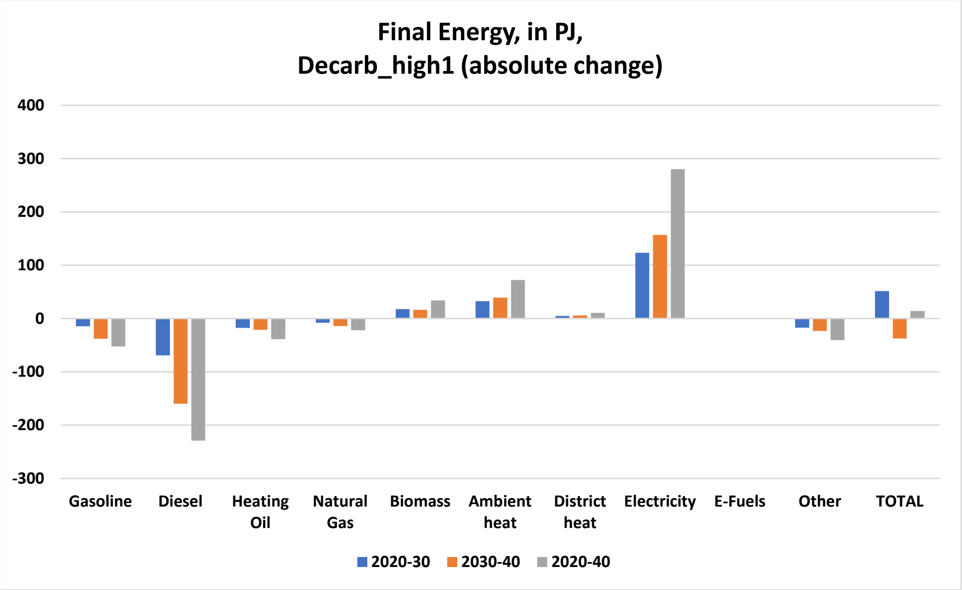


Figure 6: Efficiency effect of road transport electrification, 2022 - 40 in "Base" and "Decarb_high"



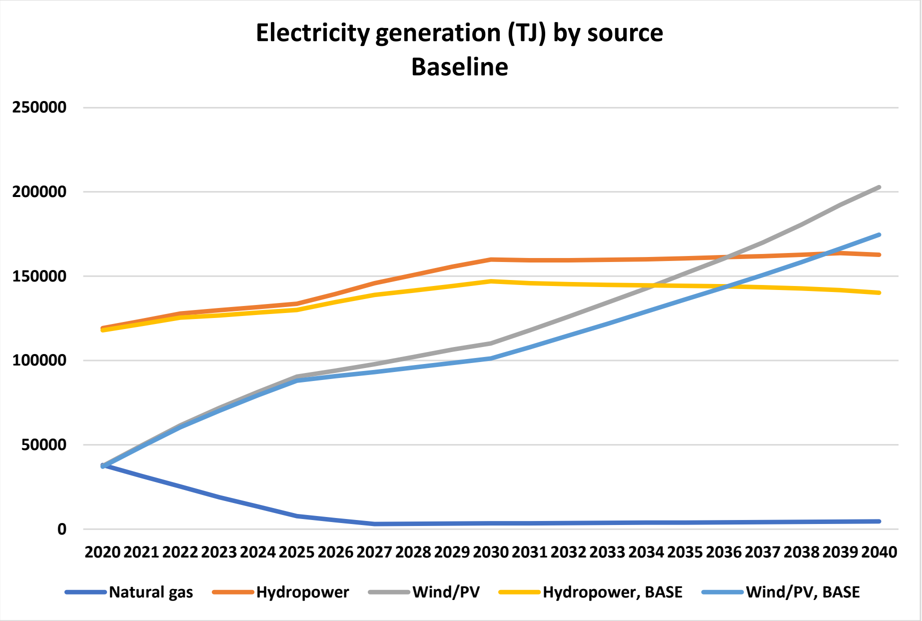
These developments trigger different potential macroeconomic mechanisms. One important channel is the change in durable expenditure (refurbishment and vehicle purchases) which according to equation (13) directly affects non-energy consumption. This is macroeconomically relevant, as the share of (employment intensive) services in non-energy consumption amounts to 72%. The other channel is the large aggregate efficiency improvement in the road transport sector 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 effect 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 and the electricity demand is considerably accelerated compared to 'Base'.

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



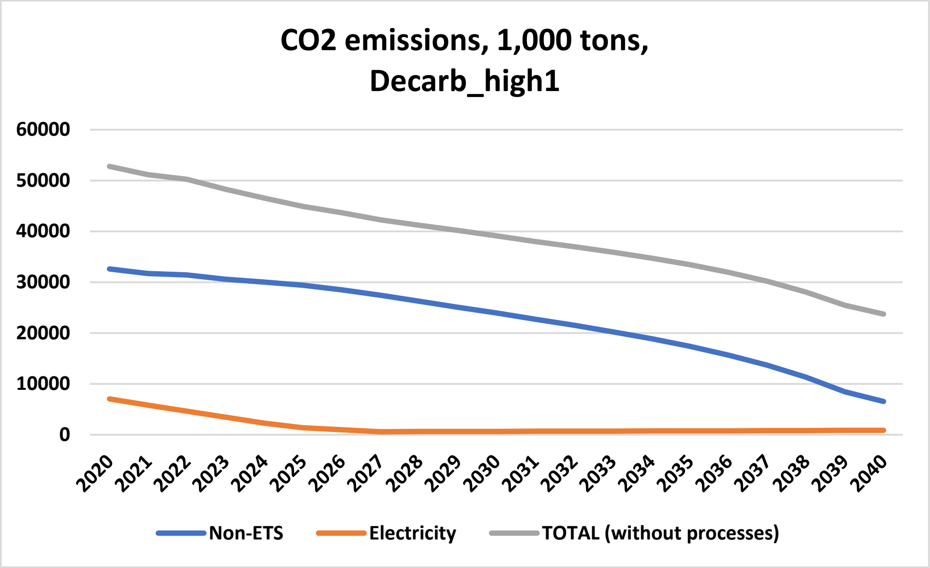
Electricity generation from natural gas is identical to the 'Base', i. e. the decarbonization of the electricity sector is preserved in the 'Decarb_high1' scenario. This is achieved by increases in generation from hydropower (though still below historical maximum levels) and from wind/PV.

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



The total picture of CO_2 emissions shows simultaneous decarbonization of electricity generation (already present in ‘Base’) as well as in the Non-ETS sector.

Figure 9: CO_2 emissions (in 1,000 t), 2022 - 40 in “Decarb_high1”



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 in this scenario (‘re-switching’ to gas). Figure 10 shows the magnitude of this sector coupling – effect in comparison to the decarbonization effect in this scenario. In 2040, this sector coupling – effect compensates 44% of the emission reduction in the Non-ETS sector. This, in turn, results in a reduced reduction effect on total emissions (Figure 11).

The re-switching effect 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’, so that private consumption develops similarly to the development 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 si positively affected compared to the ‘Base’ in construction (refurbishment) and in other personal transport (modal shift to public tranbsport).

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

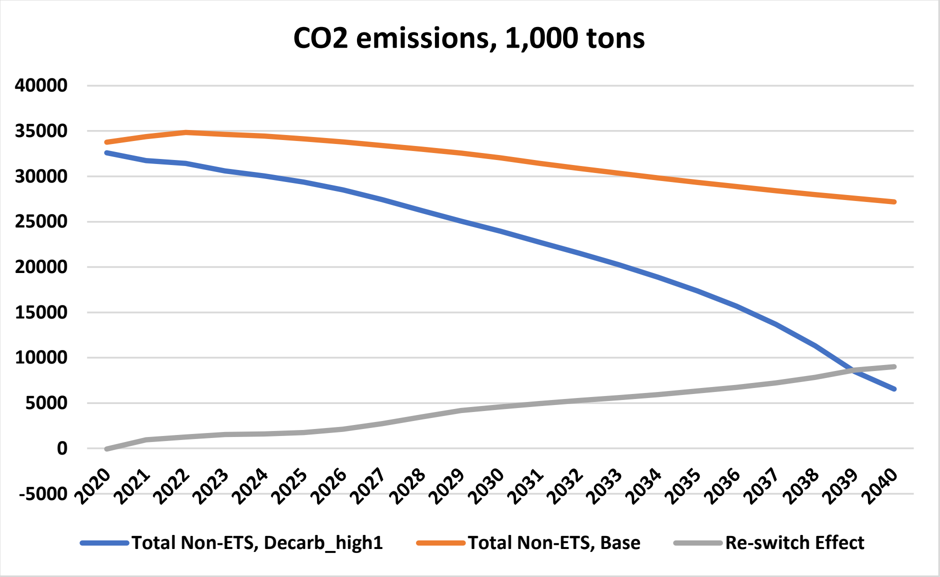


Figure 11: Total CO_2 emissions (in 1,000 t), 2022 - 40 in "Decarb_high2"

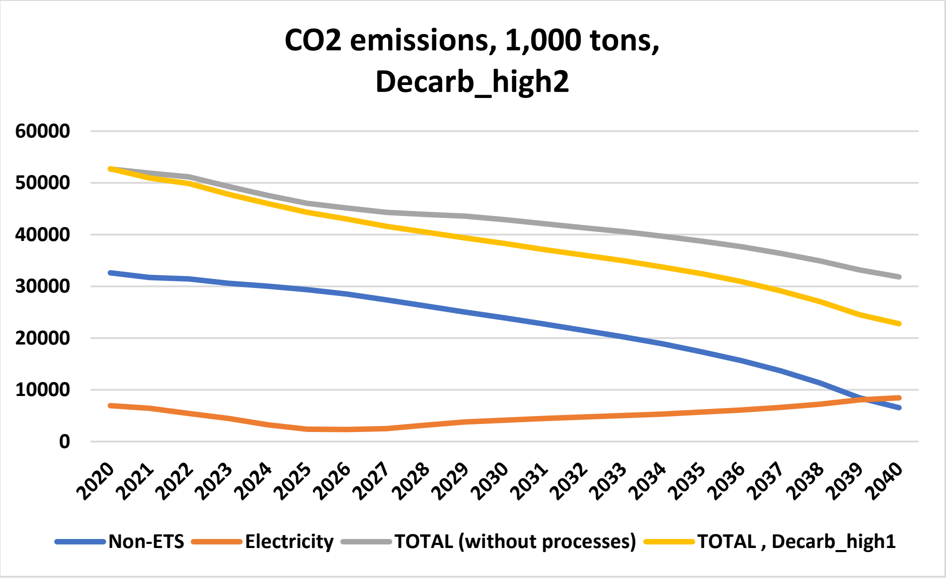


Table 1: Macroeconomic impact (in %), ‘Decarb_high2’ compared to ‘Base’

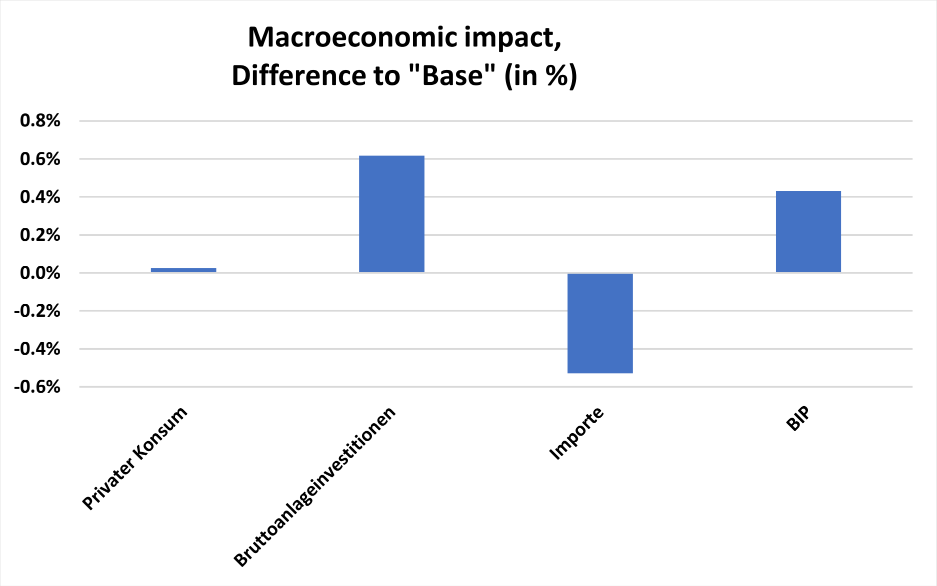
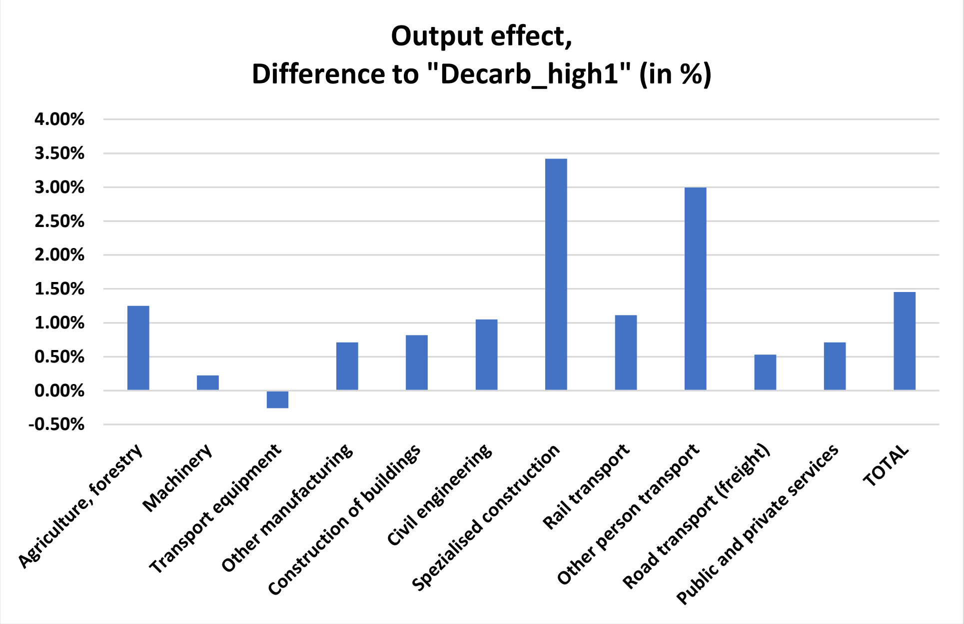


Table 2: Gross output impact (in %), ‘Decarb_high2’ compared to ‘Base’



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Appendix

The industries are identical with those in the sectoral disaggregation of final energy in the Austrian Energy Balance. The definition of these industries via NACE 2 and 3 digits has been provided by Statistics Austria.

Table A1: Industries and corresponding NACE definitions (2 and 3-digits)

01, 02, 03	Agriculture, forestry, fishing
05-07	Mining
10,11-12	Food/beverages/tobacco production
13-15	Textiles and leather
16	Wood production
17-18	Paper production
19	Cokery, refining of oil
20, 21	Chemical industry
23	Other non-m,etallic mineral production
24	Iron & Steel, non-ferrous metals
25-28	Machinery, equipment
29, 30	Transport equipment
22, 31-33	Other manufacturing
351	Electricity
352	Natural gas
353	Steam
41	Construction of buildings
42	Civil engineering
43	Specialized construction
491 - 492	Rail transport
493	Other passenger transport
494	Road freight transport
495	Transport via pipeline
50	Water transport
51	Air transport
Rest	Public and private services

The classification of goods is identical with the industry classification, except for energy mining products (= primary energy, CPA 05-07) and for products from coke oven and refinery (CPA 19). The splitting up of 05-07 started from those issues, where a 1:1 assignment was possible: crude oil to refineries, gas to natural gas (351) and metal ores to Iron&steel, non-ferrous metals (24). All other inputs along the row of the two input tables (use table in IO, final energy use in energy balance) have been assigned to coal.

For splitting up CPA 19, information of the energy balance (physical units) has been plugged in and converted into a first estimate in monetary units applying prices from Statistics Austria. This was adjusted to the totals of row 19 in the use table (monetary units). For slitting up the total use in domestic and imported products, the corresponding import shares of the energy balance for each product have been taken as a starting point. The resulting first estimate has been adjusted to the total imports of row 19 from the use table and to imports by product in the energy balance.

Table A2: Goods and corresponding CPA definitions (2 and 3-digits)

01, 02, 03	Agriculture, forestry, fishing
05-07	Coal and lignite
05-07	Crude petroleum
05-07	Natural gas
05-07	Metal ores
08-09	Other mining
10,11-12	Food products, beverages, tobacco
13-15	Textiles and leather
16	Wood, products of wood
17-18	Paper and paper prducts
19	Coke
19	Gasoline
19	Kerosine
19	Diesel
19	Gasoil
19	Fuel oil
19	Liquid gas
19	Other oil products
19	Refinery gas
20, 21	Chemicals
23	Other non-m,etallic mineral products
24	Iron & Steel, non-ferrous metals
25-28	Machinery, equipment
29, 30	Transport equipment
22, 31-33	Other manufacturing
351	Electricity
352	Natural gas
353	Steam
41	Construction of buildings
42	Civil engineering
43	Specialized construction
491 - 492	Rail transport
493	Other passenger transport
494	Road freight transport
495	Transport via pipeline
50	Water transport
51	Air transport
Rest	Public and private services

The transformation processes and the types of energy in the energy IO model in LEEM represent the maximum level of detail that is available in the Austrian Energy Blance (Statistics Austria).

Table A3: Transformation processes

Coke Oven
Blast Furnace
Refinery
Char Coal Production
Electricity Plants
Autoproducer Electricity Plants
Steam Plants
Autoproducer Steam Plants

Table A4: Types of energy

Coal
Lignite
Lignite briquette
Peat
Coke
Crude oil
Other refinery input
Gasoline
Kerosine
Diesel
Gasoil
Fuel oil
Liquid gas
Other oil products
Refinery gas
Natural gas
Blast furnace gas
Coke oven gas
Fuelwood
Waste
Biofuels
Ambient heat
Hydro power
Wind, PV
District heat
Electricity