Working Paper

No. 156. May 2023

The Environmental Medium-Term Economic (EMEC) Model: Version 4

By Vincent M. Otto and David von Below

National Institute of Economic Research

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Table of contents

1 Introduction

EMEC is a computable general equilibrium (CGE) model of the Swedish economy developed and maintained by the National Institute of Economic Research (NIER) since the 1990s. Being built upon general equilibrium theory and the system of national accounts and environmental accounts, its main virtue is its micro-economically consistent and comprehensive representation of price-dependent interactions between the different product markets, production factor markets and the public and private sector in a given economy. CGE models have been the workhorse for economic policy analysis since the 1980s and are widely employed by various international organizations (*e.g.* World Bank, see Ciecowiez and Lofgren, 2017; WTO, see Aguiar et al, 2019; OECD, see Chateau et al, 2014; and the European Commission, see Capros et al, 2013), national government organizations (*e.g.* US EPA, see Marten et al, 2021; Government Institute for Economic Research Finland, see Honkatukia, 2009; Danish Research Institute for Economic Analysis and Modeling, see Ejarque et al, 2021 and Statistics Norway, see Rosnes et al, 2019) and universities (*e.g.* MIT, see Chen et al, 2022).

At NIER, we use the EMEC model to study interactions between the economy, energy use and emissions of several pollutants in Sweden and to support policymaking. More specifically, the model allows for analysis of the long-run impacts of several energy and environmental policies on the economy and emissions of several pollutants and how these policies can be designed in effective, cost efficient and equitable ways. For example, we can use the model to answer research questions such as: Does a policy achieve its stated target objective? Can we expect any conflicts with other targets or policies to arise? Does the policy achieve its objective at the lowest cost? What are expected effects on GDP, hours worked, composition of the economy etc.? What are the expected effects on emission levels of greenhouse gases and local air pollutants? What are expected effects on the income distribution? Over the years, the EMEC model has been used to answer such questions for several governmental commissions. For example, it has been used to provide inputs to the Swedish environmental objectives committee ('Miljömålsberedningen'; see *e.g.* SOU, 2000, 2003, 2005; Östblom, 2003, 2004a, 2004b; and Broberg et al 2010), to the Swedish Long-Term Survey (*e.g.* SOU, 2019), and to the long-term energy and greenhouse gas projections of the Swedish Energy Agency (*e.g.* 2021b). We have also used the EMEC model for several inhouse reports (*e.g.* NIER, 2019, 2021) and research projects (Berg 2006; Samakovlis and Östblom 2007; Östblom 2009; Sjöström and Östblom 2010; Krook-Riekkola et al, 2017). At this point, it should be noted that the EMEC model comes with limitations on its use. Although the EMEC model can be used to identify plausible ways to reach a given target, we cannot use it to answer the question what the optimal target should be, for example. One would need to use integrated-assessment models that also specify environmental damages to answer such a question. Similarly, we cannot use the EMEC model to answer the question whether the plausible ways are also likely or feasible at the required scale. One would need to use detailed energy-system models to answer such questions. Relatedly, we can study the plausible ways in scenarios for the long run but cannot make forecasts for the short run. One would need forecasting models for such studies.

The EMEC model has the following key features. We specify firms in 35 production sectors, together producing 43 different products. Production requires capital, labour, and intermediate inputs from other industries, where the inputs can move freely between sectors. Further, we specify 6 household types differentiated by income and residential area to study income distribution. Households enjoy final consumption products and leisure time, save, invest in and own capital and own their hours available for work and leisure. We also specify a government that mainly consumes final consumption products, holds the trade balance between imports and exports, collects taxes, pays subsidies, and pays transfers to the households. We specify the economy as open but small relative to other countries meaning that world market prices are taken as given. Yet, domestically-produced products are generally assumed to be imperfect substitutes to imported products allowing for domestic product prices to differ from the world market prices. Since we use the model for studies of how energy and environmental policies affect economic activity in Sweden, we specify the supply and use of energy products and transport services in greater detail. For the same reason, we account for emissions of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases as well as emissions of the local air pollutants nitrogen oxide (NO_x), sulfur dioxide (SO_2), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), carbon monoxide (CO) and particulate matters (PM) in physical quantities and specify the main energy and climate policy instruments in place or under discussion in Sweden. These policies include the EU emission allowance under the EU Emission Trading System (ETS), the national energy and CO_2 taxes, renewable fuel standards for vehicles ('Reduktionsplikten') and feebates for vehicles ('Bonus-Malus'). Finally, we calibrate the model to base-year data from the National Accounts and the Environmental Accounts, compiled by Statistics Sweden (2022a, 2022b).

The EMEC model is currently in its fourth version.[1] Compared to the previous versions, we have further developed the model in a few respects. Firstly, we have changed the mathematical specification of the model (from a 'constrained nonlinear system' to a 'mixed-complementarity problem'). Although the model is still specified as a system of N-equations with N-unknowns, the change of mathematical specification means that the equations can now include inequalities (*i.e.* costs can exceed revenues, supply can exceed demand) and the unknown variables (*i.e.* production levels and prices) can take on zero values. Consequently, we can now model activities that are actually inactive, such as complete phase-outs of old production processes or future technologies that are not yet in use today, in a straightforward way. The change of mathematical specification also allows us to make use of the 'Mathematical Programming System for General Equilibrium' (MPSGE) interface within the GAMS software package (Rutherford, 1995, 1999). This interface represents computable general equilibrium models in a non-algebraic format and as such makes it easier to work with the model and reduces the likelihood of making programming errors in future model development. Secondly, we have specified road transports in a more detailed way. We now explicitly specify multiple vehicle and fuel choices for firms and households allowing us to study policies aimed at road transports, such as renewable fuel standards for transport fuels (Reduktionsplikten) and vehicle feebate systems (Bonus-Malus). Lastly, we continuously make improvements under the hood. Since the previous model version, for example, we have introduced several equations that can help us in targeting levels for selected macro-economic variables.

Our objective with this working paper is to describe in full this latest version of the EMEC model and how we work with the model in reference and policy scenarios. We start by first describing the basics of the model structure and how we evaluate policy with the model in section 2. We describe the model specification in full in section 3 and describe the calibration of the model to data in section 4. We subsequently describe the setup and results of a set of three reference scenarios in sec-

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[1] The first model version introduced EMEC as a CGE model comprising 17 industries, 20 commodities and a single household and has been described by Östblom (1999). The second model version introduced additional industries, commodities and households as well as a more detailed transport demand and has been described by Östblom and Berg (2006). The third model version introduced endogenous supplies of labour and capital.

tion 5 and describe the setup and results of an example policy scenario in section 6. Further, we analyse the sensitivity of a key model result of the policy scenario to changes in key parameter values in section 7. Given that it is difficult to analyse the sensitivity of model results to limitations in the model specification, we discuss future model development in section 8. In addition, we list the complete set of model sets, variables, parameters, and equations in Appendices A-D and describe the calibration of model equations in detail in Appendix E. For the interested reader, we include references to the relevant conditions and equations in these appendices between brackets throughout the text. Finally, we provide an accounting of CO_2 emissions in the base-year data and model in Appendix F.

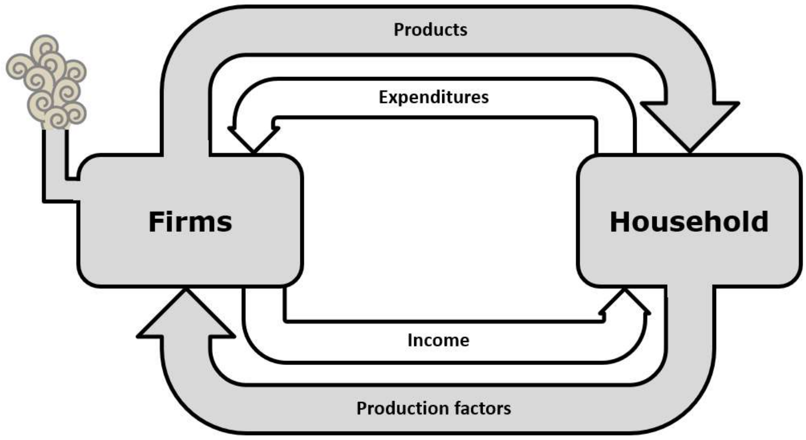
2 Model basics

This section describes the basics of the model structure and how we evaluate policy with the model. Section 2.1 describes the basic model structure and how it is derived. Section 2.2 describes a basic policy evaluation.

2.1 Basic model structure

EMEC belongs to a class of optimization models in economics known as computable general equilibrium models. General equilibrium models represent firms and households interacting with each other in markets for products and production factors in an economy. In a basic model representation (based on Arrow-Debreu, 1954), representative firms in two production sectors produce products and supply these products at a market price to a representative household who derives utility (*i.e.* economic welfare) from consuming the products (see figure 1 for a cartoon overview). The household in turn owns the production factors capital, labour and an energy source and supplies these factors at a market price to the firms for use in production. Payments flow in the reverse direction. The household receives payment for the production factors supplied and uses its income to pay the firms for the products consumed. As an extension, production leads to emissions of a pollutant. Emissions can arise from the energy use or from the entire production process. The household has the right to control and tax emissions and wants to allow emissions only at or below a targeted level with help of a tax. Firms are required to pay the tax for every tonne of the pollutant emitted and the household receives the tax revenue as income.[2]

Figure 1 Cartoon of a general equilibrium model



Key to representing the household is a description of its preferences for the products and willingness or possibility to substitute between them when relative product prices change. Key to representing the firms is a description of their production technology, *i.e.* how the firms produce a product with the inputs. With these descriptions, the behavior of the firms and household can be for-

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[2] Note that taxes and a tax rate are equivalent to the use of (tradable) allowances and an allowance price in our model. In both cases, firms are required to pay for their pollution with the payments accruing to the household. Likewise taxes and the tax rate are equivalent to a standard and an implied shadow price of the standard in our model. In both cases, firms incur a cost in meeting the emission reduction target with the cost representing a (shadow) value accruing to the household as the owner of the rights to emit.

malized as optimization problems. Firms choose levels of output and input use to maximize their profits subject to their production technology and taking prices and the tax rate as given. A firm's problem is then:

$$\max_{Y_i,K_i,L_i,E_i,EM_i} \pi_i = P_i Y_i - \Omega_i\left(PK,PL,PE,TEM\right) \;\; s.t.\; Y_i = \varphi_i\left(K_i,L_i,E_i,EM_i\right) \qquad i = 1,2 \qquad (1)$$

where π_i, Ω_i and φ_i denote the profit, cost and production functions of firms in industry *i* respectively, Y_i is the firm's output level and K_i, L_i, E_i and EM_i are the firm's input levels of capital, labour, energy and emissions subject to the tax respectively, P_i is the product price received by the firm and *PK*, *PL* and *PE* are the factor prices of capital, labour and energy respectively and *TEM* is the emission tax rate. The household chooses consumption levels to maximize its utility function subject to its expenditures being balanced by its income and taking prices and the tax rate as given. The household's problem is then:

$$\max_{C_1,C_2} U\left(C_1,C_2\right) \;\; s.t.\;\; PU\cdot U = PK\cdot k + PL\cdot l + PE\cdot e + TEM\cdot em \qquad (2)$$

where *U* denotes the household's utility function, *k*, *l* and *e* are the household endowments of capital, labour and the energy source respectively, $TEM\cdot em$ is the emission tax revenue, C_1 and C_2 are the household consumption levels of products 1 and 2 and *PU* is the welfare or utility price index. A general equilibrium is subsequently defined as the set of production and utility levels, market prices for the products and production factors and tax rate for the emissions tax, under which the firms and household cannot do better by adjusting their output, input and consumption choices and under which supply equals demand on all markets for products, production factors and the emission tax. A general equilibrium on all markets contrasts with a partial equilibrium on a single market. It can be shown that a general equilibrium exists as the solution to a single utility optimization problem of the household subject to its preferences for the two products and income, production technology and market-clearing constraints (and assuming that the household is the ultimate owner of the firms in the economy):

$$\max_{C_1,C_2} U\left(C_1,C_2\right) \;\; s.t.\;\; PU\cdot U = PK\cdot k + PL\cdot l + PE\cdot e + TEM\cdot em \qquad i\in\{1,2\} \qquad (3)$$

$$\begin{aligned}
Y_i &= \varphi_i\left(K_i,L_i,E_i,EM_i\right)\\
Y_i &= C_i\\
k &= \sum_i K_i\\
l &= \sum_i L_i\\
e &= \sum_i E_i\\
em &= \sum_i EM_i
\end{aligned}$$

This is a standard linear programming problem and its solution can be found with help of Lagrange multipliers.

Yet, finding the general equilibrium by solving a single optimization problem becomes more complicated once we introduce multiple households. There is then no longer an obvious utility function to optimize and utility of the households would have to be weighed and traded off against each other.[3] As an alternative to such weighing, one can derive the first-order conditions of the optimization problems of the firms and households, specify conditions for the remaining income balances and market clearing constraints, and find the general equilibrium by solving a square system of *n* equations (conditions) for *n* unknowns. In this approach, the optimization problems of the firms and households are then embedded in the system's conditions and the solution to the system is also the joint solution to the optimization problems. We have taken this approach to find the general equilibrium since we introduced multiple households in the second EMEC model version. In contrast to previous model versions, however, in this model version we allow many of the system's conditions to hold not only as equalities but also as inequalities and allow for complementary slackness between inequality conditions and their associated unknowns (mixed complementarity problem, see Mathiessen, 1985; Rutherford, 1995).

To specify the equation system, we first derive the first-order conditions of the firms' profit maximization problems from equation 1. Formally:

$$cost_i\left(PK, PL, PE, TEM\right) - P_i \geq 0 \qquad \perp Y_i \qquad i = 1,..,I \tag{4}$$

where $cost_i$ denote the firms' unit-cost function and the orthogonality symbol $\perp$ denotes the unknown variable determined by the condition, in this case production level Y_i of the firm in industry *i*. These first-order conditions require that any productive activity undertaken must earn zero profits or that no productive activity must be undertaken if the activity were to yield a loss.[4] Assuming constant returns to scale in production and perfect competition on all product markets in turn imply that profits are driven down to zero. These conditions are referred to as zero-profit conditions.

Similarly, we derive the first-order conditions of the households' utility maximization problems from equation 2. Formally:

$$\mathrm{e}_h\left(P_i\right) - PU_h \geq 0 \qquad \perp U_h \qquad h = 1,..,H\ , i \in I \tag{5}$$

where e_h denotes the unit-cost (expenditure) function of household *h*. These first-order conditions require that any utility enjoyed must have expenditures to match (no free lunch) or that no utility must be enjoyed if it would entail too costly expenditures (no lunch that is not worth its price). Assuming constant returns to scale in consumption and utility and perfect competition on all product markets in turn guarantee matches between utility enjoyed and expenditures. For simplicity, these conditions are also referred to as zero-profit conditions and determine utility levels as the unknown variables.

The income-balance conditions for households follow from equation 2 and simply require that the value of total income equals the sum of its parts. These conditions determine the income value levels of the households as the unknown variables. Formally:

$$INC_h = PK \cdot k_h + PL \cdot l_h + PE \cdot e_h + TEM \cdot em_h \qquad \perp INC_h \qquad h = 1,..,H \tag{6}$$

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[3] See Negishi (1960) for the original discussion of finding general equilibrium as a single optimization problem.

[4] The unknown variable is determined by the condition as follows. If the condition holds as an equality to zero (*i.e.* the unit cost of producing a product equals the product price received), then the variable (*i.e.* production level) will take on a positive value. If the condition holds as an inequality greater than zero (*i.e.* the unit cost of producing a product exceeds the product price), then the variable will go to zero instead.

where k_h , l_h and e_h now denote the capital, labour and energy endowments of household *h*, $TEM \cdot em_h$ is the household tax revenue receipts and INC_h is the household income level.

We complete the equation system with the market-clearing conditions for products, utility, production factors and the emission tax. These conditions require that prices must be strictly positive if supply equals demand or that prices must be zero if supply exceeds demand and determine prices as the unknown variables. Formally:

$$Y_i \geq \sum_{h=1}^{H} \frac{\partial e_h}{\partial P_i} U_h \qquad \perp P_i \qquad i = 1,..,I \tag{7}$$

$$U_h \geq \frac{INC_h}{PU_h} \qquad \perp PU_h \qquad h = 1,..,H \tag{8}$$

$$\sum_{h=1}^{H} k_h \geq \sum_{i=1}^{I} \frac{\partial cost_i}{\partial PK} Y_i \qquad \perp PK \tag{9}$$

$$\sum_{h=1}^{H} l_h \geq \sum_{i=1}^{I} \frac{\partial cost_i}{\partial PL} Y_i \qquad \perp PL \tag{10}$$

$$\sum_{h=1}^{H} e_h \geq \sum_{i=1}^{I} \frac{\partial cost_i}{\partial PE} Y_i \qquad \perp PE \tag{11}$$

$$\sum_{h=1}^{H} em_h \geq \sum_{i=1}^{I} \frac{\partial cost_i}{\partial TEM} Y_i \qquad \perp TEM \tag{12}$$

where we take the partial derivative of the unit-cost function with respect to the factor price or tax rate to obtain the unit demand for the factor in production (Shephard's lemma), which we subsequently can multiply with the total production level to obtain the total demand for the production factor. Similarly, we take the partial derivative of the expenditure function with respect to the product price to obtain the unit demand for the product (Shephard's lemma), which we subsequently can multiply with the total utility level to obtain the total product demand.

To compute general equilibria numerically, we follow common practice in our field and choose to specify zero-profit conditions with help of a combination of constant-elasticity-of-transformation, constant-elasticity-of-substitution (CES), Cobb-Douglas, and Leontief functions.[5] These functions have regular mathematical properties considerably easing numerical computation while still being flexible enough to capture a wide variety of economic behaviour. Further, we specify the functions in the calibrated share form allowing us to incorporate base-year data from the national accounts directly in the functions and substantially easing the calculation of free-form parameters (see Appendix F for more details and see Böhringer et al., 2003, for a fuller discussion of the calibrated share form in CGE modeling). For example, we can specify a firm's unit-cost function as a (nested) CES function in the calibrated share form and rewrite equation 4 as:

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[5] Constant-elasticity-of-transformation and constant-elasticity-of-substitution functions allow for substitution between outputs or inputs and as such quantity and value shares of the outputs or inputs can vary in these functions. Cobb-Douglas functions also allow for substitution between inputs or outputs, but only such that quantity shares can vary and value shares remain preserved. Leontief function also allow for substitution between inputs or outputs, but only such that value shares can vary and quantity shares remain preserved (*i.e.* used in fixed proportions).

$$v_i\left(\theta_i^{EM} TEM^{1-\sigma_i} + \left(1-\theta_i^{EM}\right) PKLEEM_i^{1-\sigma_i}\right)^{\frac{1}{1-\sigma_i}} - v_i P_i \geq 0 \qquad \perp Y_i \qquad i = 1,..,I \tag{13}$$

where:

$$PKLEEM_i \leq \begin{pmatrix} \theta_{KLEEM,i}^{K} \; PK^{1-\sigma_i^{KLEEM}} \\ + \quad \theta_{KLEEM,i}^{L} \; PL^{1-\sigma_i^{KLEEM}} \\ +\left(1-\theta_{KLEEM,i}^{K}-\theta_{KLEEM,i}^{L}\right) PEEM_i^{1-\sigma_i^{KLEEM}} \end{pmatrix}^{\frac{1}{1-\sigma_i^{KLEEM}}}$$

$$PEEM_i \quad \leq \theta_{EEM,i}^{E} PE + \left(1-\theta_{EEM,i}^{E}\right) TEM$$

and where v_i is the value of production in sector *i* in the base-year data, θ_i are input value shares in the various nests of the firm's unit-cost function for production in sector *i* calibrated with the base-year data and σ_i is the assumed elasticity of substitution between inputs in production sector *i*. $PEEM_i$ is the composite price of the energy and emission tax bundle in sector *i* and $PKLEEM_i$ is the composite price of the capital, labour, energy and emission tax bundle in sector *i* . The product price also covers taxes paid over process emissions per unit produced. Since the value and value share parameters are directly taken from the national accounts, (most) variables take on the value one in the base year so that changes in the variable levels can readily be interpreted as index changes. Further, quantities in the model then represent monetary values of total sales, expenditures and factor income expressed in base-year prices.[6] When moving from one general equilibrium to another, we can choose to evaluate changes in (i) quantities by looking at the quantity variables (in which prices are at base-year levels so that changes in the variables reflect underlying changes in quantity, also referred to as variables in 'constant prices'), (ii) prices by looking at the price variables and (iii) values by looking at the product of quantity and price variables (so that changes also reflect price changes, also referred to as variables in 'current prices').

With the model calibrated to monetary values, most underlying physical quantities are not explicitly accounted for in the model. If our focus is purely on economic results, the underlying quantities in their physical units (*e.g.* kilograms of steel produced) do not really matter to us. If our focus is on achieving emission reduction targets or energy intensity targets, however, the physical quantities of emissions and energy need to be accounted for explicitly in physical units. We therefore calibrate the model also to the environmental accounts that accompany the national accounts. More specifically, we introduce the emissions in their physical quantities into sectors of the economy responsible for them. Where emissions arise from energy use, we specify the emissions in a nest with the energy use in question. We do not allow for any substitution between energy and emissions then to reflect the fact that emission abatement comes about through reduced fuel use. Where emissions arise from the production process as a whole, we follow Hyman (2001) and specify the emissions in the top nest of the functions with the substitution elasticities chosen to reflect the possibilities to abate these process emissions by making changes to the production process as a whole. In addition, we specify the supply and use of energy products in greater detail so that energy substitution possi-

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[6] Flows of products and production factors in the economy are mesured in monetary values in the national accounts as it would be difficult to compare products (*e.g.* haircuts and computers) and factors (*e.g.* low-skilled vs high-skilled workers), account for quality differences and aggregate all into consistent totals. Assuming that product and factor prices reflect their marginal value as inputs into production or consumption, physical quantities can be multplied with their prices and the resulting values can be aggregated instead.

bilities are represented more realistically and changes in monetary values approximate changes in physical quantities well. And we adjust the relation between the physical measure and economic measure when we believe there is a persistent trend in the relation.

Finally, we program the model using the MPSGE interface and PATH solver (Ferris and Munson, 2000). Both MPSGE and PATH are part of the General Algebraic Modeling System (GAMS) software.

2.2 Basic policy evaluation

Since CGE models represent firm and household behavior and market interactions in the whole economy and capture multiple feedbacks between firms and households, these models lend themselves very well to studying policy effects throughout the economy. Policy effects on volumes and prices of production, value added, household income, household utility and emissions can all be readily computed in a consistent manner. We do not specify utility to be a function of environmental quality in the EMEC model, however, so we cannot compute welfare trade-offs between both the consumption possibilities and environmental damages stemming from allowed emissions and study optimal target setting.[7] Rather, we take existing emission reduction targets as given and study the ways and effects of reaching the set targets with policy. We can also study policy design itself by comparing the effects of multiple (designs of) policies with each other.

As an example, let us study a reduction in the allowed emissions from Section 2.1. A reduction in the allowed emission level will lead to an increase in the emission tax rate. Firms react to the tax increase by abating their emissions. Firms do so by using more of the production factors capital and labour as input in production instead of the pollutant. The extents to which firms abate their emissions and consequently raise their product prices depend on their pollution intensity of production and the ease at which they can substitute the other inputs for the emissions as governed by substitution elasticities. The more emission taxes firms pay per unit product produced, the more costs they have to pass on, the more they have to raise their product prices and the more product demand they lose, all else equal. Yet, the easier it is for the firm to substitute other inputs for the pollutant in production, the more the firm can avoid cost and product price increases and the less product demand they lose, all else equal.

Similarly, households respond to the changed product prices by adjusting their consumption product demands. The extents to which households adjust their demands depend on their relative product shares in consumption and the ease (or willingness) at which households can substitute other products for the relatively more expensive product as governed by substitution elasticities. The higher the consumption share of the relatively more expensive product is for households, the more their consumption and utility levels are negatively affected, all else equal. Yet, the easier it is for households (or the more willing they are) to substitute other products for the relatively more expensive product in consumption, the more they can maintain their consumption and welfare levels, all else equal.

The effects of an increased emission tax rate do not stop here. As production levels are affected, demand for and prices of the production factors change in turn affecting household income from

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[7] Models that do specify welfare to be a function of environmental damages as well are often referred to Integrated assessment models. A well-known example is the DICE model (Nordhaus, 1993).

the factor supplies. The extents to which factor prices change depend on the relative factor input shares in production and the ease at which firms can substitute inputs as governed by substitution elasticities. The higher the relative factor input share in the production of the pollution intensive (and hence more expensive) product, the more the factor demand and price are negatively affected, all else equal. Yet, the easier it is for the firm to substitute inputs in production, the more the firm can maintain production and factor demand levels and the less factor prices are affected, all else equal. The extent to which household income levels change depend on the factor income shares and tax revenue shares of the households. The higher share households receive from the tax revenue, the more their income increases, all else equal. The more households own the supplies of the production factor used intensively in the production of the pollution intensive product, however, the more households suffer from the negative factor price effect and the more their income falls, all else equal.

The effects of an increased emission tax rate do not even stop here. All the changes in the model variables described so far give rise to secondary smaller effects themselves. And these secondary effects in turn give rise to tertiary effects that are even smaller and so on until the model variables constitute a new general equilibrium that cannot be improved upon.

To evaluate the net costs of the targeted emission reduction as our example policy, we can look at the required tax rate as one cost indicator and as given by equation 12. The more difficult it is for firms to replace the pollutant with other inputs in production or the more difficult it is for households to substitute away from the pollution intensive product in consumption, or both, the more firms and households need to be incentivized. Consequently, the tax rate then needs to increase more to meet the emission reduction target.

Another possible indicator of the net policy cost is the change in Gross Domestic Product (GDP).[8] GDP is the monetary value of all produced products within a country and we can evaluate GDP expressed in constant and current prices. In our basic model from Section 2.1, we can therefore compute GDP as the sum of all production values (excluding intermediate input use), but also as the sum of all consumption values and as the value of all household income earned. The more difficult it is for firms to replace the pollutant with other inputs in production or the more difficult it is for households to substitute away from the pollution intensive product in consumption, or both, the more household income and the value of aggregate consumption fall as a result of the increasing emission tax rate, all else equal.

To evaluate how net costs are distributed between firms, we can look at changes in the value of production of the firms including intermediate input use (referred to as gross production) or excluding intermediate input use (referred to as value added) as given by equation 4. The more difficult it is for firms to replace the pollutant with other inputs in production, the more gross production levels and value-added levels fall as a result of the increasing emission tax rate, all else equal.

Finally, to evaluate how net costs are distributed between households, we can look at changes in their utility measured as 'equivalent variation.' This measure is the monetary value of income needed to compensate the households for expenditures lost as a result of the policy. In our basic model from Section 2.1, equivalent variation is given directly by equation 5. In this equation, a change in

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[8] Although GDP is often used as an indicator of net policy costs, we consider it an imperfect indicator as it does not capture any transactions outside of markets and does not say anything about the distribution of policy costs between different firms and households in the economy.

U_h indicates how much household income adjusts in line with changing expenditures by the household. For the household to maintain the same level of expenditures as before the emission tax increase, the household would thus need to receive or pay the amount of the income adjustment. The more difficult it is for households to substitute away from the pollution intensive product in consumption, the more household income and the utility level fall as a result of the increasing emission tax rate, all else equal.

3 Model specification

This section describes in detail how we implement the basic model structure in specifying the EMEC model. Section 3.1 describes the firms, households, and the government as the economic agents in the model as well as their behavior. Section 3.2 briefly describes the clearing of markets. Section 3.3 then describes the general equilibrium in any given time period and how we move from one general equilibrium to the next over time.

3.1 Firms, households and the government and their behavior

Several economic agents interact with each other by demanding and supplying commodities on markets. These agents are representative firms in 35 production sectors, representative households in 6 household categories differentiated by income and residential area, and a government. For the sake of completeness and transparency, we also specify representative firms in several other sectors of the economy: in product import sectors, product distribution sectors, product export sector, product sales sectors, fuel blend sales sectors, used-vehicle export sectors, non-fixed capital formation sector, fixed capital formation sector, and in a labour supply sector.[9]

FIRMS PRODUCING PRODUCTS

We specify representative firms in 35 sectors, together producing 43 different products where a product can be a good or a service delivered (see Tables A.2-3 in Appendix A for the complete classification of sectors and products). The firms maximize profits from producing the sector's products subject to their production function and taking all prices as given (and with zero-profit (Z) conditions Z.01-07 holding in equilibrium).

We specify the production functions as nested CES functions of capital, labour, energy and other intermediate inputs. We specify a common nesting structure for all sectors (see figures 2a-d for a schematic overview). In this nesting structure, we bundle capital and labour use in a nest constituting the value added of a production sector and assume that capital and labour can move freely between sectors. We bundle the capital-labour nest in turn with a nest of energy inputs where we specify energy use in more detail in sub-nests. We distinguish between use of electricity, district heating and fuels and further distinguish the fuel use between the use of solid and liquid fuels. Further, we bundle the capital-labour-energy nest in turn with a nest of intermediate inputs, where we specify transport service inputs in more detail. Specifically, we distinguish between sea, air, rail, and passenger road, and cargo road transport services. For both passenger and cargo road transport services we further distinguish between purchased and own road transport services. Own cargo road transports are assumed to be conducted with heavy-duty vehicles and we specify a single type of heavy-duty vehicle having a diesel engine. Own passenger road transports are assumed to be conducted with light-duty vehicles. We include a technology-rich representation of light duty vehicles by distinguishing between multiple types of light-duty vehicles differentiated by engine type: vehicles with diesel engines, petrol engines, petrol engines that can also handle E85 petrol blends (E85 vehicles), vehicles with both petrol and electric motors (PHEVs), and vehicles with electric motors only (EVs). For the first three vehicle types, we further distinguish between engines with

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[9] We like to think of firms in dedicated sectors of the economy, but there exist more institutional structures that support a decentralized equilibrium of course. Firms in each production sector can import products or invest in fixed capital themselves, for example. The precise institutional structure is irrelevant as long as the import of products or investments in fixed capital are made according to identical product import functions and fixed-capital formation functions.

relatively low and high fuel efficiency to allow for endogenous fuel efficiency improvements in the model (see Table A.4 in Appendix A for an overview of all vehicle technologies specified in the model). In addition, we follow the approach taken by Karplus (2011) and specify that all own cargo- and passenger road transport services with all vehicle types can be conducted with a new vehicle and two vintages of used vehicles. Making this distinction between new and used vehicles allows us to account for turnover in the vehicle fleet. For own road transports with new vehicles the user costs consist of vehicle, maintenance, and fuel costs. Vehicle costs can vary between vehicle technologies, but always have fixed components associated with the chassis and (in the case of electric vehicles and plug-in hybrid vehicles) the battery and have a variable component associated with the engine. Having this variable cost component allows for substitution between engine and fuel costs as another endogenous fuel efficiency option in the production function. For own road transports with used vehicles the user costs consist of the same cost components, but with the difference that we fix all cost shares based on the values of the underlying stocks of used vehicles. So, we take characteristics of used vehicles as given and do not allow for further fuel efficiency choices once they have been put into use. Supplies of the used vehicles themselves are also determined by the underlying stocks of used vehicles and are also taken as given in any period (with income balance (I) condition I.05 holding in equilibrium). Where applicable, however, we maintain the same fuel blend choices for own road transports with used vehicles as for new vehicles (see Table 1 for an overview of vehicle types and matching fuel blends and see Table A.5 in Appendix A for a classification of the fuel blends in the model). More specifically, we assume that heavy-duty vehicles can run on both B15-90 and B100 diesel blends and assume both diesel blends to be perfect substitutes in the blend choice. Similarly, we assume that plug-in hybrid electric vehicles can run on both electricity and E10-50 petrol blends but assume electricity and the petrol blend to be imperfect substitutes. Further, light duty vehicles with diesel engines are assumed to run only on B15-90 diesel blends, vehicles with regular petrol engines to run on E10-50 petrol blends only, E85 vehicles to run on E85 petrol blends only and electric vehicles to run on electricity only. Note that the volume share of the biodiesel product can vary between 15% and 90% in the B15-90 diesel blend and that the volume share of the ethanol product can vary between 10% and 50% in the B10-50 petrol blend.

Table 1 Vehicle types and matching fuel blends in the model

Heavy/light-duty vehicle type	Engine type	Possible fuel blends
HDV	Diesel	B15-90, B100
LDV	Diesel	B15-90
LDV	Petrol	E10-50
LDV	E85	E85
LDV	PHEV	E10-50, Electricity
LDV	EV	Electricity

Notes. HDV denotes heavy-duty vehicles and comprise trucks and buses weighing more than approx. 3500 kg. LDV denotes light-duty vehicles and comprise trucks and buses weighing less than approx. 3500 kg as well as passenger cars. We borrow the classification from US federal regulations. EV denotes electric vehicles without any other engine or drive train and PHEV denote plug-in hybrid electric vehicles with both petrol and electric engines. B blends denote diesel blends of fossil diesel and biodiesel products with the numbers indicating the range of volume shares of the biodiesel product that the blend can contain. Similarly, E blends denote petrol blends of fossil petrol and ethanol products with the numbers again indicating the range of volume shares of the ethanol product that the blend can contain.

Firms typically produce multiple products and we specify the output of firms with constant-elasticity-of-transformation functions. We choose low values for the transformation elasticities as we assume produced products to be rather complementary to each other in production sectors (*e.g.*

output levels of *forestry* and *biomass* products in the *forestry and logging* production sector). Stated differently, we assume firms to have relatively few possibilities to increase output of one product at the expense of another product in any given time period. In addition to being paid for selling products, firms in selected sectors may receive EU emission allowances being allocated to them for free and may receive a markup over the cost price of products if we choose to target a higher price for a (distributed) product (with condition X.04 optionally holding in equilibrium). We treat markups as capital earnings accruing to households.

Figure 2a Schematic overview of nested production functions – Main nests

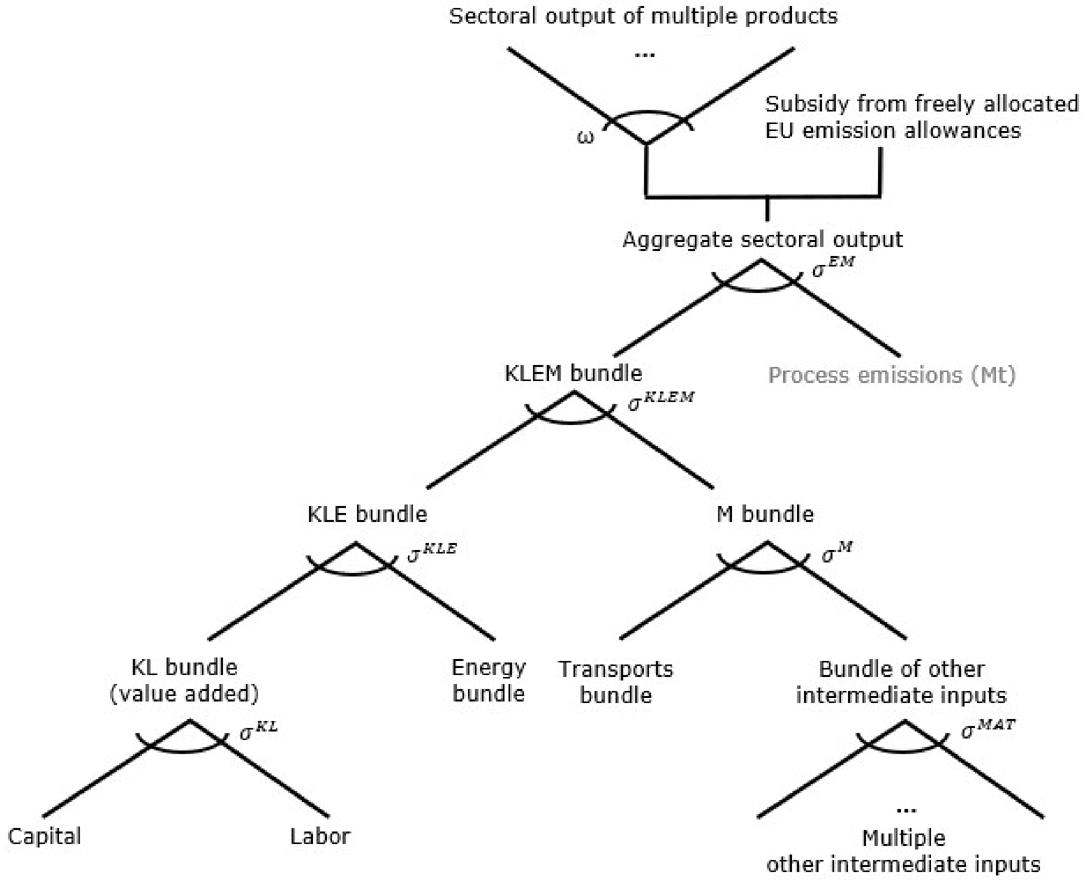


Figure 2b Schematic overview of nested production functions – Energy nests

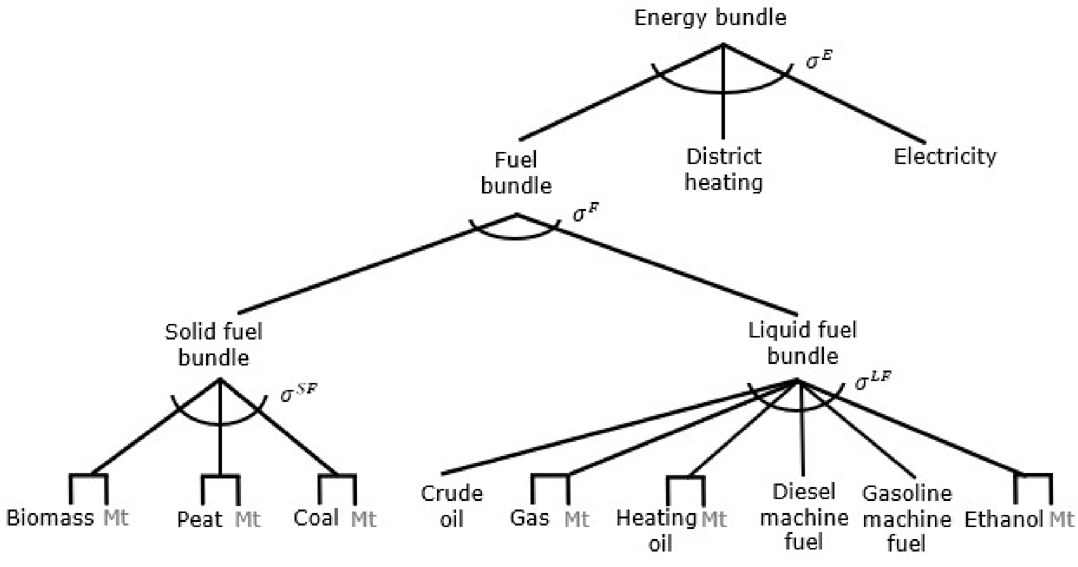


Figure 2c Schematic overview of nested production functions – Transport nests

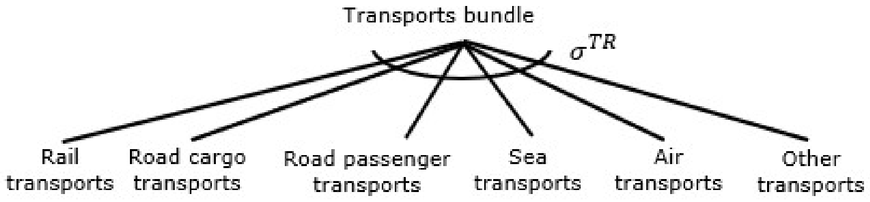
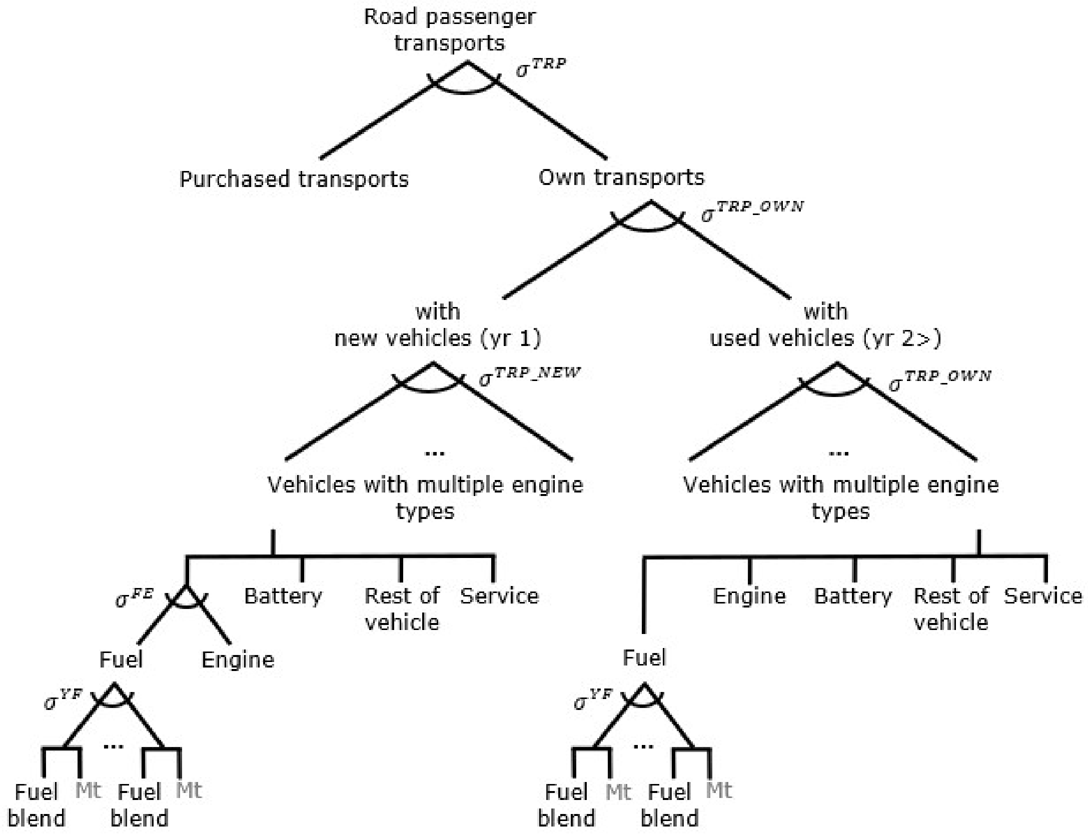


Figure 2d Schematic overview of nested production functions – Road passenger transport nests



Notes: Lines represent the constant-elasticity-of-transformation and constant-elasticity-of-substitution functional forms with ω and σ denoting the elasticities in the various nests of the function and with vertical lines in 90-degree angles representing the Leontief functional form that require quantities of the inputs or outputs in the nest to be used in fixed proportions to each other. Nests with … denote a range of products as outputs or inputs. Mt denotes million tonnes of emissions of the modeled pollutants. We specify a nested production structure for road cargo transports similar to the one we show here for road passenger transports with the main difference being that heavy-duty vehicles are used for cargo transports and light-duty vehicles are used for passenger transports.

Multiple input taxes and subsidies are imposed that can impact production choices. The use of fixed capital (*e.g.* buildings, machinery) is subject to capital taxes and hours worked are subject to social security contributions. Further, fixed costs of light-duty vehicles are subject to a bonus subsidy or malus tax depending on the vehicle's calibrated CO_2 intensity of a km driven.[10] Production processes at various stages also give rise to emissions of greenhouse gases CO_2, CH_4, N_2O and local air pollutants NMVOC, CO, SO_2, NO_x, NH_3 and PM that may be subject to policy and come with an emission price. Firms may need EU emission allowances to emit greenhouse gases, for example, if the sector and emission source are subject to the EU ETS. Firms in several production sectors also receive EU emission allowances for free, of which the value represents a lump-sum subsidy. We book the value on the income balance of the firms or on the income balance of the households (as the ultimate owners of the firms) or both. If booked on the income balance of the firms, the value allows for greater output levels under the zero-profit condition of the firm, akin to an output subsidy and all else equal (with condition I.03 holding in equilibrium).[11] Finally, intermediate inputs and fuel blends are paid for in market prices and are thus inclusive of all tariffs, value-added tax (VAT; where applicable) and excise taxes such as aviation taxes, energy and CO_2 taxes and possibly other emission taxes. Note that firms in several production sectors are also granted rebates from the energy and CO_2 taxes.

When faced with an emission tax or allowance price, firms choose to use the polluting input and pay the emission tax or allowance price, or reduce the polluting input use and avoid paying the tax or allowance price, whichever is cheaper. When choosing to reduce the polluting input use, firms can choose to do so by substituting other intermediate inputs for the polluting intermediate input, by substituting other production factors for intermediate inputs or by cutting back the production level, again whichever is cheapest. Taking the example of the use of the fossil diesel product subject to an increasing CO_2 tax, firms can choose to (i) continue using the fossil diesel product and pay the increased tax, (ii) demand a higher biodiesel content of the diesel blend for use in their own vehicles instead, (iii) use relatively more of the more recent vintage of used vehicles with a more fuel-efficient diesel engine instead, (iv) use relatively more new vehicles with more fuel efficient diesel engines instead, (v) use relatively more vehicles with other engines instead, (vi) use relatively more purchased road transport services instead of own produced transports, (vii) use relatively more sea, air and rail transport services instead of road transports, (viii) use relative less transport services and more capital and labour inputs instead, and (ix) produce less. Firms will choose the combination that maximizes their profits and given their production function. Precise production functions differ between production sectors according to the assumed production technology. Specifically, input and output values vary from sector to sector and we vary substitution elasticities from one production function to another.

Firms in the production sectors sell their products to firms in the product distribution sectors. However, some volume of the *wholesale and retail service* product is sold directly to firms in the product sales, fuel blend sales, capital formation and export sectors as a trade margin. Further, the public sector produces several products (*e.g.* accommodation, food, education, health) for own non-commercial use by households and the government only.

FIRMS IMPORTING PRODUCTS

We specify representative firms in multiple product import sectors maximizing their profits from importing a product subject to their import functions and taking all prices as given (and with condi-

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[10] In reality, the bonus subsidy is received 6 months after the purchase of a new vehicle and the malus tax is paid annually for the first three years of the vehicle's lifelength. In the model, we also impose the malus tax at the time of a new vehicle's purchase based on our assumption that buyers take the entire value of the malus tax into account at the time of purchase.

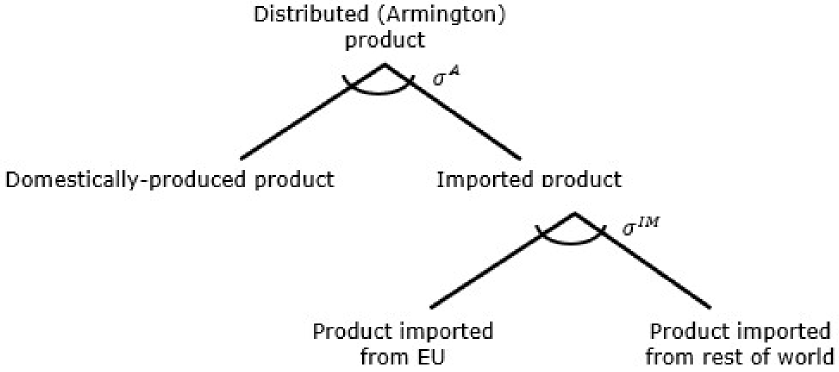
[11] Note that such firms still factor the allowance price into their production decisions since firms have the choice to sell the allowance or use it in production.

tions Z.08 holding in equilibrium). Product import functions are CES functions of products imported from the EU and products imported from the rest of the world (ROW; see also Figure 3 for a schematic overview). Imported products are paid for in foreign exchange. We assume imports to be available in limitless supplies at given prices. Tariffs may be levied on imported products from the rest of the world. Precise product import functions differ from import product to import product based on input and output values and as we vary substitution elasticities from one product import function to another. Firms in the product import sectors sell the imported products to firms in the product distribution sectors.

FIRMS DISTRIBUTING PRODUCTS

We specify representative firms in multiple product distribution sectors maximizing profits from distributing bundles of the imported and domestically-produced versions of a product subject to their product distribution functions and taking all prices as given (and with conditions Z.09 holding in equilibrium). Product distribution functions are CES functions of the imported and domestically-produced product (see Figure 3 for a schematic overview). We follow Armington (1969) and assume imported and domestically-produced products to be heterogeneous and hence imperfect substitutes to each other. That way products can be both imported and exported at the same time (*e.g.* vehicles) and domestic product prices can differ from world market prices. Precise product distribution functions differ from distributed product to distributed product based on input and output values and as we vary (Armington) substitution elasticities from one product distribution function to another. Firms in the product distribution sectors sell the distributed products to firms in the fuel blend sales, product sales, capital formation and product export sectors.[12]

Figure 3 Schematic overview of product distribution functions



Notes: Lines represent the CES functional forms with σ denoting the elasticities in the various nests of the function.

FIRMS SELLING FUEL BLENDS

We specify representative firms in multiple fuel-blend sales sectors maximizing profits from selling fuel blends subject to their fuel-blend sales functions and taking all prices as given (and with conditions Z.10-12 holding in equilibrium). Fuel-blend sales functions are Leontief functions of a distributed (fuel) product, fuel standards and applicable excise taxes (see Figure 4 for a schematic overview). We specify such a function for each combination of a fuel blend (*e.g.* E10-50 petrol

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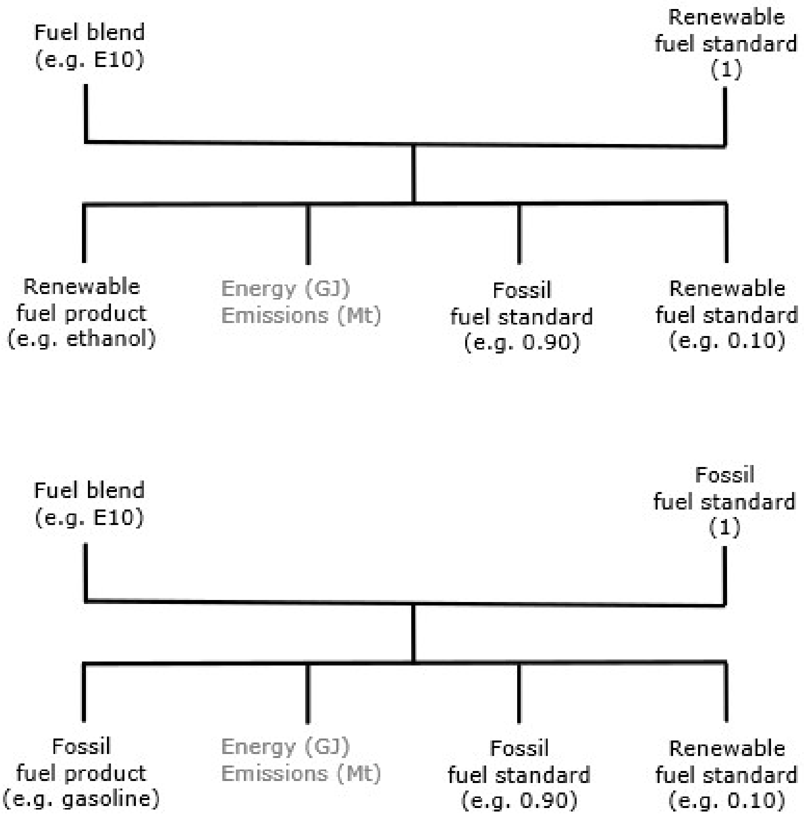
[12] We thus implicitly assume that firms in the fuel blend sales, product sales, capital formation and product export sectors face identical shares of the imported and domestically-produced products when buying a distributed product.

blend) and matching fuel products (*e.g.* fossil petrol and ethanol). Mathematically, multiple fuel products can thus be sold as the same fuel blend. A set of fuel standards, however, ensures that fuel blends meet minimum and maximum volume requirements on the use of renewable and fossil fuel products. For example, we require the E10-50 blend to have a minimum volume content of 10% for ethanol and a minimum volume content of 90% for fossil petrol initially. We can change the volume requirements over time and between scenarios. For example, we can require the E10-50 blend to have a minimum volume content of 30% for ethanol and a minimum volume content of 50% for fossil petrol at a future date.

Figure 4 Schematic overview of fuel blending functions



Notes: The vertical lines in 90-degree angles representing the Leontief functional form that require quantities of the inputs or outputs in the nest to be used in fixed proportions to each other.

We implement the fuel standards with help of tradable allowances within the fuel-blend sales sectors. All firms selling a fuel blend subject to minimum renewable and fossil fuel requirements (*e.g.* the E10-50 blend) need to submit certain shares of the renewable fuel allowance (10%) and the fossil fuel allowance (90%) for each liter sold. At the same time, firms selling the renewable fuel product (ethanol) as the fuel blend receive one renewable fuel allowance per liter sold whereas firms selling the fossil fuel product (fossil petrol) as the fuel blend receive 1 fossil fuel allowance per liter sold. In case the initial renewable fuel content is already sufficiently high to meet the renewable fuel requirement, supply of the renewable fuel allowance will exceed its demand and the renewable fuel allowance price will be zero. In case the initial renewable fuel content is too low, however, demand for the renewable fuel allowance will exceed its supply and the renewable fuel allowance price will increase until it is profitable enough to supply the minimum required amount of the renewable fuel. The same price setting applies for the fossil fuel allowances. Note that we can assume that tradable allowances are specific to a fuel blend or uniform between multiple fuel blends. In the latter case, allowances can be traded between fuel blends (*e.g.* renewable fuel allowances earned from selling ethanol can be used to meet renewable fuel requirements for diesel blends with biodiesel contents) whereas in the former case they cannot. Note also that it does not matter that tradable allowances have not been introduced in the real world. In the model, tradable allowance prices are then simply interpreted as shadow prices of required cross-subsidization within the sectors. Either way, we assume firms within the sectors to meet the fuel standards themselves without any money exchanges with the government.

Taxes and trade margins may be imposed that can impact blending choices as well. The taxes include VAT and the energy and CO_2 taxes and may also possibly include taxes on emissions of other greenhouse gases and local air pollutants. VAT and trade margins do not differ between fuel products and are added to the cost price of the fuel blends instead. However, VAT and trade margins can differ between fuel blends, between fuel blends being sold to households and firms in production sectors. The energy and CO_2 taxes can differ between fuel products and also between fuel blends. Firms in several production sectors are also granted rebates from the energy and CO_2 taxes, in turn further differentiating the tax rates applied. Furthermore, if the taxes are changed at different rates, both the relative costs of the fuel products used within a blend and the relative costs of the blends themselves will change. The taxes can thus also steer toward (or away from) minimum fuel requirements.

Firms in the fuel blend sales sectors sell the fuel blends in market prices to households and firms in the production sectors.

FIRMS SELLING PRODUCTS

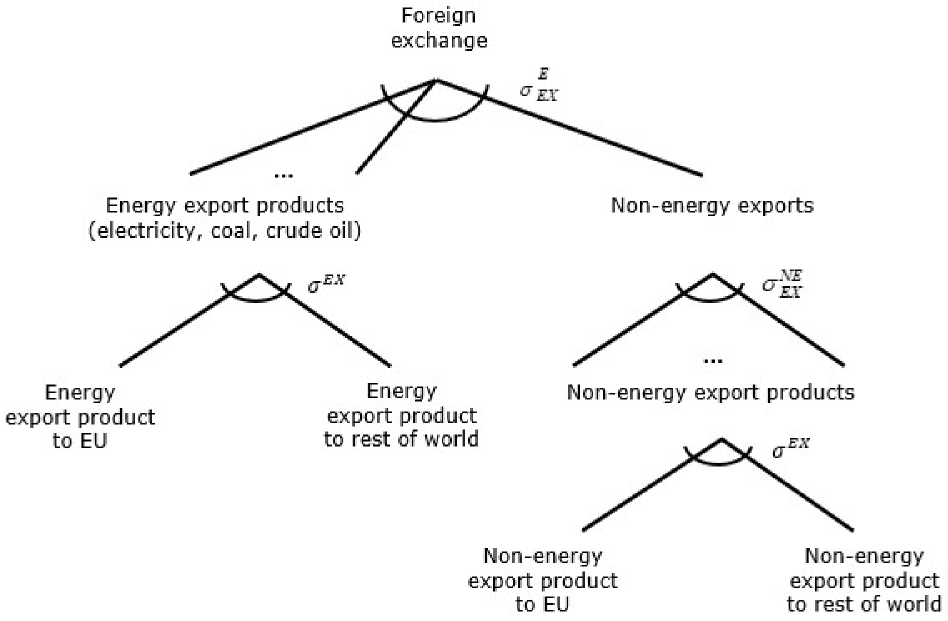
We specify representative firms in multiple product sales sectors maximizing profits from selling products in market prices domestically subject to their product sales functions and taking all prices as given (and with conditions Z.13-15 holding in equilibrium). We specify a function for each product being sold as a final consumption product to households, for each product being sold as a final consumption product to the government and for each product being sold as an intermediate input to a production sector. The functions themselves are Leontief functions of a (distributed) product, applicable excise taxes, trade margins and VAT. The excise taxes include aviation taxes, energy and CO_2 taxes and may also possibly include taxes on emissions of other greenhouse gases and local air pollutants. Tax rates and trade margins may differ from product to product and may also differ between products being sold to households, the government, and firms in production sectors. When sold to these firms, tax rates and trade margins may also differ between destined production sector and applicable sectoral tax rebates are reflected in the estimated tax rates.

FIRM EXPORTING PRODUCTS

We specify a representative firm in a product export sector maximizing its profits from exporting a composite export product subject to its export function and taking all prices as given (and with conditions Z.16-19 holding in equilibrium). To mimic the observed fact that exports of different products respond to different extents to changes in given world-market product prices, we seek to control the extents to which product export volumes can respond and specify the export function as a nested CES function of the different products (see figure 5). We specify nests differentiated between energy and non-energy export products and between products being exported to the EU and the rest of the world. In each nest, the substitution elasticity between products governs the ease at which products can be substituted for each other when exporting and by extension governs the extent to which the product exports respond to given price changes. In the lower nests of export products destined for the EU and for the rest of the world, we assume relatively high values for the substitution elasticities since we consider the export destination of products to be governed by price differentials to a relatively greater extent. In the nest of non-energy export products, we also assume a relatively high value for the substitution elasticity since we consider most products to be net substitutes in export and most product exports to be governed by price changes to a greater extent. In the upper nest of a few selected energy export products (electricity, coal and crude oil) and the bundle of non-energy export products, we assume a low value for the substitution elasticity since we consider these energy exports to be governed by price changes to a lesser extent (*e.g.* interconnector capacity for electricity, crude oil being imported and exported simultaneously).

All products to be exported are sourced from the product distribution sectors and excise taxes and subsidies may apply. Excise taxes mainly include energy taxes on electricity exports and export subsidies mainly include export subsidies for food, beverage and tobacco products. The firm in the export sector sells the composite export product in world markets in exchange for foreign currency.

Figure 5 Schematic overview of the nested export function



Notes: Lines represent the CES functional forms with σ denoting the elasticities in the various nests of the function. Nests with … denote a range of export products as inputs. The sub-nests are applicable for each export product in the range.

FIRMS EXPORTING USED VEHICLES

To capture more of policy effects on vehicle stocks, we introduce the option for used vehicles to be exported instead of being used for transport services only. To this end, we specify representative firms in used-vehicle export sectors maximizing profits from exporting used vehicles and subject to their used-vehicle export functions and taking all prices as given (and with conditions Z.20-21 holding in equilibrium). We specify a function for each combination of vehicle technology, vintage, and the vehicle originally being used for intermediate consumption or final consumption. The functions describe the firms selling the used vehicles in exchange for foreign currency in world markets minus a transaction cost.

FIRM FORMING NON-FIXED CAPITAL

We specify a representative firm in a non-fixed capital formation sector maximizing profits from forming non-fixed capital (*i.e.* inventories) subject to its non-fixed capital formation function and taking all prices as given (and with conditions Z.22-23 holding in equilibrium). The non-fixed capital formation function is a Cobb-Douglas function of distributed products inclusive of applicable excise taxes, VAT and trade margins. The representative firm sells the non-fixed capital in market prices to households who ultimately own the capital.

FIRM FORMING FIXED CAPITAL

We specify a representative firm in a fixed-capital formation sector maximizing profits from forming fixed capital (*e.g.* buildings and machinery) subject to its fixed-capital formation function and taking all prices as given (and with conditions Z.24-25 holding in equilibrium). The fixed-capital formation function is also a Cobb-Douglas function of distributed products inclusive of applicable excise taxes, VAT and trade margins. The representative firm sells the fixed-capital in market prices to households who save to invest in fixed capital and ultimately own the capital.

FIRM SELLING WORKING HOURS

We specify a representative firm in a labour supply sector maximizing its profits from selling labour in the form of working hours subject to its labour supply function and taking all prices as given (and with condition Z.26 holding in equilibrium). The labour supply function is a Cobb-Douglas function of the working hours of the six household types and is inclusive of labour income taxes. The firm in the labour supply sector sells the working hours to firms in the production sectors.

HOUSEHOLDS DERIVING UTILITY FROM CONSUMPTION AND LEISURE

We specify representative households in 6 household categories differentiated by income (below and above median income) and residential area (large urban area, smaller urban area and rural area; see Table A.6 in Appendix A for the classification of the household categories). Households maximize utility subject to their utility functions and taking all prices as given (and with conditions Z.27-34 and I.06 holding in equilibrium). We specify the utility functions as nested CES functions of final consumption products and leisure hours (see also figures 6a-d for a schematic overview).

By letting households derive utility from leisure hours, we introduce a trade-off between households devoting their hours to leisure or work and thus make their supplies of working hours endogenous. Enjoying more leisure hours increases utility but also decreases labour income and utility derived from consumption. In these functions, the substitution elasticities govern the ease at which households can substitute leisure hours for consumption and we assume leisure hours and consumption to be imperfect substitutes. Any change in hours worked is thus voluntary and we do not specify involuntary unemployment.

We specify consumption in terms of multiple bundles of final consumption products, differentiated by purpose according to the COICOP classification and with fixed product shares in the bundles (see Table A.7 in Appendix A for the full classification of consumption bundles). We specify four aggregate consumption bundles: a housing bundle, a transports bundle, a bundle with other goods and a bundle with other services. Note that we do not include final consumption products consumed by the government in these household consumption bundles (we describe government consumption separately below). Within the aggregate housing bundle, we distinguish between non-energy and energy related consumption and further distinguish between electricity, district heating and various heating fuels as energy carriers. Consumption of heating fuels might give rise to emissions of greenhouse gases and local air pollutants. Within the aggregate transports bundle, we distinguish between air, sea, sea, rail, and passenger road transport services. For passenger road transport services, we further distinguish between purchased and own road transport services. We again follow Karplus (2011) and specify consumption of own road transport services similarly to our specification of intermediate input use of own passenger road transport services with the same choice of light-duty vehicles and fuels. Further, we assume an income elasticity of demand for road transport services less than 1 to reflect the fact that some household road transport demands are non-discretionary (*e.g.* commuter travels) and therefore increase less than proportional to increases in household income. To achieve these reduced increases, we follow Stone (1954) and Geary (1950) and adjust the utility function by only including expenditures on discretionary road transports in the utility function and specifying expenditures on non-discretionary road transports as a fixed quantity in the household income balance instead.

Figure 6a Schematic overview of utility functions – main nests

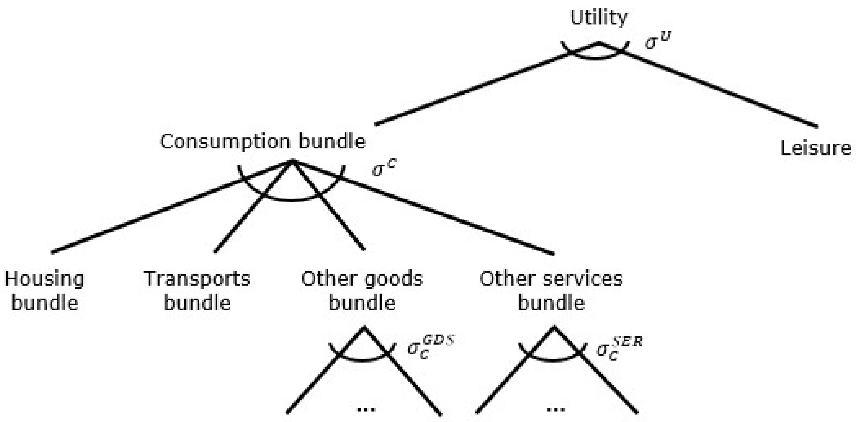


Figure 6b Schematic overview of utility functions – Housing nests

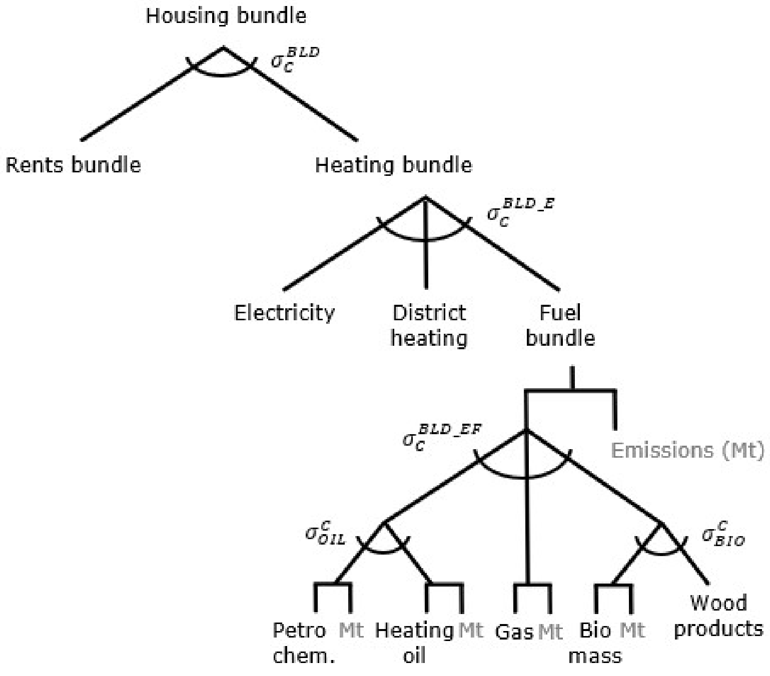


Figure 6c Schematic overview of utility functions – Transport nest

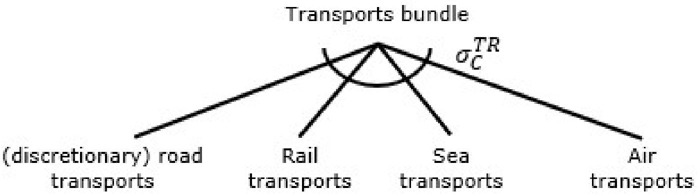
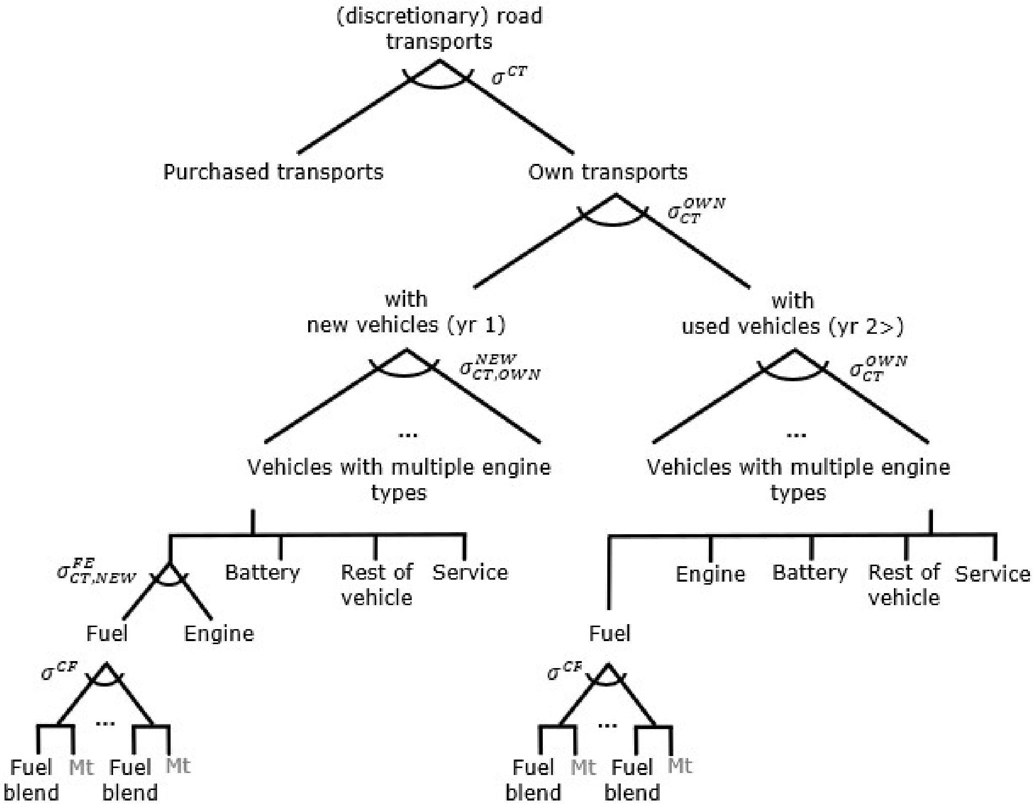


Figure 6d Schematic overview of utility functions – Road transport nests



Notes: Lines represent the CES functional forms with σ denoting the elasticities in the various nests of the function and with vertical lines in 90-degree angles representing the Leontief functional form that require quantities of the inputs or outputs in the nest to be used in fixed proportions to each other. Nests with … denote a range of products as outputs or inputs. Mt denotes million tonnes of emissions of the modeled pollutants.

Multiple taxes and subsidies are imposed that can impact private consumption and leisure choices. Purchase of new light-duty vehicles can be subject to bonus subsidies and malus taxes. Further, consumption of heating and transport fuels give rise to emissions of greenhouse gases and local air pollutants that may be subject to policy and come with an emission price. Finally, fuel blends and the final consumption products in the bundles are paid for in market prices and are thus inclusive of all tariffs, VAT and excise taxes such as aviation taxes, energy and CO_2 taxes and possibly other emission taxes.

When faced with an emission tax, households choose to consume the polluting product and pay the emission tax, or consume less of the product and avoid paying the tax, whichever gives higher utility. When choosing to consume less of the product, households can choose to do so by (i) consuming more of other products instead or (ii) consuming less altogether and enjoy more leisure instead. Taking again the example of the use of the fossil diesel product subject to an increasing CO_2 tax, households can choose to (i) continue using the fossil diesel product and pay the increased tax, (ii) demand a higher biodiesel content of the diesel blend for their own vehicles instead, (iii) use relatively more of the more recent and more fuel-efficient vintage of used vehicles with a diesel engine instead, (iv) use relatively more new vehicles with more fuel efficient diesel engines instead, (v) use relatively more vehicles with other engines instead, (vi) consume relatively more purchased road transport services instead of own produced transports, (vii) consume relatively more sea, air and rail transport services instead of road transports, (viii) consume relatively more of the other goods and services instead of transport services, and (ix) consume less altogether and enjoy more leisure hours instead. Households will choose the combination that maximizes their utility level given their utility function and income.

The precise utility functions differ between households according to the assumed preferences. Specifically, we calibrate the utility functions to varying household shares of expenditure on the consumption bundles and vary substitution elasticities between households.

HOUSEHOLDS BALANCING INCOME

Households balance their income with expenditures on private consumption, leisure and savings (and with conditions I.01 holding in equilibrium). Starting with their income, households earn income from supplying their working hours at a wage rate for use in production. Households also own their leisure hours, value them at the gross wage rate and count them toward their income as well. Further, households earn income from owning and supplying fixed capital at a price (real rate of return) for use in production. The supply of fixed capital is determined by underlying capital stock dynamics in any period and the real rate of return adjusts endogenously to clear supply with demand for the capital. Furthermore, households as the ultimate owners of the firms receive value from any product price markup as well as from EU Emission Allowances that are allocated for free. Finally, households receive government transfers.

Turning to their expenditures, households purchase a fixed quantity of non-fixed capital goods (inventories) and save a share of their income to invest in fixed capital (*e.g.* buildings and machinery; with conditions Z.35 holding in equilibrium). Savings thus determine the level of investment in fixed capital in the model. We can adjust the savings shares to target an overall investment level (with condition X.05 optionally holding in equilibrium). Further, households purchase a fixed quantity of non-discretionary road transports and spend the remainder of their income on private consumption and leisure as included in the utility function.

The precise income balances differ between households according to their income shares as observed in the base-year data.

GOVERNMENT BALANCING INCOME

We specify a government balancing a range of income and expenditures (with condition I.02 holding in equilibrium). Firstly, the government spends a fixed quantity on final consumption where we specify final consumption with help of a nested CES function of bundles of final consumption products. We specify four aggregate bundles: a housing bundle, a purchased-transports bundle, a bundle with other goods and a bundle with other services. We do not further distinguish between types of consumption within these aggregate bundles.

Secondly, the government spends a fixed quantity on foreign currencies as the government holds savings abroad. The quantity spent equals the surplus of the trade balance between exports and imports. Note that in model scenarios we can choose to adjust the trade balance to target increases in net exports with the real exchange rate adjusting (and with condition X.06 optionally holding in equilibrium) or we can choose to adjust the trade balance to target real exchange rates with net exports adjusting instead (and with condition X.07 optionally holding in equilibrium).

Thirdly, the government receives income from net tax revenues. In the model, the government receives net revenue from capital taxes, social security contributions, labour income taxes, import tariffs and export subsidies, VAT, malus taxes and bonus subsidies on light-duty vehicles, aviation taxes, energy and CO_2 taxes and possibly taxes on emissions of other greenhouse gases and local air pollutants (with conditions Z.36-40 holding in equilibrium). Note that we can choose to adjust several tax-related parameters and variables in model scenarios. For many of the taxes, we can choose to adjust tax rates to target tax revenues or adjust tax revenue to target tax rates (with conditions X.09-13, X.15-17 and X.21 optionally holding in equilibrium). For the energy tax, we can also choose to adjust the tax revenue to target an energy intensity of the economy (*e.g.* the Swedish energy intensity target for 2030; with auxiliary condition X.14 optionally holding in equilibrium). For the CO_2 tax, we can also choose to adjust the tax revenue to target emission reductions (with auxiliary conditions X.18-20 optionally holding in equilibrium). Finally, we can choose to adjust the rate for the social security contributions to keep overall tax revenue unchanged in response to other taxes or subsidies changing (with condition X.08 optionally holding in equilibrium). We use this option when studying the effects of using the revenue of energy and climate policies to offset social security contributions.

Fourthly, the government imports EU emission allowances at a given auctioning price from the European Commission on behalf of firms in the production sectors subject to the EU ETS (with conditions X.22 and X.24 holding in equilibrium). The government receives a share of the total auction revenue under the EU ETS back from the EU.

Fifthly, the government also has the option to sell (or buy) parts of the national emission allocations under the EU Effort Sharing Regulation matching overachievement (or underachievement) at home as well as under any other international emission allowance still to be negotiated at an exogenous price (with auxiliary condition X.25 optionally holding in equilibrium).

Finally, the government transfers the remaining net income back to the households.

3.2 Clearing of markets

We specify conditions for the clearing of all supplies with demands for the various products, fuel blends, used vehicles, consumption bundles, utility, capital formation, capital, hours, foreign exchange and modeled policy instruments. These market-clearing conditions determine the respective prices (with market-clearing (M) conditions M.01-58 holding in equilibrium).

3.3 General equilibrium

Firms, households and the government solve their respective optimization problems and markets clear. When all associated equilibrium conditions hold at the same time, the set of unknown variables determined by the conditions constitute an equilibrium. We avoid overdetermination of the set of variables by letting investment in fixed capital adjust endogenously to savings ('closure rule') and by keeping one variable fixed at its base-year value (numeraire).[13] We choose the price of the CES-aggregate consumption bundle of one of the households (household with income below the median income in smaller urban area) as the numeraire. Note that all price variables are to be interpreted in relative terms to this consumption bundle as a consequence.

The model is static in that the optimization problems are based on current-period variables only. We solve the static model for the years 2019-2050 allowing us to do comparative-static analysis of policies in these years. In between these years, we impose several exogenous changes to the equilibrium conditions to let the economy develop. For example, factor supplies, technologies and policies can and do all change. We cannot account for business-cycle behavior. Instead, we calculate the new equilibria under the assumption that all agents have sufficient time to adjust their behavior (*e.g.* allocation of fixed capital and working hours between production sectors) to the changes imposed.

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[13] See Ratssö (1982) for a full discussion of our chosen closure rule as well as of two other closure rules.

4 Model calibration

We calibrate the model to historic data of the Swedish economy in 2019. We use the National Accounts as our main economic data source (Statistics Sweden, 2022a). We also make use of complementary economic data sources to calibrate parts of the model for which national accounting data is not available. To calibrate the trade values to and from the rest of the EU and the rest of the world, we use the World Input-Output Database as a complementary data source (Timmer et al, 2015). Further, to calibrate income and expenditure shares for the six household types, we use the Household Income Survey (Statistics Sweden, 2022d) and the Household Budget Survey (Statistics Sweden, 2013) as complementary data sources. We calibrate the number of leisure hours that households derive utility from to be a quarter of the number of working hours.

CALIBRATION OF OWN ROAD TRANSPORTS

To calibrate the values for own road transports, we disaggregate the National Accounts in a couple of places. Firstly, we adjust the Supply tables of the National Accounts to account for biodiesel as a fuel product. We specify the biodiesel product to comprise both Hydrotreated Vegetable Oils (HVO) and Fatty Acid Methyl Ester (FAME) and find both to be accounted for in the Supply-and-Use tables as part of the diesel product. Making use of data on energy flows in Sweden, we identify the total supply of the biodiesel product separate from the fossil diesel product as well as the extent to which the two diesel products are blended in the diesel blends (Swedish Energy Agency, 2019, 2020). We then assume a split between imported and domestically-produced diesel products informed by 2015 data for FAME (Swedish Energy Agency, 2016). Further, we identify input values for the domestic refinery of biodiesel separate from those for the refinery of fossil diesel. In the refinery of the biodiesel product, we assume feedstocks to have a large (ca 80%) input value share and we assume the feedstocks to be sourced from the *chemical manufacturing* sector. Ethanol is already accounted for as a product in the Supply tables and we therefore do not need to make any adjustments for ethanol.

Secondly, we adjust the Use tables of the National Accounts to account for the use values of electricity and the fuel products for own road transports. Specifically, we use data on energy flows and use market share data for fuel blends and technology to distribute electricity and the fuel products between the fuel blends, sector of use, vehicle technologies and between new and used vehicle technologies (Swedish Energy Agency, 2019, 2020; Swedish Transport Analysis, 2020, 2022). We also compute annual depreciation rates for the used vehicle technologies to distribute the electricity and fuel use of used vehicles between the used vehicle vintages.

Thirdly, we calibrate the use values of the other cost components of own road transports such that the resulting use value shares of the fuel blends per vehicle technology matches the market share data mentioned above in the base year. Here we assume slightly lower fuel costs and slightly higher engine costs for the higher fuel-efficient version of the vehicle technologies relative to the lower fuel-efficient version. For the vehicle cost components, we specify firms to use capital in line with vehicles being considered a fixed investment good for firms in the National Accounts. We specify households to use the *motor vehicles and other transport equipment* product since (purchase of new) vehicles are considered an expenditure for households in the National Accounts. Yet, we follow Gitiaux et al (2012) and reinterpret annual expenditures on new vehicle purchases as annual services derived from vehicles as capital goods. We assume a lifetime of 15 years for the vehicles. For the maintenance cost component, we specify households and firms to use the *business services* product. Finally, we assume identical technology cost shares for the various sectors of use.

Table 2 Emission sources, associated economic activities and applicable price instrument in the modeled base year

Emission source	Economic Activity	Price instrument
CO_2		
Industry processes, diffuse sources	Production in ETS sectors (to varying degrees)	EU ETS
	Production in ETS sectors (to remaining degrees) and in non-ETS sectors and household consumption of heating fuels	-
Stationary combustion of furnace gases in steel furnaces	Production in JSTAL sector	EU ETS
Stationary combustion of coal and cokes, gas, petro-chemical fuels, other liquid fossil fuels and peat	Consumption of KOL, GAS, PETRO, BRANS and TORV products as fuels in ETS sectors (to varying degrees)	EU ETS
	Consumption of KOL, GAS, PETRO, BRANS and TORV products as fuels in ETS sectors (to remaining degrees) and in non-ETS sectors and by households	CO_2 tax
Stationary combustion of diesel	Consumption of DIESEL product in ETS sectors	-
	Consumption of DIESEL product in non-ETS sectors and by households	CO_2 tax
Stationary combustion of waste	Consumption of AVFL product as fuel in EL and FJ sectors (to varying degree)	EU ETS
	Consumption of AVFL product as fuel in FJ sector (to remaining degree) and in other sectors	-
Stationary combustion of black liquors (avlutar)	Production in MASSA and EL sectors	-
Stationary combustion of ethanol and solid biomass	Consumption of ETHANOL and BIO products as fuel	-
Mobile combustion of gas and petro-chemical fuels	Consumption of GAS and PETRO products as fuel in ETS sectors	-
	Consumption of GAS and PETRO products as fuel in non-ETS sectors and by households	CO_2 tax
Mobile combustion of kerosene	Consumption of BRANS product in LUFTTP sector	EU ETS
	Consumption of BRANS product in GOV sector	-
Mobile combustion of diesel and petrol	Consumption of DIESEL and BENSIN products	CO_2 tax

Mobile combustion of biodiesel and ethanol	Consumption of BIODIESEL and ETHANOL products in E10-50 and B15-90 fuel blends	CO_2 tax
	Consumption of BIODIESEL and ETHANOL products in E85 and B100 fuel blends	-
CH_4		
Industry processes, diffuse sources	Production in most production sectors	-
Combustion of coal and cokes, gas, diesel, petrol, petrochemical fuels, other liquid fuels, waste, peat, solid biomass and ethanol	Consumption of KOL, GAS, DIESEL, BENSIN, BRANS, PETRO, AVFL, TORV, BIO and ETHANOL products as fuel in all sectors and by households	-
N_2O		
Industry processes, diffuse sources	Production in KEMI sector	EU ETS
	Production in KEMI sector (to remaining degree) and in other production sectors and household consumption of heating fuels	-
Combustion of coal and cokes, gas, diesel, petrol, petrochemical fuels, other liquid fuels, waste, peat, solid biomass and ethanol	Consumption of KOL, GAS, DIESEL, BENSIN, BRANS, PETRO, AVFL, TORV, BIO and ETHANOL products as fuel in all sectors and by households	-
F-gases		
Industry processes, diffuse sources	Production in METALL sector	EU ETS
	Production in other production sectors and household consumption of heating fuels	-
NMVOC, CO, SO_2, NO_X, NH_3 and PM		
Industry processes, diffuse sources	Production and household consumption of heating fuels	-
Combustion of coal and cokes, gas, diesel, petrol, petrochemical fuels, other liquid fuels, waste, peat, solid biomass and ethanol	Consumption of KOL, GAS, DIESEL, BENSIN, PETRO, BRANS, AVFL, TORV, BIO and ETHANOL products as fuel in all sectors and by households	-

Notes: ETS sectors are production sectors whose emissions of the greenhouse gases CO_2, CH_4, N_2O and F-gases have in principle been classified by the European Commission to be subjected to the EU ETS. In practice, however, these emissions are subject to the EU ETS to varying degrees due to minimum firm size limits and exceptions. ETS sectors include GUMMI, METLTILL, GAS (all sectors and greenhouse gases to the degree of 0% in the base year in Sweden); TRAV, ANTILL and VERKTILL (CO_2 5%, other GHGs 0%); FORDTILL (CO_2 35%, other GHGs 0%); LIVS (CO_2 40%, other GHGs 0%); GRUV (CO_2 75%, other GHGs 0%); KEMI (CO_2 90%, N_2O 95%, other GHGs 0%); METALL (CO_2 90%, F-gases 100%, other GHGs 0%); FJ (CO_2 95%, other GHGs 0%); MASSA, RAFF, RAFF_BIO, JSTEN, JSTAL, EL and LUFTTP (CO_2 100%, other GHGs 0%). We estimate the degrees based on ETS installation data (Swedish Environmental Protection Agency,2020) and the Environmental Accounts (Statistics Sweden, 2022b). Non-ETS sectors are all other production sectors except SJOTP, which is exempt from all price instruments in the base year. Applicable price instruments might change in scenarios. See also Tables A.1-3 for set, sector, and product classifications and Table F.1 for emission source classifications.

CALIBRATION OF PHYSICAL QUANTITIES OF ENERGY USE AND EMISSIONS

We use the Environmental Accounts (Statistics Sweden, 2022b) as our main data source for the physical quantities of energy use and emissions. Table 2 shows how we attribute emissions of greenhouse gases and local air pollutants to economic activity and how we subsequently subject the emissions to emission price instruments in the model. Regarding the price instruments, we calibrate the rates of the EU ETS emission allowances and CO_2 taxes to their historic rates in 2019. In the National Accounts, we then deduct the CO_2 tax values from the total of excise taxes paid and deduct the allowance values from the firms' gross operating surplus.

CALIBRATION OF SUBSTITUTION ELASTICITIES

Turning to the substitution elasticities in the model, we choose values for the elasticity parameters based on a surveying of econometric and other modeling studies (see tables C.1-5 in Appendix C).[14] We reserve some judgement about the precise elasticity values obtained from such studies as these elasticity values tend to be valid for the economic relation under (partial) study and do not necessarily work well when combined with many other economic relations in our general equilibrium setting. The elasticity values of substitution between foreign and domestic goods, between input goods and between factors of production have been based on a survey of a number of studies and models (Koschel, 2000; Honkatukia, 2009; Paltsev et.al. 2005; Okagawa and Ban, 2008; Van der Werf 2008; Danielsson 2015; Capros et al., 2013).

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[14] Choosing elasticity values for all the CES functions of a large CGE model like EMEC seldom includes an econometric estimation of the model equations due to the large amount of data needed and the huge effort of estimating all equations.

5 Reference scenarios with stated energy and environmental policies

In this section, we describe a set of reference scenarios for the Swedish economy until 2050. We developed these reference scenarios as input to further modeling of energy use over time by the Swedish Energy Agency and as input to estimates of emissions over time by the Swedish Environmental Protection Agency in September 2022. We also use reference scenarios to analyse if there is a need for additional policies to reach nationally-set emissions and energy related targets and compare the additional policies to. We calibrate these scenarios to match other NIER projections of sectoral productivity, economic growth and other macro-economic developments as well as energy price projections from the Swedish Energy Agency and the European Commission. We include only climate and energy policies that have been stated and agreed upon. Naturally, economic scenarios for the medium to long term are subject to uncertainty and economic growth is especially uncertain. Besides a central reference scenario, we therefore also construct reference scenarios with relatively lower and higher economic growth. To account for more uncertainties, we conduct sensitivity analyses as described in section 7. We describe the precise set-up of the reference scenarios in section 5.1 and describe the resulting development of the economy in section 5.2.

5.1 Reference scenario set-up

In this section, we describe the set-up of our reference scenarios in terms of assumptions made to let the economy develop as well as in mathematical terms of which parameters and equilibrium conditions we change.

CHANGES IN GDP AND ITS EXPENDITURE COMPONENTS

In the central reference scenario, we calibrate changes in GDP and its expenditure components (private consumption, government consumption, capital formation and net exports) to match the variable levels in the main scenario from our inhouse fiscal sustainability report (NIER, 2022) (see Table 3). The latter scenario represents a possible development of the Swedish economy until 2100 and is developed to analyse the fiscal sustainability of Swedish public finances in the long term. Main scenario assumptions include projected population growth (Statistics Sweden, 2022c), increasing retirement ages, slight decreases in social security demands over time and that the Swedish economy continues to be open to trade. GDP and its expenditure components are assumed to grow at a slower pace in the modeled years compared with the historic years 1995-2019. Slower growth of the population in general and the working population as well as slower growth of labour productivity since the 2008 financial crisis underlie this assumption. In the reference scenarios with lower and higher economic growth respectively, we assume that GDP and its expenditure components develop somewhat slower and faster, respectively, than in the central reference case, mainly due to the relatively lower and higher sectoral productivities (see Table 3 and see further discussion of assumed sectoral productivities below).

Table 3 Historical and assumed development of GDP and its expenditure components in the reference scenarios

Average annual percentage change; underlying variables in constant prices

	1995–2019	2019–2050		
		Low	Central	High
GDP	2.5	1.4	1.7	2.1
Household consumption	2.5	1.1	1.7	2.3
Government consumption	1.1	0.9	0.9	0.9
Fixed-capital formation	3.3	1.7	2.0	2.4
Non-fixed capital formation	0.3	-1.7	-1.7	-1.6
Exports	4.7	2.1	2.5	2.9
Imports	4.5	1.9	2.3	2.7

Note: ‘Low’, ’Central’, and ’High’ refer to the reference scenarios with low, mid, and high economic growth.
Source: NIER (2022) and own calculations.

Mathematically, we make multiple adjustments to the model to match the targeted variable levels. Firstly, we adjust the total factor productivity of one of the largest production sectors in the model, the financial services sector, to match the targeted GDP levels in the reference scenarios (with condition X.03 now also required to hold in equilibrium). Secondly, we adjust a final consumption parameter for the government to match the targeted government consumption levels (see equation D.05). Thirdly, we adjust the household savings shares to match the targeted levels of fixed-capital formation in the central reference case (with condition X.05 now required to hold in equilibrium). In the reference scenarios with lower and higher economic growth, we do not target levels of fixed-capital formation and assume the household savings shares from the central reference scenario to hold (with condition X.05 no longer required to hold in equilibrium). Fourthly, we adjust a parameter for investments in non-fixed capital (inventories) to match the targeted levels of non-fixed capital formation (see equation D.04). Note that letting the inventory investments grow at a relatively low or negative rate allows for higher growth rates of the other expenditure components of GDP. Fifthly, to match the targeted export and import levels as best as possible, we adjust world market demand parameters for Swedish export products, adjust world market product price parameters (see equations D.28-30) and adjust the trade balance (with condition X.06 now required to hold in equilibrium as well). Regarding world-market prices for many energy products, we match external world-market price projections from the Swedish Energy Agency and in extension the European Commission (see further discussion below). Regarding world-market prices for the remaining products, we base our adjustment of price parameters on the assumption that Sweden’s main trading partners are impacted by similar projections on productivity growth and energy prices. Finally, we do not target household consumption levels in the reference scenarios since this variable remains as the free variable in the computation of GDP after we have matched GDP and its other expenditure components to their targeted levels. We do, however, calibrate the value shares of discretionary road transport services in consumption (see equations D.06-08) and the fixed value spent on non-discretionary road transport services in the household income balances to an income elasticity of household demand for road transport services of 0.75 in the base year (based on Karplus (2011). From then on, we do not adjust the values and let the income elasticity change endogenously over time (to approx. 0.83 in the three reference scenarios by 2050).

CHANGES IN THE STOCKS OF FIXED CAPITAL

We assume that the stock of fixed capital that is available for use in production grows over time in all reference scenarios (see Table 4). The precise capital-stock growth rates differ somewhat between the scenarios in line with the varying economic growth rates.

Table 4 Historical and assumed development of the fixed-capital stock in the reference scenarios

Average annual percentage change; underlying variables in constant prices

	1995–2019	2019–2050		
		Low	Central	High
Fixed-capital stock	2.2	2.2	2.4	2.6

Note: 'Low', 'Central', and 'High' refer to the reference scenarios with low, mid, and high economic growth.
Source: SCB and own calculations

Mathematically, we adjust both the stock and the supply of fixed capital upward between the model years (see equations D.02-03). We specify the stock as the value of the stock from the previous model year net of depreciation plus the value of investments in fixed capital from the previous model year. In this specification, we assume a 5% annual depreciation rate and deduce an annual rate of capital financing cost of ca 5.5%. We deduce the latter rate from base-year national accounting data on fixed-capital investments and the fixed-capital stock. We assume both rates to remain constant over time.

CHANGES IN USED VEHICLE SUPPLIES

We adjust the available supplies of used vehicles for own road transports between the modeled years in all reference scenarios, where we differentiate the used vehicles between vehicle technology, vintage and whether the vehicles are in use by firms or households (see equations D.09 and D.13). We also adjust the cost shares of using used vehicles for own road transports in production between the modeled years where we further differentiate the used vehicles between the production sectors of use (see equations D.14-15) or households (see equations D.10-11). Both adjustments in turn are based on changes in the underlying stocks of used vehicles (see equations D.12 and D.16). We adjust the stocks upward by adding the use of new vehicles for own road transports from the previous period. We adjust the stocks downward by correcting for depreciation, export and scrapping of used vehicles from the previous period. We assume that used vehicles have fully depreciated and are scrapped altogether after 15 years. The precise stock adjustments differ somewhat between the scenarios in line with the varying economic growth rates.

CHANGES IN THE LABOUR FORCE SIZE

We assume that the number of hours available for work and leisure increases over time in all reference scenarios, allowing for higher levels of income, utility, consumption and production. We assume that the increase is due to population growth and that the increase is offset somewhat by slight reductions in labour force participation or the average hours worked or both (from ca 58% in 2019 to 53% in 2050) (see Table 5). We assume the same increases in all scenarios.

Table 5 Historical and assumed development of the population and hours worked in the reference scenarios

Average annual percentage change

	1995-2019	2019–2050
		All
Hours worked	0.8	0.5
Population growth	0.6	0.5

Note: 'All' refers to all three reference scenarios with low, mid, and high economic growth.
Source: SCB and own calculations

Mathematically, we simply adjust the growth parameter for the hours available upward between the modeled years (see equation D.01).

CHANGES IN SECTORAL LABOUR PRODUCTIVITY

We assume varying productivity increases for firms in all private production sectors over time and in all reference scenarios allowing for reduced input costs and increased value added and production levels over time. These productivity increases represent non-price driven changes in a firm's technology over time that have been observed historically and can reasonably be expected to continue. We express the productivity increases in terms of labour productivity, which we define as value added per hour worked. We assume lower productivity increases in the reference scenario with low economic growth and higher productivity increases in the reference scenario with high economic growth than we do in the central reference scenario.

Table 6 lists historical and targeted labour productivities in all production sectors and in all reference scenarios. We assume average annual productivity increases of 1.2 – 2.0% for all private sectors together from 2019 onward. For the total of all goods sectors, we assume average annual productivity increases of 1.1 – 1.9% from 2019 onward. For the total of all services sectors, we assume slightly higher average annual productivity increases of 1.2 – 2.0% from 2019 onward. The slightly higher productivity growth for the total of the services sectors is a reversal of the historic productivity trend between the goods and services sectors. Historically, services sectors have been more labour intensive than goods sectors and have benefited less from automation and digitalization than goods sectors. From 2019 onward, we assume that services sectors especially will catch up to goods sectors when it comes to benefiting from automation and digitalization.

To match the totals of goods and services sectors, we assume that average annual productivity increases for most individual sectors are also a bit lower from 2019 onward than the increases were historically. Exceptions include the household services sector, the real-estate services sector and the iron, steel and metal manufacturing sectors. These manufacturing sectors experience much international competition, which we expect to lead to consolidation within the sectors with relatively high productivity growth as a result. The mining sector is another exception. This sector experienced an average annual productivity decrease between 1995 and 2019, which can be partly explained by investments in expansion that required capital and labour and that had not yet contributed to productivity growth by 2019. We assume that productivity will increase in line with production from 2019 onward. For a few sectors, we assume that average annual productivity increases are substantially lower from 2019 onward. Especially for the agriculture and fishery sector and the forestry sector we assume that historic productivity increases from automation and digitalization will not continue at the same pace from 2019 onward. Finally, for the public sector (*e.g.* public admin

Table 6 Historical and assumed development of sectoral labour productivity in the reference scenarios

Value added (in constant prices) per hour worked (average annual percentage change)

	1995-2019	2019–2050		
		Low	Central	High
Total	**1.7**	**0.9**	**1.2**	**1.6**
Private sector	**2.1**	**1.2**	**1.6**	**2.0**
Private sector - goods	**2.4**	**1.1**	**1.5**	**1.9**
Agriculture and fishery	2.7	0.7	1.0	1.2
Forestry	1.2	0.3	0.4	0.4
Mining	-1.0	0.9	1.2	1.5
Manufacturing of food products	1.6	1.3	1.7	2.2
Manufacturing of wood products	1.7	1.0	1.3	1.7
Manufacturing of paper products	3.0	1.6	2.1	2.7
Refineries	3.3*	1.4	1.9	2.4
Refineries – biodiesel	3.3*	1.4	1.9	2.4
Manufacturing of chemicals and pharmaceuticals	3.3*	2.3	3.1	3.9
Manufacturing of plastics and rubber products	1.9	1.1	1.5	1.9
Manufacturing of non-metallic mineral products	2.4	1.2	1.6	2.0
Manufacturing of basic iron and steel products	0.7*	2.2	2.9	3.6
Manufacturing of non-ferrous metals and casting of metals	0.7*	2.3	3.0	3.9
Manufacturing of metal products	0.6	1.3	1.7	2.2
Manufacturing of optical and electronic products, machines	3.7	2.7	3.6	4.6
Manufacturing of motor vehicles and other transport eq.	5.1	2.5	3.3	4.2
Manufacturing of other products (*e.g.* furniture)	1.5	1.3	1.7	2.1
Electricity supply	-0.9*	0.4	0.6	0.7
Gas supply	-0.9*	0.5	0.7	0.8
District heating and cooling supply	-0.9*	0.4	0.6	0.7
Water supply, sewerage and waste management	-0.9*	0.7	0.9	1.2
Construction	0.1	0.4	0.5	0.6
Private sector - services	**1.8**	**1.2**	**1.6**	**2.0**
Wholesale and retail services	3.2	1.7	2.2	2.8
Rail road transports	3.2	0.8	1.1	1.4
Road passenger transports	-0.9	1.2	1.5	2.0
Road goods transports	1.6	1.4	1.8	2.3
Sea transports	5.3	1.2	1.6	2.0
Air transports	1.6	1.2	1.6	2.0
Warehousing, transport support and postal services	1.4	1.1	1.4	1.8
Household services	-0.3	0.4	0.6	0.7
Information and communication services	5.0	2.6	3.4	4.3
Financial and insurance services	3.4	1.5	2.0	2.6
Real estate services	0.1	0.5	0.7	0.9
Business services	1.1	1.0	1.2	1.7
Public sector	**0.1**	**0.0**	**0.0**	**0.0**

Note: ’Low’, ’Central’, and ’High’ refer to the reference scenarios with low, mid, and high economic growth. The public sector includes public administration, defence and social security. * means that we only have data for a more aggregated SNI category available. Source: NIER and own calculations istration, defence and social security) we assume no productivity increases from 2019 onward, which is per definition and in line with the measured productivity for the historic period 1995-2019.[15]

Mathematically, we adjust capital and/or labour-augmenting technical change parameters for various sectors upward between the model years in a first step (see equations D.18-19). In a second step, we then adjust the productivity of all production factors combined (here referred to as total factor productivity) in all sectors (but for the business services sector) within the model years (with conditions X.01-02 now also required to hold in equilibrium).

CHANGES IN THE PRODUCTIVITY OF BATTERIES AND ENERGY

We assume that the productivity of firms and households using energy and electric-vehicle batteries increase exogenously over time in all reference scenarios allowing for reduced costs of battery and energy use, reduced emission intensity of production and consumption and increased production and consumption levels. For battery use, we assume a 5% productivity increase per year implying that battery costs halve approximately every 15 years. For most energy use, we assume a 1% efficiency increase per year due to autonomous efficiency improvements with a few exceptions. One exception is for (primary) energy use in the steel, oil refinery, electricity, district heating and gas sectors, for which we assume lower efficiency increases of 0.1% per year to reflect the relatively limited scope for further efficiency improvements for existing production technologies. Another exception is for electricity use in production and consumption (except electric vehicles). For electricity use in production we also assume a much lower 0.1% efficiency increase per year to reflect exogenous shifts toward using more electricity in production (electrification). For electricity use in consumption, however, we assume a higher 1.5% efficiency increase per year to reflect exogenous shifts toward using more heat pumps instead of electric heating. We assume the same increases in all reference scenarios.

Mathematically, we simply adjust the respective productivity parameters between the modeled years (see equations D.20-27).

CHANGES IN ENERGY PRICES

We base prices of electricity, district heating and fossil fuels on price projections from the Swedish Energy Agency and in extension from the European Commission in all scenarios. We base prices of biomass and biofuels on price projections from the EU Agricultural Outlook 2018-2030 in all scenarios (see Table 7; EC, 2018). We assume the same energy prices in all reference scenarios.

Mathematically, we adjust world-market price parameters for coal, crude oil, gas, fuel oils, fossil petrol, fossil diesel, biofuels and biomass as these energy products are all traded internationally with Sweden assumed to be a price taker and. Their domestically-traded prices are determined endogenously in the model, but follow the world market prices closely. Electricity and district heating are (predominantly) produced domestically with Sweden being assumed to be more of a price setter and we therefore target the (distributed) product price variables for electricity and district heating to match the external price projections from the Swedish Energy Agency (2021b) with help of cost-

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[15] Productivity of the public sector has been constant for long (SOU, 2019). Production of public services is calculated based on costs (*e.g.* defense expenditures) or volumes (*e.g.* number of patients in health care) and as such labour productivity increases are more difficutl to measure.

price markups in domestic production (and with condition X.04 now also required to hold in equilibrium).

Table 7 Historical and assumed development of selected energy prices in the reference scenarios

Average annual percentage change

	2005-2019	2019–2050
		All
Coal	-1.2	1.8
Crude oil	-0.1	2.1
Gas	-2.0	3.1
Biomass	1.2	1.0
Biodiesel	-	1.0
Ethanol	-3.0	2.1
E10-50 petrol blend	1.2	2.9
B15-90 diesel blend	1.8	2.3
Fuel oils	1.8	0.7
District heating	1.1	-0.7
Electricity	2.0	0.8

Notes: 'All' refers to all three reference scenarios with low, mid, and high economic growth. Prices for the coal, crude oil, gas, biomass, biodiesel and ethanol products are excluding taxes and the assumed price development for these energy products between 2019 and 2050 relate to the world-market price parameters. The prices for the E10-50 petrol blend, B15-90 diesel blend, fuel oils and district heating are including distribution and taxes, are for households and their assumed price development between 2019 and 2050 relate to the domestically-traded prices that are determined endogenously in the model. The price for electricity is excluding transformation, distribution and taxes and its assumed price development between 2019 and 2050 relate to the external price parameter. All underlying prices are in constant terms.

Sources: Swedish Energy Agency (2021a, 2021b), EC (2018) and own calculations

CHANGES IN STATED ENERGY AND ENVIRONMENTAL POLICIES

We adjust several policy parameters in line with energy- and environmental policies that have been stated and adopted by the European Commission and the Swedish government per September 2022. We make the same adjustments in all reference scenarios.

Starting with EU policies, we base prices of EU emission allowances under the EU ETS on price projections from the Swedish Energy Agency and in extension from the European Commission (see Table 8). EU emission allowances are traded internationally with Sweden assumed to be a price taker within the EU ETS and we therefore adjust allowance price parameters. We also adjust Sweden's revenue from auctioning EU emission allowances under the EU ETS (see equation D.33) and decrease the number of EU emission allowances allocated for free over time in line with the linear reduction of the total emission allowance (see equation D.32).

Table 8 Historical and assumed development of EU emission allowance prices under the EU ETS in the reference scenarios

Average annual percentage change

	2005-2019	2019–2050
		All
EU emission allowance	0.9	6.2

Notes: 'All' refers to all three reference scenarios with low, mid, and high economic growth.

Source: Swedish Energy Agency

Besides EU policies, we also adjust several national policy parameters between the modeled years and in line with stated policies (see Table 9). Firstly, we adjust the rates of energy and CO_2 taxes on the E10-50 petrol blend and B15-90 diesel blend used as transport fuels as stated by the government (Swedish Ministry of Finance, 2022). For 2020-2022, we adjust the rates to levels stated. From 2023 onward, we adjust the CO_2 tax rates to the changing renewable fuel contents, increase both the energy and CO_2 tax rates with 2% per year ('GDP indexing') and further adjust rates with changes in relative prices of consumer products of the previous time period (see equation D.31).

Secondly, we adjust the rebates from the energy and CO_2 taxes that have been granted to firms in several production sectors to stated levels for the years 2020-2022. Specifically, we phase out the 40% rebate to the CO_2 tax on fossil diesel and biodiesel use for heavy machinery that had been granted to firms in the mining sector between 2019 and 2020. We also phase out the 70% rebate to the energy tax on coal, gas, refined petrochemicals and fuel oils that had been granted to firms in all non-service sectors between 2021 and 2022.

Thirdly, we adjust the renewable fuel standards for the fuel blends with low renewable fuel content in line with stated volume requirements under the Swedish 'Reduktionsplikten' (SFS, 2017). By 2030, the E10-50 petrol blend is to contain at least 37% renewable fuel in volume terms and the B15-90 diesel blend is to contain at least 74% renewable fuel in volume terms. From 2030 onward, we keep the renewable fuel standards at these levels. From 2022 onward, we also adjust the fossil fuel standards for these blends. We require the E10-50 petrol blend to contain at least 50% fossil petrol. This standard directly translates into a maximum volume share of 50% for ethanol over time. Similarly, we require the B15-90 diesel blend to contain at least 10% fossil diesel. This standard directly translates into a maximum volume share of 90% for biodiesel over time. Fuel blends with high renewable fuel content (E85> and B100) are at present not covered by the Swedish 'Reduktionsplikten' policy. We therefore keep the renewable fuel standards at 2019 levels over time ensuring that the renewable fuel content of these fuel blends cannot fall below these levels. At the same time, we require the E85 petrol blend to contain at least 10% fossil petrol so that the blend can contain maximum 90% ethanol.

Fourthly, we adjust capital tax rates for sectors to account for stated changes in subsidy levels under the Swedish 'Klimatklivet' policy (from 800 MSEK in 2019 to 3700 MSEK in 2024 to 500 MSEK in 2026; SFS, 2022; see also equation D.34) and the Swedish 'Industriklivet' policy (from 500 MSEK in 2019 to 750 MSEK in 2024; SFS, 2017; see also equation D.34).

Finally, we keep rates for the aviation tax, bonus subsidies and malus taxes at 2019 levels (Swedish Ministry of Finance, 2022; with conditions X.09-11 required to hold in equilibrium).

Table 9 Modeled changes of energy and environmental policies stated by the Swedish government in the reference scenarios

Policy instrument	Modeled changes	Year
CO_2 tax	- Adjustment of tax rates to stated levels	2020-2022
	- Adjustment of tax rates on E10-50 petrol blend and B15-90 diesel blend to account for (i) the changing renewable fuel contents, (ii) GDP growth of 2% per year and (iii) changes in the relative prices of consumer products	2023 →
	- Phase out of the 40% tax rebate for use of all diesel blends in heavy machinery granted to firms in the mining sector	2019-2020
Energy tax	- Adjustment of tax rates to stated levels	2020-2022
	- Adjustment of tax rates on E10-50 petrol blend and B15-90 diesel blend to account for (i) GDP growth of 2% per year and (ii) changes in the relative prices of consumer products	2023 →
	- Phase out of the 70% tax rebate for use of coal, gas, refined petrochemicals and fuel oils granted to firms in all non-service sectors	2021-2022
Renewable fuel standards ('Reduktionsplikten')	- Linear increase of the standard for the E10-50 petrol blend to contain at least 37% renewable uel by 2030 - Linear increase of the standard for the B15-90 blend to contain at least 74% renewable fuel by 2030	2019-2030
Industry leap subsidies ('Industriklivet')	- Adjustment of capital tax rates for the *basic-iron and steel-manufacturing* and *paper manufacturing* sectors to account for changes in subsidy levels (from 500 MSEK in 2019 to 750 MSEK in 2024)	2019-2024
Climate leap subsidies ('Klimatklivet')	- Adjustment of capital tax rates for non-ETS production sectors to account for changes in subsidy levels (from 800 MSEK in 2019 to 3700 MSEK in 2024 to 500 MSEK in 2026)	2019-2026

Notes: This table only lists the policy instruments for which we assume and model changes over time. Policy instruments for which we assume no changes over time are modeled but not listed in this table.
Sources: (Swedish Ministry of Finance, 2022)

5.2 Reference scenario results

In this section, we describe the development of the economy in our reference scenarios in terms of the value of production, hours worked in production, energy intensity of economic activity and emissions of greenhouse gases and local air pollutants.

STRUCTURAL CHANGE OF PRODUCTION

Starting with the value of production excluding intermediate input use (also referred to as value added) and hours worked in production, we find that the structure of production continues to change in the direction of the production of services and away from the production of goods over time in the reference scenarios in the modeled years 2019-2050 compared to the historical years 1995-2019 (see Tables 10 and 11). The change is less pronounced in the modeled years, however.

Assumed differences in labour productivity growth between sectors are an important driver of the modeled structural change of production and we assume a more equal distribution of productivity growth between goods and services sectors in modeled years than in the historical years. The more we assume labour productivity to grow in a sector, the more value the sector can add (given a number of hours worked) or the fewer working hours the sector needs to use (given a level of value added) or a combination of both. The more intensively a sector uses labour in production, the more the sector gains from the assumed labour productivity growth, keeping all else equal.

Besides differences in assumed labour productivity growth between sectors, the assumed increases in energy prices, EU emission allowance prices and energy and CO_2 tax levels (see also Section 5.1 and Tables 6-8) also drive the modeled structural change of production. Effects of increasing energy prices, emission allowance prices, and energy and CO_2 taxes can go both ways, however. On the one hand, these price and tax increases add to the cost of production and have a negative effect on production levels and hence on value added and hours worked in the production sectors. The easier it is for other firms and consumers to find substitutes for the goods or services that the sector produces, the larger the negative effect is for the sector, keeping all else equal. Similarly, the more intensively a sector uses energy in production, the larger the negative effect is for the sector. On the other hand, these price and tax increases provide incentives to substitute capital and labour for the energy inputs in production (*e.g.* by implementing energy efficiency measures) and thus also have a positive offsetting effect on value added and hours worked in the production sectors. The more of such substitution possibilities a sector has, the larger the offsetting effect is for the sector, keeping all else equal.

Looking at the sectors in Tables 10 and 11, we find that levels of especially value added continue to grow faster in the services sectors than in the goods sectors in the modeled years. The assumed lower productivity growth in the goods sectors and the assumed steep price increases for EU emission allowances under the EU ETS mostly drive this finding. Many of the goods sectors are included in the EU ETS whereas few of the services sectors are. Service sectors for which we model relatively fast growth in terms of value added include the *Wholesale and retail services* and *Information and communication services* sectors for which we assume relatively high labour productivity growth. The *air transports* and *sea transports* sectors also grow relatively fast in terms of hours worked. In these two transport sectors we do not assume relatively high labour productivity growth, but services provided by these sectors are in relatively high demand as firms and households respond to increasing road transport prices by looking for substitutes. The increasing road transport prices in turn are a result of the increasing energy and CO_2 taxes and the more stringent renewable fuel standards. Goods sectors for which we model relatively slow growth in terms of value added include the *electricity supply, gas supply,* and *district heating and cooling supply* sectors. These sectors face many of the assumed increases in energy prices, EU emission allowance prices and energy and CO_2 taxes. We find that value added levels also grow relatively slowly in the *agriculture and fishery* and *forestry* sectors. We assume relatively low labour productivity growth as we expect these sectors to become more labour intensive over time (in the case of the *agriculture and fishery* sector due to shifts in consumer preferences for higher-quality food products and in the case of the *forestry* sector due to a shift away from clear cutting) and as these sectors also face steeply increasing energy and CO_2 taxes due to the removal of their tax exemptions under these taxes. The *basic iron and steel products* and *non-ferrous metals and casting of metals* sectors also grow relatively slow in terms of hours worked. Besides facing the assumed price increases of energy products and EU emission allowances, we assume that these sectors also face a fierce competition from abroad and relatively high labour productivity growth due to consolidation in the sector. Further, a few sectors break the trend of the modeled structural change. For example, we find that levels of value added and hours worked grow relatively slower in the *road passenger transports* service sector than in the other services sectors. This sector faces the assumed increases in energy prices and cost price increases due to the renewable fuel standards for transport fuels. In conjunction with the introduction of this policy instrument, we also find that the *biodiesel refining* sector is a goods sector that increases its gross production levels significantly. Finally, we find that the public sector grows at relatively slow pace in terms of value-added levels because of the assumed slow growth in government consumption relative to GDP growth. Yet, the public sector grows at relatively fast pace in terms of the number of hours worked because of the assumed lack of labour productivity growth.

Table 10 Historical and modeled development of value added in the reference scenarios

Average annual percentage change; underlying values in constant prices

	1995-2019	2019–2050		
		Low	Central	High
Total	**2.5**	**1.4**	**1.7**	**2.1**
Private sector	**3.1**	**1.5**	**1.9**	**2.4**
Private sector - goods	**2.2**	**1.4**	**1.8**	**2.2**
Agriculture and fishery	0.3	1.5	1.9	2.4
Forestry	2.8	1.1	1.5	1.8
Mining	-1.3	1.3	1.7	2.1
Manufacturing of food products	0.0	1.3	1.8	2.4
Manufacturing of wood products	0.9	1.5	1.9	2.2
Manufacturing of paper products	-0.1	1.7	2.2	2.7
Refineries	2.7*	1.0	1.4	1.8
Refineries – biodiesel	2.7*	7.2	9.2	10.6
Manufacturing of chemicals and pharmaceuticals	2.7*	1.6	2.2	2.8
Manufacturing of plastics and rubber products	0.9	1.4	1.9	2.3
Manufacturing of non-metallic mineral products	2.2	1.2	1.6	1.9
Manufacturing of basic iron and steel products	-0.3*	0.7	1.2	1.7
Manufacturing of non-ferrous metals and casting of metals	-0.3*	1.7	2.2	2.7
Manufacturing of metal products	0.3	1.4	1.8	2.2
Manufacturing of optical and electronic products, machines	2.2	1.6	2.2	2.7
Manufacturing of motor vehicles and other transport eq.	4.9	1.7	2.3	2.8
Manufacturing of other products (*e.g.* furniture)	0.4	1.2	1.7	2.1
Electricity supply	0.8*	1.0	1.4	1.9
Gas supply	0.8*	-0.5	0.6	1.5
District heating and cooling supply	0.8*	0.2	0.7	1.1
Water supply, sewerage and waste management	0.8*	1.4	1.8	2.1
Construction	2.1	1.2	1.3	1.5
Private sector - services	**3.5**	**1.6**	**2.0**	**2.5**
Wholesale and retail services	4.0	1.7	2.2	2.7
Rail road transports	-1.3	1.3	1.7	2.2
Road passenger transports	0.3	1.0	1.3	1.6
Road goods transports	2.0	2.0	2.1	2.0
Sea transports	4.8	1.9	2.4	2.8
Air transports	3.5	2.6	3.0	3.5
Warehousing, transport support and postal services	0.9	1.6	2.0	2.5
Household services	3.1	1.2	1.6	2.0
Information and communication services	7.6	2.1	2.7	3.3
Financial and insurance services	3.5	1.4	2.0	2.2
Real estate services	1.4	1.2	1.7	2.2
Business services	4.0	1.5	1.8	2.2
Public sector	**0.5**	**0.8**	**0.8**	**0.8**

Note: ‘Low’, ’Central’, and ’High’ refer to the reference scenarios with low, mid, and high economic growth. * means that we only have data for a more aggregated SNI category available. The public sector includes public administration, defence and social security. Source: SCB, NIER and own calculations

Table 11 Historical and modeled development of hours worked in the reference scenarios

Average annual percentage change

	1995-2019	2019–2050		
		Low	Central	High
Total	**0.8**	**0.5**	**0.5**	**0.5**
Private sector	**1.0**	**0.3**	**0.4**	**0.4**
Private sector - goods	**-0.2**	**0.3**	**0.3**	**0.3**
Agriculture and fishery	-2.3	0.7	0.9	1.1
Forestry	1.6	0.9	1.1	1.3
Mining	-0.3	0.4	0.5	0.6
Manufacturing of food products	-1.6	0.0	0.1	0.1
Manufacturing of wood products	-0.8	0.5	0.6	0.5
Manufacturing of paper products	-3.0	0.1	0.1	0.0
Refineries	-0.6*	-0.4	-0.5	-0.6
Refineries – biodiesel	-0.6*	5.6	7.1	8.0
Manufacturing of chemicals and pharmaceuticals	-0.6*	-0.7	-0.8	-1.0
Manufacturing of plastics and rubber products	-1.0	0.2	0.4	0.4
Manufacturing of non-metallic mineral products	-0.3	0.0	0.0	-0.1
Manufacturing of basic iron and steel products	-0.9*	-1.4	-1.6	-1.9
Manufacturing of non-ferrous metals and casting of metals	-0.9*	-0.6	-0.9	-1.2
Manufacturing of metal products	-0.3	0.1	0.1	0.1
Manufacturing of optical and electronic products, machines	-1.4	-1.1	-1.4	-1.8
Manufacturing of motor vehicles and other transport eq.	-0.1	-0.8	-1.0	-1.3
Manufacturing of other products (*e.g.* furniture)	-1.1	-0.1	0.0	-0.1
Electricity supply	1.7*	0.5	0.9	1.2
Gas supply	1.7*	-1.0	-0.1	0.6
District heating and cooling supply	1.7*	0.2	0.1	0.4
Water supply, sewerage and waste management	1.7*	0.7	0.9	0.9
Construction	2.0	0.8	0.8	0.8
Private sector - services	**1.7**	**0.3**	**0.4**	**0.4**
Wholesale and retail services	0.8	0.0	-0.1	-0.1
Rail road transports	-4.4	0.4	0.6	0.8
Road passenger transports	1.2	-0.2	-0.2	-0.4
Road goods transports	0.4	0.7	0.3	-0.3
Sea transports	-0.5	0.6	0.7	0.7
Air transports	-4.8	1.4	1.4	0.7
Warehousing, transport support and postal services	-0.4	0.5	0.6	0.7
Household services	3.4	0.7	1.0	1.3
Information and communication services	2.5	-0.5	-0.7	-1.0
Financial and insurance services	0.1	-0.1	-0.1	0.5
Real estate services	1.2	0.7	1.0	1.3
Business services	2.8	0.5	0.5	0.5
Public sector	**0.4**	**0.8**	**0.8**	**0.8**

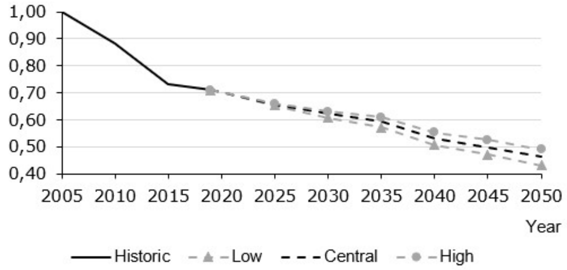
Note: ‘Low’, ’Central’, and ’High’ refer to the reference scenarios with low-, mid-, and high economic growth. * means that we only have data for a more aggregated SNI category available. The public sector includes public administration, defence and social security. Source: NIER and own calculations

ENERGY INTENSITY OF ECONOMIC ACTIVITY

The energy intensity of GDP summarizes the relation between primary energy use in physical terms and economic activity and is targeted by the Swedish government to fall with 50% from its 2005 level by 2030. We find that the energy intensity has already fallen with approx. 29% from its 2005 level by 2019 (Swedish Energy Agency, 2022). We project that the energy intensity falls with approx. 37-39% from its 2005 level by 2030 in the reference scenarios, missing the government target by 11-13% (see Figure 7).

Figure 7 Historical and modeled development of energy intensity of GDP in the reference scenarios

Primary energy use in physical terms as a share of GDP in constant prices, indexed to 1 in 2005

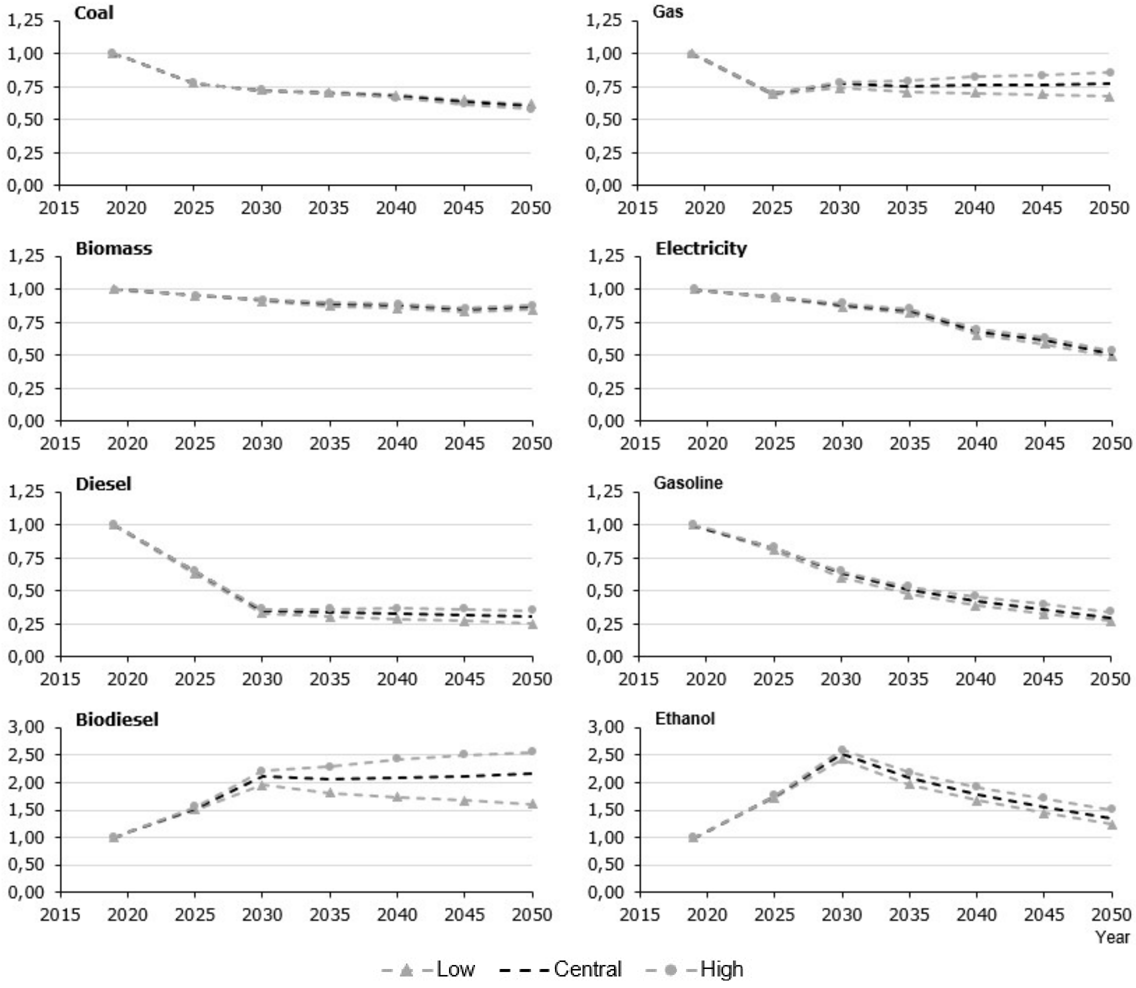


Note: 'Low', 'Central', and 'High' refer to the reference scenarios with low, mid, and high economic growth.
Source: Swedish Energy Agency (2022) and own calculations

Between energy products, we find that the energy intensity of GDP changes to various extents and mostly in line with assumed changes in (world-market) product prices and the stated policies (see Figure 8). For coal and gas that are used intensively in manufacturing sectors subject to the EU ETS, we project that the energy intensities fall over time as a mirror image of assumed changes in their world-market product prices and the EU emission allowance price. In addition, the EU emission allowance price affects the use of gas to a lesser extent than the use of coal due to gas being considerably less CO_2-intensive in its use than coal. For biomass, we project that the energy intensity also falls over time, but to a much lesser extent than for coal and gas. We follow the EU Agricultural Outlook 2018-2030 and assume that the world-market price for biomass increases at a lower rate than the price for coal and gas (EC, 2018). We also assume that biomass is exempt from stated policies in the model. For electricity, we project that the energy intensity also falls to a lesser extent than coal and gas initially. We assume that the electricity price increases at a relatively low rate over time and electricity is in relatively high demand due to its low CO_2 intensity. Yet, we project the (primary) energy intensity for electricity to fall at a faster rate after 2035 as we assume a phase-out of nuclear power based on the stated goal of 100% renewable power consumption in Sweden by 2040. For fossil diesel and petrol that are subject to energy and CO_2 taxes as well as to the renewable fuel standards, we project that their energy intensities fall relatively much. On the contrary, for biodiesel and ethanol we project that the energy intensities increase over time and in line with their mandated levels in transport fuels. Moreover, both biofuels are exempt from energy and CO_2 taxes when used in the B100 and E85 fuel blends. From 2030 onward, the energy intensity of ethanol falls back whereas the energy intensity of biodiesel stabilizes at 2030 levels. Fuel standards are kept at their 2030 levels from then on and due to assumed changes in world-market prices for biodiesel and ethanol over time, households and firms use relatively more of the B15-90 and B100 diesel fuel blends (and electricity) at the expense of the E10-50 and E85 petrol fuel blends.

Figure 8 Modeled development of energy intensity of GDP for selected energy products in the reference scenarios

Primary energy use in physical terms as a share of GDP in constant prices, indexed to 1 in 2019



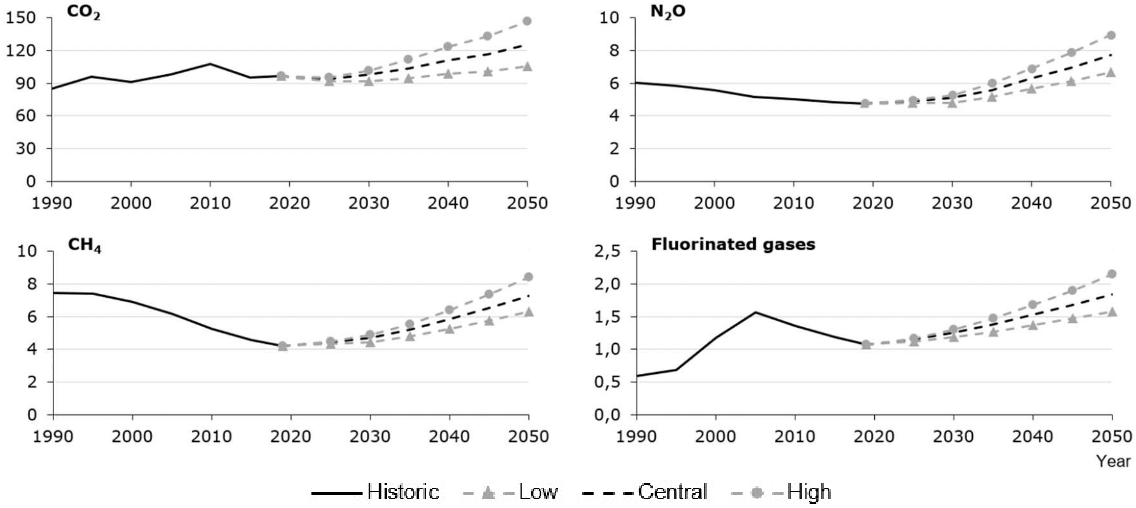
Note: ‘Low’, ’Central’, and ’High’ refer to the reference scenarios with low, mid, and high economic growth.

EMISSIONS OF GREENHOUSE GASES AND LOCAL AIR POLLUTANTS

Figures 9 and 10 show the historical and modeled development of emissions of greenhouse gases and local air pollutants in the reference scenarios. We find that emissions of most modeled gases have decreased between 1990 and 2019, with the exception of emissions of CO_2 and fluorinated gases that have increased slightly instead. Going forward in time, we project that emissions of all modeled gases increase again in absolute terms in the reference scenarios as a result of economic growth and despite the stated policies. That is, even though the stated policies achieve reductions in energy use relative to GDP, these reductions tend be insufficient to reduce associated emissions in absolute terms. Emissions of CO are perhaps an exception. These emissions stay mostly flat and even decrease somewhat in absolute terms over time in line with reduced use of coal, oil, and gas in the reference scenario with relatively low growth.

Figure 9 Historical and modeled development of emissions of greenhouse gases in the reference scenarios

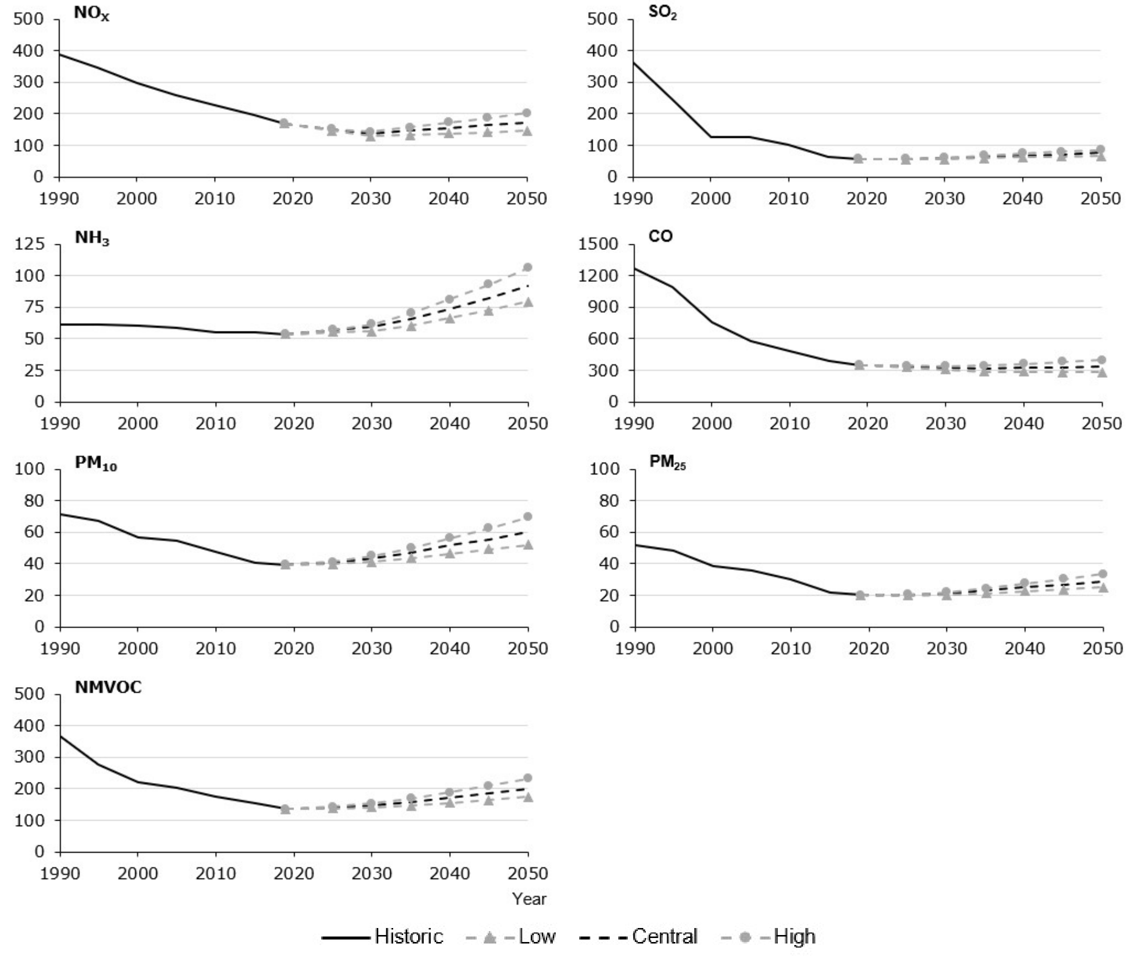
Emissions in Mtonnes CO_2-eq



Note: 'Low', 'Central', and 'High' refer to the reference scenarios with low, mid, and high economic growth.
Source: SCB, Swedish Environmental Protection Agency and own calculations

Figure 10 Historical and modeled development of emissions of local air pollutants in the reference scenarios

Emissions in ktonnes



Note: 'Low', 'Central', and 'High' refer to the reference scenarios with low-, mid-, and high economic growth.
Source: SCB, Swedish Environmental Protection Agency and own calculations

6 An example policy scenario

In this section, we describe an example policy scenario to show how the EMEC model performs when used to evaluate climate policy. For the sake of simplicity and clarity, we evaluate as our example policy a reduction in allowed emission levels that is highly stylized and far removed from current policy making, but similar to the basic policy evaluation in Section 2. Specifically, we reduce the allowed level of aggregate CO_2 emissions with 50% relative to the base year level by 2030. We keep the emission allowance at this level thereafter. Similarly, we focus on CO_2 emissions only and make the simplifying assumption that these emissions are reduced by having all emissions subjected to a price that is harmonized between all emissions, irrespective from which economic activity these emissions arise and if the emissions come from fossil or biogenic sources. The implication is that those emitters for whom it is cheaper to abate than to pay the emission price now have the incentive to abate, in turn ensuring that the emission reduction is achieved at a low overall abatement cost. We describe the precise set-up of the policy scenario in terms of assumptions made to achieve the emission reduction and to let the economy develop in section 6.1 and describe the resulting development of the economy in section 6.2.

6.1 Policy scenario setup

We set up the example policy scenario identical to the central reference scenario except for the following changes. We now target a 50% reduction of aggregate CO_2 emissions from both fossil and biogenic sources relative to the base year by 2030. We already start targeting emission reductions in 2021 and assume a linear reduction path between the modeled emission level in 2020 and the targeted emission level in 2030. From then on, we keep the allowed emission level capped at the 2030 target level. Further, we assume emission prices as our policy instrument of choice to reach the emission reduction target. More specifically, we choose to keep the CO_2 emissions that are subject to the EU ETS in the reference scenario also subject to the EU ETS in the policy scenario (with revenues accruing to the EU). We choose to subject all other CO_2 emissions to a uniform CO_2 tax in the policy scenario (with tax revenues accruing to the Swedish government). The uniform CO_2 tax implies that we assume away any indexing of CO_2 tax rates as well as any emission tax rebates. We also assume harmonized prices between the EU ETS and the domestic GHG tax.[16] Note that if the CO_2 prices are not introduced or raised in the real world, the prices can be interpreted as shadow prices of the targeted emission reduction in the model world.

Mathematically, we model the emission reduction by imposing a cap on aggregate CO_2 emissions that determines the allowed aggregate level of CO_2 emissions that are subject to the CO_2 tax (with condition X.20 now required to hold as an equality in equilibrium from 2021 onward). Balance between the capped supply of and demand for these emissions in turn determines the height of the required CO_2 tax level (with condition M.50 now required to hold as an equality in equilibrium from 2021 onward). We also require the EU ETS price to equal the CO_2 tax rate (with condition X.23 instead of condition X.22 now required to hold in equilibrium from 2021 onward).[17] Further, we

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[16] Even though we harmonize CO_2 price levels between the EU ETS and the domestic CO_2 tax, note that the CO_2 price is not fully uniform and that some differentiation remains between the CO_2 prices that the polluters ultimately face due to VAT being levied on the domestic CO_2 tax and not on the EU Emission allowances. Also, we leave the energy taxes as they are in the reference scenarios.

[17] Note that CO_2 emissions subject to the EU ETS can adjust freely in response to the ETS price. The allowed aggregate level of CO_2 emissions that are subject to the CO_2 tax will adjust endogenously to the extent needed to keep aggregate CO_2 emissions at or under the cap.

now impose the total factor productivity changes computed in the central reference scenario (see equation D.17) and let sectoral labour productivities and GDP be affected by the policy changes over time instead (with conditions X.01-03 no longer required to hold in equilibrium). Similarly, we now impose the markups computed in the central reference scenario onto the cost prices of electricity and district heating and let their prices be affected by the policy changes over time instead (with condition X.04 no longer required to hold in equilibrium). We now also impose the household savings shares computed in the central reference scenario and let investments in fixed capital change be affected by the policy changes over time instead (with condition X.05 no longer required to hold in equilibrium). Finally, we impose the value for the trade balance computed in the central reference scenario and let imports and exports be affected by the policy changes over time instead (with condition X.06 no longer required to hold in equilibrium).

6.2 Policy scenario results

In this section, we describe the development of the economy in our example policy scenario in terms of (i) CO_2 emissions and the required CO_2 price levels to keep the emissions at their targeted levels, (ii) emissions of other greenhouse gases and local air pollutants, (iii) energy intensity of economic activity, (iv) goods and services produced and hours worked in production, (v) changes in GDP and its expenditure components and (vi) economic welfare of the households.

CO_2 EMISSIONS AND PRICE

Figure 11 shows both the targeted development of CO_2 emissions and the required CO_2 price levels to keep the emissions at their targeted levels in the policy scenario. We find that the required CO_2 price increases over time. From 2021 onward, the price increases slowly at first. Our emission reduction target is not that stringent yet in the early 2020s and there are still relatively cheap abatement options available that do not need a high CO_2 price to become profitable. Between 2025 and 2030, the price increases at a faster rate. Our emission reduction target is now becoming stringent and remaining abatement options need a higher CO_2 price to become profitable. From 2030 onward, the price continues to increase albeit at a slower rate. Our 50% emission reduction target continues to become more stringent relative to the growing size of the economy and remaining abatement options need a higher CO_2 price to become profitable. Yet, vehicle stock dynamics lead to the availability of relatively more non-CO_2 intensive vehicles over time, in turn dampening the required CO_2 price increase somewhat. Further, we find that the required CO_2 price for our 50% emission reduction is approximately six times the level of today's CO_2 tax rate of 1180 kr per tonne. This CO_2 price is in line with CO_2 prices computed with a suite of other CGE models and as compiled by Böhringer et al (2021).[18] Besides our assumptions on economic growth, the required CO_2 prices are also a direct result of our assumptions on substitution possibilities and abatement costs. The easier (more difficult) we believe it to be to substitute away from products or production processes giving rise to the emissions, the lower (higher) the abatement costs and required CO_2 prices are, all else equal. We further analyse the sensitivity of the required CO_2 price to various assumptions on substitution possibilities in section 7 below.

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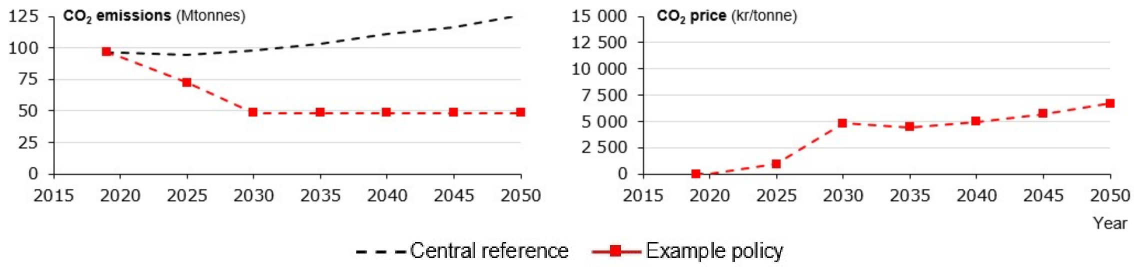
[18] Even though our targeted CO_2 emission reduction differs from the targeted CO_2 emission reduction in the compilation of other model studies in several ways, we find that we compute a similar combination of CO_2 emission reduction relative to the (central) reference scenario and required CO_2 price in the year 2025.

Figure 11 Modeled development of CO_2 emissions and the required CO_2 price in the policy scenario



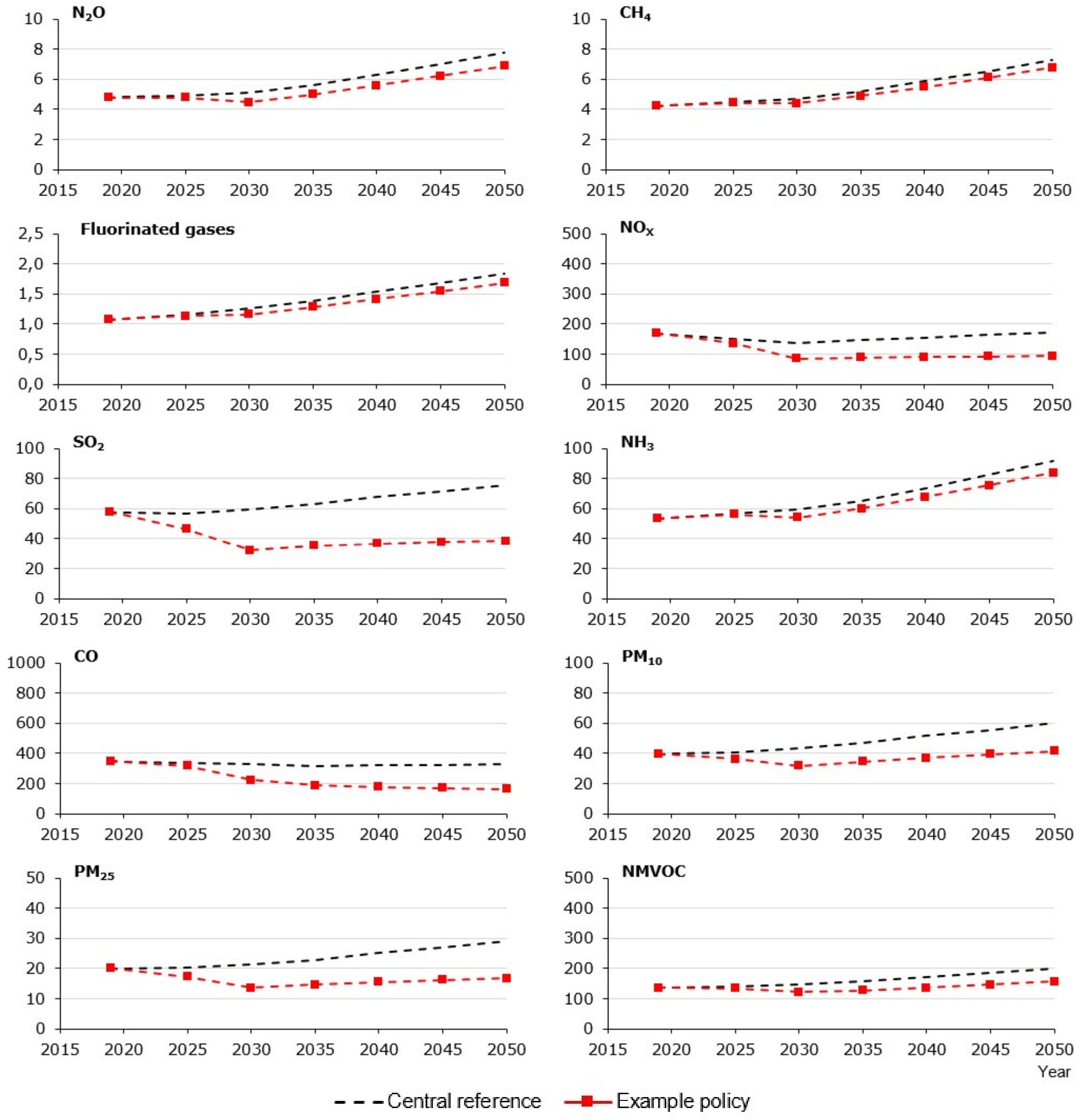
Note: We model harmonized prices for EU emission allowances and CO_2 taxes from 2021 onward. For 2019-2021, we model the stated prices for EU emission allowances and CO_2 taxes.
Source: SCB and own calculations

EMISSIONS OF OTHER GREENHOUSE GASES AND LOCAL AIR POLLUTANTS

As a co-benefit of reaching our CO_2 emission reduction target, we find that emission levels of all pollutants are lower in the policy scenario than in the central reference scenario (see Figure 12). And except for fluorinated gases, we find that modeled emission levels are also lower from 2030 onward than they were in 2019 in the policy scenario. The extent to which the modeled emission levels are lower in the policy scenario depends mostly on the pollution intensities of the economic activities and the available substitution possibilities between the economic activities. The more (less) the use of a product or production process gives rise to joint emissions of CO_2 and other pollutants, the more (less) emissions of the other pollutants will decrease in tandem with the CO_2 emission reduction, all else equal. For example, fossil diesel is not only relatively CO_2-intensive in its use, but also relatively NOx-intensive and SO_2-intensive. As CO_2 emissions from fossil diesel fall to a relatively large extent as a result of the increasing CO_2 price, we find that NOx and SO_2 emissions also fall a relatively large extent. Further, the easier (more difficult) we believe it to be to substitute away from products or production processes giving rise to CO_2 emissions, the more (less) emissions of the other pollutants will decrease in tandem with the CO_2 emission reduction, all else equal. For example, we have specified multiple possibilities to switch away from the use of fossil diesel in the model (*e.g.* choosing more fuel-efficient engines, switching to other fuel blends containing less fossil diesel, switching to electricity) further contributing to the relatively large reductions in emissions of CO_2, NOx and SO_2. As a contrary example, emissions of fluorinated gases arise from production processes throughout the economy (including service sectors) and come with fewer easy possibilities to switch from. As a consequence, we find that these emissions fall to a relatively small extent in our scenarios.

Figure 12 Modeled development of emissions of other greenhouse gases and local air pollutants in the central reference and policy scenarios

GHG emissions in Mtonnes CO_2 -eq, emissions of local air pollutants in Ktonnes



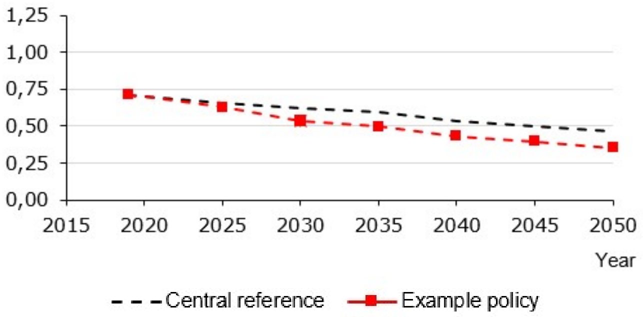
Source: SCB and own calculations

ENERGY INTENSITY OF ECONOMIC ACTIVITY

As a secondary effect of reaching our CO_2 emission reduction target, we find that the energy intensity further decreases from 2021 onward in the policy scenario compared to the central reference scenario (see Figure 13). Since CO_2 emissions arise predominantly from combustion of fuels, use of fuel energy products (*e.g.* coal, oil, gas, biomass) decreases mostly in line with the CO_2 emission reduction and faster than any decrease in economic activity. Use of electricity as a non-fuel and non-CO_2 intensive energy product increases and dampens the overall decrease in energy intensity in the policy scenario compared to the central reference scenario, however.

Figure 13 Modeled development of energy intensity of GDP in the central reference and policy scenarios

Primary energy use in physical terms as a share of GDP in constant prices, indexed to 1 in 2005



STRUCTURAL CHANGE OF PRODUCTION

Table 12 shows the modeled development of value added and hours worked in the central reference scenario and policy scenario. We find that the modeled CO_2 emission reduction has only a slight negative effect on the growth rates of value added and hours worked in the policy scenario compared to the central reference scenario. The increasing CO_2 prices add to the cost of production and have a negative effect on production levels and hence on value added and hours worked in production. Moreover, households choose to work fewer hours and enjoy more leisure hours in response to product price increases in their consumption bundles and a negative wage pressure caused by the dampened production growth. Yet, the increasing CO_2 prices also provide incentives to substitute capital and labour for energy inputs in production and thus also have a positive effect on value added and hours worked in production.

We find that the negative effects weigh heavier for sectors producing goods than for sectors producing services and that the structure of production continues to change more in the direction of the production of services over time in the policy scenario. In general, industrial sectors producing goods are more CO_2 intensive and lose relatively more from the increasing CO_2 prices than service sectors. Notable exceptions include the electricity sector and the road-transport service sectors. As electricity gains market share as a non- CO_2 intensive energy product, the electricity sector grows faster under increasing CO_2 prices in the policy scenario. On the contrary, the road-transport service sectors grow relatively slower in this scenario as road-transport services lose market share as a CO_2 -intensive service to *e.g.* rail transport services. Finally, we find that the structure of production in the public sector is hardly affected by the increasing CO_2 prices because of our assumption of unchanged demand for its goods and services in the policy scenario and our assumption of there existing relatively few possibilities to substitute labour for energy products in government production.

Table 12 Modeled development of value added and hours worked in the central reference and policy scenarios

Average annual percentage changes between 2019 and 2050, underlying values in constant prices

	Value added		Hours worked	
	Central reference	Policy	Central reference	Policy
Total	1.71	1.66	0.48	0.45
Private sector	1.93	1.87	0.36	0.31
Private sector - goods	1.78	1.62	0.27	0.12
Private sector - services	2.00	1.99	0.40	0.40
Public sector (public administration, defence, social security)	0.77	0.77	0.77	0.77

Source: SCB and own calculations

CHANGES IN GDP AND ITS EXPENDITURE COMPONENTS

In line with the dampened growth of production levels, we find that the modeled CO_2 emission reduction also has a slight negative effect on the growth rate of GDP in the policy scenario compared to the central reference scenario (see Table 13). If we look at the expenditure components of GDP, we find that the modeled CO_2 emission reduction also has negative effects on some, but not all, of the growth rates in the policy scenario compared to the central reference scenario. Firstly, fixed-capital formation grows at a slightly slower pace because of the dampened GDP growth and imposed saving shares in the policy scenario. Secondly, exports grow at a slower pace because of increasing prices of domestically-produced products and hence reduced world demand for these products in the policy scenario. Thirdly, imports also grow at a slower pace in the policy scenario. Although we find that imported products are substituted more for domestically products (esp. CO_2-intensive products), growth in imports slows mostly in line with the dampened growth of production levels. Fourthly, household consumption also grows at a slower pace in the policy scenario. Especially consumption of fuel energy products and other CO_2-intensive products decreases in response to the increasing CO_2 prices. Finally, we keep non-fixed capital formation and government consumption at fixed levels over time and their growth rates therefore remain unchanged in the policy scenario.

Table 13 Modeled development of GDP and its expenditure components in the central reference and policy scenarios

Average annual percentage change between 2019 and 2050; underlying variables in constant prices

	Central reference	Policy
GDP	1.74	1.68
Household consumption	1.72	1.60
Government consumption	0.85	0.85
Fixed-capital formation	2.02	1.90
Non-fixed capital formation	-1.66	-1.66
Exports	2.51	2.43
Imports	2.31	2.16

Source: Own calculations.

ECONOMIC WELFARE OF HOUSEHOLDS

We find that the modeled CO_2 emission reduction also has negative effects on the growth rates of household utility as an economic welfare measure in the policy scenario compared to the central reference scenario (see Table 14). Household utility increases on average 1.25 – 1.35 % per year between 2019 and 2050 in the policy scenario and on average 1.3 – 1.5 % per year between 2019 and 2050 in the central reference scenario. Our modeled development of household utility is in line with utility levels computed with a suite of other CGE models as well (Böhringer et al, 2021). As mentioned in sections 2 and 3, note that this utility measure gives a partial picture of welfare only and excludes the benefits of government consumption as well as benefits of the CO_2 emission reduction itself and of the other emission reductions.

Looking at the distribution of the welfare effects between the household types, we find that households with an income below the median income experience smaller drops in their utility than households with an income above the median income in the policy scenario. From the Household Budget Survey (Statistics Sweden, 2013) to which we have calibrated the base year of the model, we know that households with an income below the median income consume relatively fewer CO_2-intensive products (*e.g.* road transports) and are therefore less exposed to the increasing CO_2 prices than households with an income above the median income. Moreover, we assume that households with an income below the median income receive a larger share from the revenue generated by the domestic CO_2 tax in than households with an income above the median income. Although this revenue share is stylized and by our own design, it shows that emission reductions can be achieved while protecting low-income households. Turning to the differentiation of household categories by residential area, we find that households in smaller urban areas and rural areas experience slightly smaller drops in their utility than households in large urban areas in the policy scenario. From the Household Budget Survey, we know that households in rural areas consume relatively more CO_2-intensive products (*e.g.* transports) and are therefore more exposed to the increasing CO_2 prices than households in urban areas. Yet, households in rural areas receive a larger share from the revenue generated by the domestic CO_2 tax than households in more urban areas. Although this revenue share is again stylized and by our own design, it shows that emission reductions can also be achieved while protecting households in rural areas.

Table 14 Modeled development of household utility in the policy scenario relative to the central reference scenario

Difference in the average annual percentage change between 2019 and 2050

	Policy
Households with income below the median income in large urban areas	- 0.06
Households with income above the median income in large urban areas	- 0.13
Households with income below the median income in smaller urban areas	- 0.04
Households with income above the median income in smaller urban areas	- 0.12
Households with income below the median income in rural areas	- 0.03
Households with income above the median income in rural areas	- 0.13

Note: We measure changes in utility as equivalent variation, i.e., the value of income needed to compensate the households for expenditures lost because of the policy
Source: Own calculations.

7 Sensitivity analysis

Table 15 shows the sensitivity of the required CO_2 price in the policy scenario to changes in key parameter values. We use central parameter values in all sensitivity simulations except for the parameter subject to analysis. We analyse one parameter at a time. We analyse all substitution elasticity parameters. Given the importance of assumed abatement possibilities for our findings, we also analyse all energy efficiency parameters and several other parameters used to govern changes in the capital and vehicle stocks between time periods. We show results for the ten parameters to which the required CO_2 price is most sensitive and report results as differences (in the required CO_2 price in kr/tonne CO_2 by 2050) to the regular policy scenario.

Table 15 Sensitivity of the required CO_2 price in the policy scenario to changes in key parameter values

Required CO_2 price in terms of kr/tonne CO_2 by 2050

Regular policy scenario			6 687	
σ_i^{EM}	Elasticity of substitution between the nest of process emissions and the nest of capital, labour, energy, and other intermediate inputs in production sector *i*	High	-874	
		Low		+945
σ_h^{U}	Elasticity of substitution between leisure hours and aggregate consumption in utility of household *h*	High		+604
		Low	-788	
σ_i^{KLE}	Elasticity of substitution between the nest of capital and labour and the nest of energy inputs in production sector *i*	High	-735	
		Low		+819
σ_i^{E}	Elasticity of substitution between electricity, district heating and the nest of fuel energy inputs in production sector *i*	High	-533	
		Low		+588
σ_i^{KL}	Elasticity of substitution between capital and labour in production sector *i*	High	-444	
		Low		+1 093
σ_{EX}^{NE}	Elasticity of substitution between products in the nest of non-energy products in exports	High	-429	
		Low		+677
σ_{pr}^{A}	Elasticity of substitution between imported and domestic products pr	High	-382	
		Low		+452
π_{FJ}^{E}	Energy efficiency increase of using district heating in production and consumption	High	-354	
		Low		+422
$\sigma_{CT,OWN,h}^{NEW}$	Elasticity of substitution between own road transports with new vehicle technologies in the bundle of own road transports of household *h*	High	-339	
		Low		+639
δ^{K}	Annual depreciation rate of fixed capital	High	-321	
		Low		+519

Note: Sensitivity results are sorted from the parameter yielding the largest decreases in the required CO_2 price to the parameter yielding the smallest decrease and are truncated after 10 parameters. More parameters have been analyzed as well but yield smaller decreases (and increases) and are not shown here. High refers to a parameter value that is 50% higher than in the regular scenarios. Low refers to a parameter value that is 50% lower than in the regular scenarios. See Tables C.1-5 for the values of the substitution elasticities in the regular scenarios. The energy efficiency parameter takes on values between 0.1 and 1% per year for the use of district heating in the regular scenarios. The depreciation rate of fixed capital takes on the value of 5% per year in the regular scenarios.
Source: Own calculations.

One general result from Table 15 is that the required CO_2 price for our 50% emission reduction in the policy scenario remains a multiple of today's CO_2 tax rate of 1180 kr per tonne under the range of parameter values considered. Another general result is that we indeed find that the required CO_2 price is a direct result of our assumptions on substitution possibilities and abatement costs as discussed in section 6.2. The easier (more difficult) we assume it to be to substitute away from products or production processes giving rise to the CO_2 emissions, the lower (higher) the abatement costs and required CO_2 prices are, all else equal. Assuming a higher value for the elasticity of substitution between the nest of process emissions and the nest of capital, labour, energy, and other intermediate inputs in production, for example, yields a sizable decrease in the required CO_2 price by 2050.

Turning to a few specific parameters subject to analysis, assuming a higher elasticity of substitution between leisure hours and aggregate consumption in household utility leads to an increase in the required CO_2 price relative to the regular policy scenario and all else equal. The higher substitution elasticity makes the labour supply more responsive and decreases the price of labour supplied relative to the regular scenarios and all else equal. Consequently, we find that the lower price of labour supplied leads to slightly faster economic growth and higher emission levels in the reference scenario, in turn leaving a larger emission gap to close and requiring a higher CO_2 price in the policy scenario. We find the opposite effects if we assume a lower elasticity of substitution between leisure hours and aggregate consumption in household utility. Further, assuming higher autonomous energy-efficiency increases in the use of district heating (as well as other energy products) also leads to a decrease in the required CO_2 price relative to the regular policy scenario and all else equal. The higher energy efficiency increases lead to lower CO_2 emissions already in the reference scenario and hence leave a smaller emission gap to close in the policy scenario and require a lower CO_2 price in this scenario. We find the opposite effects if we assume lower autonomous energy-efficiency increases. Finally, assuming a higher depreciation rate for fixed capital also leads to a decrease in the required CO_2 price relative to the regular policy scenario and all else equal. A higher depreciation rate for fixed capital decreases the capital stock and increases the price of capital relative to the regular scenarios and all else equal. Given that capital and energy are net complements in many production sectors, we find that the higher price of capital leads to lower emission levels already in the reference scenario, in turn leaving smaller emission gaps to close in the policy scenarios. Consequently, we find that the required CO_2 tax levels now are slightly lower as well in this scenario. We find the opposite effects if we assume a lower depreciation rate.

8 Future model development

Limitations in the model specification have an effect on model results as well, but are difficult to analyse the sensitivity of the model results for. We therefore work continuously to maintain and further develop the model to meet the needs imposed by our research questions. Maintenance work includes keeping the model calibrated to most recent data available and improving the estimates of key parameters. Planned model developments include the following:

- A more detailed specification of capital use by specifying capital vintages and limiting the mobility of fixed capital between sectors so we capture sunk costs incurred under stringent emission reduction targets and so the model exhibits a short-term and long-term response to changes in relative input prices.

- A more detailed specification of the electricity sector so we can study more aspects of the electricity supply and study its role in energy policy proposals and in reaching emission reduction targets.

- A more detailed specification and calibration of fuels and vehicles for own road transports so we can study more aspects of reaching the 2030 interim target on emission reductions from domestic transports.

- A more detailed specification of abatement options within the steel and cement industries so we can study the role of these industries in reaching the 2045 target on national net-zero emissions more realistically.

- Accounting for greenhouse gas emissions from land use, land-use changes, and forestry (LULUCF) so we can study their role in reaching the 2045 target on national net-zero emissions and in EU policy proposals.

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Appendix A: Model sets

Table A.1 Sets

Symbol	Elements	Description
I	See full list in Table A.2	Set of all production sectors (with index *i* ∈ *I*)
PR	See full list in Table A.3	Set of all products (with index *pr* ∈ *PR*)
PR_B	ETANOL, BIODIESEL, DIESEL, BENSIN, EL	Subset of fuel products for transports and machines (*PR_B* ⊂ *PR*)
PR_BL	ETANOL, BIODIESEL, DIESEL, BENSIN	Subset of liquid fuel products for transports and machines (*PR_BL* ⊂ *PR*)
PR_EX_E	EL, KOL, RAOLJA	Subset of energy products for exports (*PR_EX_E* ⊂ *PR*)
PR_G_GDS	JORD, SKOG, GRUV, LIVS, TRAV, MASSA, KEMI, JSTEN, JSTAL, METLTILL, VERKTILL, FORDTILL, BYGG, METALL	Subset of goods for final consumption by the government (*PR_G_GDS* ⊂ *PR*)
PR_G_SER	FTTJ, AVFL, HAND, HHTJ, KOMU, BANK	Subset of services for final consumption by the government (*PR_G_SER* ⊂ *PR*)
PR_G_TR	JVAG, PASSTP, LASTBTP, OTHERTP, SJOTP, LUFTTP	Subset of transport products for final consumption by the government (*PR_G_TR* ⊂ *PR*)
PR_TE	GAS, EL, BENSIN, DIESEL, BIO,PETRO, KOL, BRANS	Subset of products that are subject to energy taxes (*PR_TE* ⊂ *PR*)
PR_TCO2	GAS, BENSIN, DIESEL, PETRO, KOL, BRANS	Subset of products that are subject to CO_2 taxes (*PR_TCO2* ⊂ *PR*)
TE	See full list in Table A.4	Set of all machine and vehicle technologies (with index *te* ∈ *TE*)
TE_M	M_DIESEL, M_BENSIN	Subset of machine technologies (*TE_M* ⊂ *TE*)
TE_DV	HDV_DIESEL, LDV_BENSIN_LO, LDV_BENSIN_HI, LDV_ETANOL_LO, LDV_ETANOL_HI, LDV_DIESEL_LO, LDV_DIESEL_HI, LDV_PHEV, LDV_EV	Subset of duty-vehicle technologies (*TE_DV* ⊂ *TE*)
TE_DV_CES	HDV, LDV_PHEV	Subset of duty-vehicle technologies with imperfectly substitutable fuel use (*TE_DV_CES* ⊂ *TE*)
TE_LDV	LDV_BENSIN_LO, LDV_BENSIN_HI, LDV_ETANOL_LO, LDV_ETANOL_HI, LDV_DIESEL_LO, LDV_DIESEL_HI, LDV_PHEV, LDV_EV	Subset of light-duty vehicle technologies (*TE_LDV* ⊂ *TE*)
DVCOST	CHS,BAT,ENG,MAINT;F	Set of all vehicle cost components (with index *dvcost* ∈ *DVCOST*)
V	v1 (< 3 years old) v2 (≥ 3 years old)	Set of aggregate duty-vehicle technology vintages (with index *v* ∈ *V*)
VT	2000,..,2050	Set of annual duty-vehicle technology vintages (with index *vt* ∈ *VT*)
BL	See full list in Table A.5	Set of all fuel blends (with index *bl* ∈ *BL*)
FN	See full list in Table A.6	Set of all consumption bundles (of final consumption products; with index *fn* ∈ *FN*)
FN_GDS	FOOD, CLOTH, FURN, HGOODS, GOOD	Subset of consumption bundles of goods (*FN_GDS* ⊂ *FN*)
FN_SER	ENTERTAIN, SERVICE	Subset of consumption bundles of services (*FN_SER* ⊂ *FN*)
FN_HF	HGAS, HOIL, HBIO	Subset of consumption bundles of fuels for heating (*FN_HF* ⊂ *FN*)
FN_TR	RAIL, AIR, SEA	Subset of consumption bundles of purchased (non-road) transports (*FN_TR* ⊂ *FN*)
H	See full list in Table A.7	Set of all households (with index *h* ∈ *H*)
PO	See full list in Table A.8	Set of all pollutants (with index *po* ∈ *PO*)
PO_GHG	CO_2, CH_4, N_2O, Fgas	Subset of greenhouse gases (*PO_GHG* ⊂ *PO*)

D	C (consumption by households) G (consumption by the government) LA (investment in non-fixed capital) I (investment in fixed-capita) EX (exports)	Set of all final demand categories (with index $d \in D$)
T	2019,..,2050	Set of all time periods (years; with index $t \in T$)

Table A.2 Production sectors

EMEC abbr.	SNI–2007 codes	Description
JORD	A01, A03	Agriculture and fishery
SKOG	A02	Forestry and logging
GRUV	B	Mining and quarrying
LIVS	C10–15	Manufacturing of food, beverages and tobacco products
TRAV	C16	Manufacturing of wood products
MASSA	C17-18	Manufacturing of paper products
RAFF	Part of C19	Manufacturing of refined petroleum products
RAFF_BIO	Part of C19	Manufacturing of biodiesel products
KEMI	C20, C21	Manufacturing of chemical and pharmaceutical products
GUMMI	C22	Manufacturing of plastics and rubber products
JSTEN	C23	Manufacturing of non-metallic mineral products
JSTAL	C241–C243	Manufacturing of basic iron and steel products
METALL	C244–C245	Manufacturing of non-ferrous metals and casting of metals
METLTILL	C25	Manufacturing of metal products
VERKTILL	C26–C28	Manufacturing of optical and electronic products, machines
FORDTILL	C29–30	Manufacturing of motor vehicles and other transport equipment
ANTILL	C31-33	Manufacturing of other products (e.g. furniture)
EL	D351	Electricity supply
GAS	D352	Gas supply
FJ	D353	District heating and cooling supply
VAAVFL	E36–39	Water supply, sewerage and waste management
BYGG	F41–43	Construction
HAND	G	Wholesale and retail services
JVAG	H491–H492	Rail road transports
PASSTP	H493	Road passenger transports
LASTBTP	H494–H495	Road goods transports
SJOTP	H50	Sea transports
LUFTTP	H51	Air transports
OTHERTP	H52–53	Wharehousing, transport support and postal services
HHTJ	I, P – T	Household services (Accomodation, food, education, health, entertainment, recreation)
KOMU	J	Information and communication services
BANK	K	Financial and insurance services
BOST	L	Real estate services
FTTJ	M, N	Business services
GOV	O	Public administration, defence and social security

Table A.3 Products

EMEC abbr.	SNI-2007 codes	Description
JORD	A01, A03	Agriculture and fishery products
SKOG	A02 excl. A02109A, A0220004	Forestry products
BIO	A02109A, A0220004, C16291, C2014A, incl. products C161 delivered to C351 and C353	Biomass
KOL	B05	Coal
RAOLJA	B061	Crude oil
GAS	B062, D352	Gas, incl. distribution
GRUV	B07–B09	Mining products
LIVS	C10–15	Food, beverage and tobacco products
TRAV	C16 excl delivieries to D351 and D353	Wood products
MASSA	C17-18	Paper products
PETRO	C19A, C1910004, C191000A, C1920012-17	Non-fuel refined petrochemical products
TORV	C1920003	Peat
BENSIN	C192000B	Petrol
DIESEL	Part of C192000E	Diesel
BIODIESEL	Part of C192000E	Biodiesel
BRANS	C192000C, C192000D, C1920000F, C190011	Fuel oil and fuel for aircraft
KEMI	C20-21 excl C2014A, C2014B	Chemical and pharmaceutical products
ETANOL	C2014B	Ethanol
GUMMI	C22	Plastic and rubber products
JSTEN	C23	Non–metallic mineral products
JSTAL	C241–C243	Basic iron and steel
METALL	C244	Non–ferrous metals
METLTILL	C25	Fabricated metal products
VERKTILL	C26–C28	Optical and electronic products, machines
FORDTILL	C29–C30	Motor vehicles and other transport equipment
ANTILL	C31-C33	Other manufactured products (e.g. furniture)
EL	D351	Electricity, incl distribution
FJ	D353	District heating and cooling
VA	E36–37	Water and sewerage
AVFL	E38–E39	Waste management services
BYGG	F41–43	Construction
HAND	G	Wholesale and retail services
JVAG	H491–H492	Rail road transports
PASSTP	H493	Road passenger transports
LASTBTP	H4942001, H494A	Road goods transports
SJOTP	H50	Sea transports
LUFTTP	H51	Air transports
OTHERTP	H495, H52–53	Transport support and postal services
HHTJ	I, O–S	Household services (Accomodation, food, education, health, entertainment, recreation)
KOMU	J	CInformation and communication services
BANK	K	Financial and insurance services
BOST	L	Real estate services
FTTJ	M, N	Business services

Table A.4 Heavy machinery and vehicle technologies

EMEC abbr.	Description
M_DIESEL	Heavy machinery with diesel engine
M_BENSIN	Heavy machinery with petrol engine
HDV_DIESEL	Heavy-duty vehicles with diesel engine
LDV_BENSIN_LO	Light-duty vehicle with petrol engine and rel. low CO_2 emissions
LDV_BENSIN_HI	Light-duty vehicle with petrol engine and rel. high CO_2 emissions
LDV_ETANOL_LO	Light-duty vehicle with petrol engine that can run on E85 blend and with rel. low CO_2 emissions
LDV_ETANOL_HI	Light-duty vehicle with petrol engine that can run on E85 blend and with rel. high CO_2 emissions
LDV_DIESEL_LO	Light-duty vehicle with diesl engine and rel. low CO_2 emissions
LDV_DIESEL_HI	Light-duty vehicle with diesel engine and rel. high CO_2 emissions
LDV_PHEV	Light-duty vehicle with a hybrid petrol and electric engine
LDV_EV	Light-duty vehicle with an electric engine

Table A.5 Fuel blends

EMEC abbr.	Description
BENSIN_ETANOL_LO	Petrol blend with relatively low ethanol content (E10-50)
BENSIN_ETANOL_HI	Petrol blend with relatively high ethanol content (E85)
DIESEL_BIODIESEL_LO	Diesel blend with relatively low biodiesel content (B15-90)
DIESEL_BIODIESEL_HI	Diesel blend with relatively high biodiesel content (B100)
EL	Electricity

Table A.6 Households

EMEC abbr.	Description	H-region respektive income quartile
SMG1	Large urban area, low income	H-region: H1, H8, H9, Income quartile 1,2
SMG2	Large urban area, high income	H–region:H1, H8, H9, Income quartile 3,4
MELLAN1	Smaller urban area , low income	H–region: H3, H4, Income quartile 1,2
MELLAN2	Smaller urban area , high income	H–region: H3, H4, Income quartile 3,4
GLES1	Rural area, low income	H–region: H5, H6, Income quartile 1,2
GLES2	Rural area, high income	H–region: H5, H6, Income quartile 3,4

Table A.7 Consumption bundles

EMEC abbr.	COICOP codes	Description
FOOD	01-02	Food and beverages
CLOTH	03	Clothing & Footwear
RENTS	041-044CO2 1252	Actual and imputed rents for housing
HEL	0451	Electricity
HGAS	0452	Gas
HOIL	0453	Liquid fuels
HBIO	0454	Biofuels
HHEAT	0455	Heat energy
FURN	051-052	Furniture and furnishings, and houehold textiles
HGOODS	053-056, 1212	Household appliances and tools
TRANSEQ	0711-0712	Purchase and operation of vehicles
TR_FUEL	0722	Fuels and lubricants for personal vehicles
MAIN	0721, 0723	Maintenance of vehicles
RAIL	0731	Passenger transport by railway
ROAD	0732, 0735, 0736	Passenger transport by road
AIR	0733, 096	Passenger transport by air & package holidays
SEA	0734	Passenger transport by sea
ENTERTAIN	091-095, 11	Recreational items, equipemt and services
SERVICE	06, 0724, 08, 10, 1211, 122, 124, 1251, 1253-1255, 126-127 (incl NPISHs (13) and consumtion abroad)	Other services
GOOD	0713-0714, 1213, 123	Other goods

Table A.8 Pollutants

EMEC abbr.	Description
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrate oxides
NOx	Nitrogen oxides
SO_2	Sulfur dioxides
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
CO	Carbon monoxides
PM_{10}	Particular matter (with diameter of 10 micrometers or less)
PM_{25}	Particular matter (with diameter of 2,5 micrometers or less)
Fgas	Fluorinated gases

Appendix B: Model variables

Table B.1 Activity variables determined by zero-profit conditions

Symbol	Description
$Y_{i,t}$	Production of domestic products
$VA_{i,t}$	Value added in sector *i* in period *t*
$YF_{te,i,t}$	Intermediate use of fuel blends per technologies *te* in sector *i* in period *t*
$YF_{te,i,t}^{CES}$	Intermediate use of fuel blends per technology *te* (for which different fuel blends are imperfect substitutes) in sector *i* in period *t*
$YF_{te,i,t}^{NCES}$	Intermediate use of fuel blends per technology *te* (for which different fuel blends are perfect substitutes) in sector *i* in period *t*
HM_{t}	Sales of (merchant) trade services in period *t*
$IM_{pr,t}$	Imports of product *pr* in period *t*
$A_{pr,t}$	Bundling of imported and domestic products *pr* in period *t* (under Armington assumption)
$B_{bl,pr,t}$	Blending of (liquid) fuel products *pr* into fuel blends *bl* in period *t*
$BM_{bl,i,t}$	Sales of fuel blend *bl* for intermediate use by firms in sector *i* in period *t*
$BC_{bl,t}$	Sales of fuel blend *bl* for final consumption by households in period *t*
$M_{pr,i,t}$	Sales of product *pr* for intermediate use by firms in sector *i* in period *t*
$C_{pr,t}$	Sales of product *pr* as final consumption product to households in period *t*
$C_{fn,t}$	Consumption of consumption bundle *fn* by households in period *t*
$C_{h,t}$	Consumption by household *h* in period *t*
$CT_{h,t}$	Consumption of road transport services by household *h* in period *t*
$CF_{te,t}$	Consumption of fuel blends per technology *te* by households in period *t*
$CF_{te,t}^{CES}$	Consumption of fuel blends per technology *te* (for which different fuel blends are imperfect substitutes) by households in period *t*
$CF_{te,t}^{NCES}$	Consumption of fuel blends per technology *te* (for which different fuel blends are imperfect substitutes) by households in period *t*
$G_{pr,t}$	Sales of product *pr* as final consumption product to the government in period *t*
G_{t}	Consumption of final consumption products by the government in period *t*
$I_{pr,t}$	Fixed capital formation of product *pr* in period *t*
I_{t}	Fixed capital formation in period *t*
$LA_{pr,t}$	Non-fixed capital formation (inventories) of product *pr* in period *t*
LA_{t}	Non-fixed capital formation (inventories) in period *t*
$EX_{pr,t}$	Exports of product *pr* in period *t*
$EX_{pr,t}^{EU}$	Exports of product *pr* to the EU in period *t*
$EX_{pr,t}^{ROW}$	Exports of product *pr* to the rest of the world in period *t*
EX_{t}	Aggregate exports of products in period *t*
$EXYV_{te,v,t}$	Exports of used vehicles of technology *te* and vintage *v* that were available to firms in period *t*
$EXCV_{te,v,t}$	Exports of used vehicles of technology *te* and vintage *v* that were available to households in period *t*

Table B.1 Activity variables determined by zero-profit conditions

Symbol	Description
$LS_{i,t}$	Supply of labour (hours worked) to sector *i* in period *t*
LS_{t}	Supply of labour (hours worked) in period *t*
$U_{h,t}$	Utility of household *h* (Hicksian equivalent variation) in period *t*
$BU_{h,t}$	Budget of household *h* in period *t*
$EM^{po}_{bl,pr,t}$	Emission allowances for pollutant *po* associated with using product *pr* in blend *bl* in period *t*
$EM^{po}_{pr,t}$	Emission allowances for pollutant *po* associated with using product *pr* in period *t*
$EM^{po}_{pr,i,t}$	Emission allowances for pollutant *po* associated with using product *pr* in sector *i* in period *t*
$EM^{po}_{i,t}$	Emission allowances for pollutant *po* associated with the production process in sector *i* in period *t*
$EM^{po}_{fn,h,t}$	Emission allowances for pollutant *po* associated with using consumption bundle *fn* by household *h* in period *t*

Table B.2 Price and tax variables determined by market-clearing conditions

Symbol	Description
$P_{pr,t}$	Price of product *pr* in period *t*
$P^{EA}_{pr,t}$	Price of product *pr* for own use (egen användning) in period *t*
$P^{EM}_{i,t}$	Price of aggregate process emissions in sector *i* in period *t*
$P^{KLEM}_{i,t}$	Price of aggregate use of capital, labour, energy and material intermediate inputs in sector *i* in period *t*
$P^{M}_{i,t}$	Price of aggregate intermediate input use in sector *i* in period *t*
$P^{MAT}_{i,t}$	Price of aggregate material intermediate input use in sector *i* in period *t*
$P^{TR}_{i,t}$	Price of aggregate transport use in sector *i* in period *t*
$P^{TRL}_{i,t}$	Price of aggregate cargo (last) transport use in sector *i* in period *t*
$P^{TRL\_OWN}_{i,t}$	Price of own cargo (last) transport use in sector *i* in period *t*
$P^{TRL\_NEW}_{i,t}$	Price of own cargo (last) transport with new heavy-duty vehicles in sector *i* in period *t*
$P^{TRP}_{i,t}$	Price of aggregate person transport use in sector *i* in period *t*
$P^{TRP\_OWN}_{i,t}$	Price of own person transport use in sector *i* in period *t*
$P^{TRP\_NEW}_{i,t}$	Price of own person transport with new light-duty-vehicles in sector *i* in period *t*
$P^{KLE}_{i,t}$	Price of aggregate use of capital, labour and energy inputs in sector *i* in period *t*
$P^{E}_{i,t}$	Price of aggregate energy use in sector *i* in period *t*
$P^{F}_{i,t}$	Price of aggregate fuel energy use in sector *i* in period *t*
$P^{SF}_{i,t}$	Price of aggregate solid-fuel energy use in sector *i* in period *t*
$P^{LF}_{i,t}$	Price of aggregate liquid-fuel energy use in sector *i* in period *t*
$PVA_{i,t}$	Price of value added in sector *i* in period *t*

$PTN_{te,i,t}$	Price of own transport with new duty-vehicles of technology *te* in sector *i* in period *t*
$PTN^{FE}_{te,i,t}$	Price of fuel-engine bundle used within own transport with new duty-vehicles of technology *te* in sector *i* in period *t*
$PTU_{te,v,i,t}$	Price of own transport with used duty-vehicles of technology *te* and vintage *v* in sector *i* in period *t*
$PF_{te,i,t}$	Price of transport fuel for vehicle technology *te* paid by producers in sector *i* in period *t*
$PV^{NEW\_CHS}_{te,i,t}$	Price of new vehicle chassis of technology *te* for intermediate use in sector *i* in period *t*
$PV^{NEW\_BAT}_{te,i,t}$	Price of new electric vehicle battery of technology *te* for intermediate use in sector *i* in period *t*
$PV^{NEW\_ENG}_{te,i,t}$	Price of new vehicle engine of technology *te* for intermediate use in sector *i* in period *t*
$PV^{USED}_{te,v,t}$	Price of used vehicles of technology *te* and vintage *v* in period *t*
PHM_{t}	Price of (merchant) trade margins in period *t*
$PIM_{pr,t}$	Price of imported product *pr* in period *t*
$PIM^{EU}_{pr,t}$	Price of import product *pr* from the EU in period *t*
$PIM^{ROW}_{pr,t}$	Price of import product *pr* from the rest of the world in period *t*
$PA_{pr,t}$	Price of Armington aggregate of imported and domestic product *pr* in period *t*
$PB_{bl,t}$	Price of (liquid) fuel blend *bl* in period *t*
$PBM_{bl,i,t}$	Price of (liquid) fuel blend *bl* for intermediate use in sector *i* in period *t* (in market prices)
$PBM^{pp}_{bl,i,t}$	Price of (liquid) fuel blend *bl* for intermediate use in sector *i* in period *t* in producer prices
$PBC_{bl,t}$	Price of (liquid) fuel blend *bl* used for final consumption by households in period *t* (in market prices)
$PBC^{pp}_{bl,t}$	Price of (liquid) fuel blend *bl* used for final consumption by households in period *t* in producer prices
$PM_{pr,i,t}$	Price of intermediate input product *pr* used in sector *i* in period *t* (in market prices)
$PM^{pp}_{pr,i,t}$	Price of intermediate inpuit product *pr* used in sector *i* period *t* in producer prices
$PC_{pr,t}$	Price of final consumption product *pr* used by households in period *t* (in market prices)
$PC^{pp}_{pr,t}$	Price of final consumption product *pr* used by households in period *t* in producer prices
$PC_{fn,t}$	Price of consumption bundle *fn* used by households in period *t*
$PCF_{te,t}$	Price of transport fuel for vehicle technology *te* paid by consumers in period *t*
$PCV^{NEW\_CHS}_{te,t}$	Price of new vehicle chassis of technology *te* for use by consumers in period *t*
$PCV^{NEW\_BAT}_{te,t}$	Price of new electric vehicle battery of technology *te* for use by consumers in period *t*
$PCV^{NEW\_ENG}_{te,t}$	Price of new vehicle engine of technology *te* for use by consumers in period *t*
$PCV^{USED}_{te,v,t}$	Price of used vehicle of technology *te* and vintage *v* for use by consumers in period *t*
$PCT_{h,t}$	Price of consumption of road transports by household *h* in period *t*
$PCT^{OWN}_{h,t}$	Price of consumption of own road transports by household *h* in period *t*
$PCT^{LDV\_NEW}_{h,t}$	Price of consumption of own road transports with new vehicles by household *h* in period *t*
$PCT^{LDV\_NEW}_{te,h,t}$	Price of consumption of own road transports with new vehicles of technology *te* by household *h* in period *t*
$PCT^{LDV\_USED}_{te,v,h,t}$	Price of consumption of own road transports with used vehicles of technology *te* and vintage *v* by household *h* in period *t*

$PC_{h,t}^{TR}$	Price of consumption of (bundles of) transports by household h in period t
$PC_{h,t}^{BLD\_EF}$	Price of consumption of (bundles of) housing-related energy fuel products by household h in period t
$PC_{h,t}^{BLD\_E}$	Price of consumption of (bundles of) housing-related energy products by household h in period t
$PC_{h,t}^{BLD}$	Price of aggregate consumption of (bundles of) housing-related products by household h in period t
$PC_{h,t}^{GDS}$	Price of consumption of (bundles of) goods by household h in period t
$PC_{h,t}^{SER}$	Price of consumption of (bundles of) services by household h in period t
$PC_{h,t}$	Price of aggregate consumption by household h in period t
$PG_{pr,t}$	Price of final consumption product pr used by the government in period t (in market prices)
$PG_{pr,t}^{pp}$	Price of final consumption product pr used by the government in period t in producer prices
PG_{t}^{gds}	Price of the consumption bundle of goods used by the government in period *t*
PG_{t}^{ser}	Price of the consumption bundle of services used by the government in period *t*
PG_{t}^{bld}	Price of the consumption bundle of housing-related products used by the government in period *t*
PG_{t}^{tr}	Price of the consumption bundle of transports used by the government in period *t*
PG_{t}	Price of the aggregate consumption bundle used by the government in period *t*
$PEX_{pr,t}$	Price of export product *pr* in period *t*
$PEX_{pr,t}^{EU}$	Price of export product *pr* from the EU in period *t*
$PEX_{pr,t}^{ROW}$	Price of export product *pr* from the rest of the world in period *t*
$PEX_{pr,t}^{TOT}$	Price of aggregate export product *pr (*from the EU and the rest of the world) in period *t*
PEX_{t}^{NE}	Price of aggregate non-energy products in exports in period *t*
PLA_{t}	Price of inventories in period *t*
$PLA_{pr,t}$	Price of inventory product *pr* in period *t* (in market prices)
$PLA_{pr,t}^{pp}$	Price of inventory product *pr* in period *t* in producer prices
PI_{t}	Price of fixed capital formation in period *t*
$PI_{pr,t}$	Price of fixed capital formation of product *pr* in period *t* (in market prices)
$PI_{pr,t}^{pp}$	Price of fixed capital formation of product *pr* in period *t* in producer prices
PK_{t}	Price of fixed capital (real rate of return) in period *t*
$PL_{h,t}$	Price of hours available for work and leisure of household *h* in period *t*
$PLS_{i,t}$	Price of labour supplied (hours worked) to sector *i* in period *t*
PLS_{t}	Price of labour supplied (hours worked) in period *t*
PFX_{t}	Price of foreign exchange in period *t*

$PRFS_t$	(Shadow) price of renewable fuel standard that is uniform for multiple fuel blends in period *t*
$PRFS\_B_{bl,t}$	(Shadow) price of renewable fuel standard that is specific to fuel blend *bl* in period *t*
$PFFS\_B_{bl,t}$	(Shadow) price of fossil fuel standard that is specific to fuel blend *bl* in period *t*
$PEM^{po}_{bl,pr,t}$	(Shadow) price on emissions of pollutant *po* from the use of product *pr* in blend *bl* in period *t*
$PEM^{po}_{pr,t}$	(Shadow) price on emissions of pollutant *po* from the use of product *pr* in period *t*
$PEM^{po}_{pr,i,t}$	(Shadow) price on emissions of pollutant *po* from the use of product *pr* in sector *i* in period *t*
$PEM^{po}_{i,t}$	(Shadow) price on process emissions of pollutant *po* in sector *i* in period *t*
$PEM^{po}_{fn,h,t}$	(Shadow) price on emissions of pollutant *po* from household *h* using consumption bundle *fn* in period *t*
$PETS_t$	Price of an EU emission allowance under the EU ETS in period *t*
$T^{CO2}_{bl,pr,t}$	Tax rate for CO₂ taxes levied on the use of product *pr* in blend *bl* in period *t*
$T^{CO2}_{pr,t}$	Tax rate for CO₂ taxes levied on the use of product *pr* in period *t*
$T^{CO2}_{TR,t}$	Tax rate for additional CO₂ taxes needed to reach interim reduction target on CO₂ emissions from domestic transports in period *t*
T^{GHG}_{t}	Tax rate for the additional GHG tax needed to reach the reduction target for GHG emissions in period *t*
$T^{E}_{pr,t}$	Tax rate for energy taxes levied on the use of product *pr* in period *t*
T^{EI}_{t}	Tax rate for energy taxes needed to achieve the energy intensity target in period *t*
T^{FLYG}_{t}	Tax rate for aviation taxes in period *t*
$T^{MALUS}_{te,i,t}$	Tax rate for malus taxes on vehicles of technology *te* in sector *i* in period *t*
$T^{MALUS}_{te,h,t}$	Tax rate for malus taxes on vehicles of technology *te* for household *h* in period *t*
$T^{OTH}_{pr,t}$	Tax rates for other excise taxes levied on the use of product *pr* in period *t*
$S^{free}_{ETS,i,t}$	Subsidy rates of EU emission allowances being allocated for free to firms in sector *i* in period *t*
$PU_{h,t}$	Price of utility of household *h* in period *t*
$PBU_{h,t}$	Price of household *h's* budget in period *t*

Table B.3 Variables determined by income balances

Symbol	Description
$INC^{H}_{h,t}$	Net income of household *h* in period *t*
INC^{G}_{t}	Net income of the government (transferred to households) in period *t*
$INC^{F}_{ETS,i,t}$	Income of firms in sector *i* from EU emission allowances allocated for free under the EU ETS in period *t*
$INC^{VA}_{i,t}$	Value of the price and quantity adjustments of value added in sector *i* in period *t*
$YV^{USED}_{te,v,t}$	Value of used vehicles of technology *te* and vintage *v* available to producers in period *t*

$CV^{USED}_{te,v,t}$	Value of used vehicles of technology *te* and vintage *v* available to consumers in period *t*

Table B.4 Variables determined by auxiliary conditions

Symbol	Description
$P^{ADJ}_{pr,t}$	Price adjustment for product *pr* in period *t* in line with rents earned
$P^{ADJ}_{VA,i,t}$	Price adjustment for value added in sector *i* in period *t* in line with targeted total factor productivity increases
$VA^{ADJ}_{i,t}$	Quantity adjustment for value added in sector *i* in period *t* in line with targeted total factor productivity increases
SAV^{ADJ}_{t}	Adjustment in aggregate household savings used to target the investment level in period *t*
BOP_{t}	Trade balance in period *t*
GDP_{t}	Gross domestic product (in constant prices) in period *t*
$IM^{auct}_{ETS,t}$	Net imports of EU emission allowances auctioned under the EU ETS in period *t*
$EM^{auct}_{ETS,t}$	EU emission allowances auctioned under the EU ETS in period *t*
$EM^{TCO2}_{bl,pr,t}$	CO_2 emissions from using product *pr* in blend *bl* subject to CO_2 taxes in period *t*
$EM^{TCO2}_{pr,t}$	CO_2 emissions from using product *pr* subject to CO_2 taxes in period *t*
$EM^{TCO2}_{TR,t}$	Aggregate of emissions that are subject to the additional CO_2 tax levied to reach reduction targets for CO_2 emissions from domestic transports in period *t*
EM^{TGHG}_{t}	Aggregate of emissions that are subject to the additional GHG tax levied to reach reduction targets for GHG emissions in period *t*
$REV^{TE}_{pr,t}$	Revenue from energy taxes levied on the use of energy product *pr* in period *t*
REV^{TEI}_{t}	Revenue from additional energy taxes levied on the use of energy products in period *t*
$REV^{MALUS}_{te,i,t}$	Revenue from malus taxes on vehicles of technology *te* in sector *i* in period *t*
$REV^{MALUS}_{te,h,t}$	Revenue from malus taxes on vehicles of technology *te* for household *h* in period *t*
REV^{TFLYG}_{t}	Revenue from aviation taxes in period *t*
$REV^{TOTH}_{pr,t}$	Revenue from other excise taxes levied on the use of product *pr* in period *t*
$EX^{SE}_{EUESR,t}$	Net exports of national allocations under the EU ESR in period *t*
$S^{E}_{bl,i,t}$	Rate of rebates from energy taxes levied on fuel blend *bl* in sector *i* in period *t*
$S^{CO2}_{bl,i,t}$	Rate of rebates from CO_2 taxes levied on fuel blend *bl* in sector *i* in period *t*
T^{LS}_{t}	Rate of social security contributions in period *t*
$SH^{TR}_{bl,t}$	Share of fuel blends *bl* used in road transports in period *t*

Appendix C: Model parameters

Table C.1A Substitution elasticity parameters in production

Symbol	Value	Description
ω_i	0.1	Elasticity of transformation between products as outputs of production in sector *i*
σ_i^{EM}	0.1	Elasticity of substitution between the nest of process emissions and the nest of fixed capital, labour, energy and other intermediate inputs in sector *i*
σ_i^{KLEM}	See Table C.1B	Elasticity of substitution between the nest of fixed capital, labour and energy inputs and the nest of other intermediate inputs in sector *i*
σ_i^{KLE}	See Table C.1B	Elasticity of substitution between the nest of fixed capital and labour and the nest of energy inputs in sector *i*
σ_i^{KL}	See Table C.1B	Elasticity of substitution between fixed capital and labour in sector *i*
σ_i^{E}	See Table C.1B	Elasticity of substitution between electricity, district heating and the nest of fuel energy inputs in sector *i*
σ_i^{F}	See Table C.1B	Elasticity of substitution between the nest of solid-fuel energy inputs and the nest of liquid-fuel energy inputs in sector *i*
σ_i^{SF}	See Table C.1B	Elasticity of substitution between solid-fuel energy inputs in sector *i*
σ_i^{LF}	See Table C.1B	Elasticity of substitution between liquid-fuel energy inputs in sector *i*
σ_i^{M}	0.1	Elasticity of substitution between material intermediate inputs and transports in sector *i*
σ_i^{MAT}	0.1	Elasticity of substitution between material intermediate inputs in sector *i*
σ_i^{TR}	See Table C.1B	Elasticity of substitution between types of transports (road, air, sea etc) in sector *i*
σ_i^{TRL}	0.5	Elasticity of substitution between purchased and own cargo road transports in sector *i*
$\sigma_i^{TRL\_OWN}$	0.2	Elasticity of substitution between own cargo road transports with new and used heavy-duty vehicles in sector *i*
$\sigma_i^{TRL\_NEW}$	4.0	Elasticity of substitution between own cargo road transports with new heavy-duty vehicles of technology *te* in sector *i*
σ_i^{TRP}	0.5	Elasticity of substitution between purchased and own person road transports in sector *i*
$\sigma_i^{TRP\_OWN}$	0.2	Elasticity of substitution between own person road transports with new and used light-duty vehicles in sector *i*
$\sigma_i^{TRP\_NEW}$	4.0	Elasticity of substitution between own person road transports with new light-duty vehicles of technology *te* in sector *i*
$\sigma_{YTN,i}^{FE}$	0.2	Elasticity of substitution between fuel and engine costs in the cost of using vehicles for own road transports in sector *i*
$\sigma_{te,i}^{YF}$	See Table C.2	Elasticity of substitution between fuel blends when used with technology *te* in sector *i*

Table C.1B Substitution elasticity parameters in production ctd.

Production sector	σ^{KLEM}	σ^{KLE}	σ^{KL}	σ^{E}	σ^{F}	σ^{LF}	σ^{SF}	σ^{TR}
JORD	0.2	0.5	0.5	0.5	0.7	0.7	0.7	0.1
SKOG	0.2	0.5	0.5	0.5	0.7	0.7	0.7	0.1
GRUV	0.2	0.5	0.3	0.5	0.6	0.8	0.9	0.1
LIVS	0.2	0.5	0.7	0.5	0.7	0.7	0.7	0.2
TRAV	0.2	0.5	0.7	0.5	0.7	0.7	0.7	0.2
MASSA	0.2	0.5	0.3	0.5	0.5	0.7	0.7	0.1
RAFF	0.1	0.1	0.3	0.4	0.4	0.7	0.7	0.1
RAFF_BIO	0.1	0.1	0.3	0.4	0.4	0.7	0.7	0.1
KEMI	0.2	0.5	0.3	0.5	0.5	0.7	0.7	0.1
GUMMI	0.2	0.5	0.3	0.5	0.5	0.7	0.7	0.1
JSTEN	0.2	0.5	0.3	0.5	0.7	0.7	0.7	0.1
JSTAL	0.2	0.5	0.3	0.5	0.5	0.7	0.7	0.1
METALL	0.2	0.5	0.3	0.5	0.5	0.7	0.7	0.1
METLTILL	0.2	0.5	0.7	0.6	0.6	0.7	0.7	0.3
VERKTILL	0.2	0.5	0.7	0.6	0.6	0.7	0.7	0.3
FORDTILL	0.2	0.5	0.7	0.6	0.6	0.7	0.7	0.3
ANTILL	0.2	0.5	0.7	0.6	0.6	0.7	0.7	0.3
EL	0.2	0.5	0.3	0.3	0.3	0.8	0.9	0.1
GAS	0.2	0.1	0.3	0.2	0.2	0.2	0.2	0.1
FJ	0.2	0.5	0.3	0.3	0.3	0.8	0.9	0.1
VAAVFL	0.2	0.5	0.3	0.4	0.4	0.7	0.7	0.1
BYGG	0.2	0.4	0.5	0.5	0.5	0.7	0.7	0.1
HAND	0.2	0.3	0.5	0.6	0.6	0.7	0.8	0.2
JVAG	0.2	0.4	0.3	0.3	0.3	0.2	0.2	0.1
PASSTP	0.2	0.4	0.3	0.3	0.3	0.2	0.2	0.1
LASTBTP	0.2	0.4	0.3	0.3	0.3	0.2	0.2	0.1
SJOTP	0.2	0.4	0.3	0.2	0.2	0.2	0.2	0.1
LUFTTP	0.2	0.4	0.3	0.2	0.2	0.2	0.2	0.1
OTHERTP	0.2	0.3	0.5	0.6	0.6	0.7	0.7	0.2
HHTJ	0.2	0.3	0.3	0.6	0.6	0.7	0.8	0.2
KOMU	0.2	0.3	0.3	0.6	0.6	0.7	0.8	0.2
BANK	0.2	0.3	0.5	0.6	0.6	0.7	0.8	0.2
BOST	0.2	0.3	0.3	0.6	0.6	0.7	0.8	0.1
FTTJ	0.2	0.3	0.3	0.6	0.6	0.7	0.8	0.2
GOV	0.2	0.3	0.3	0.6	0.6	0.7	0.8	0.1

Note: See Table A.2 for production sector definitions

Table C.2 Substitution elasticity parameters in fuel choice

Technology	σ^{YF}, σ^{CF}
Machines with diesel engine (M_DIESEL)	-
Machines with petrol engine (M_BENSIN)	-
Heavy-duty vehicles with diesel engine (HDV_DIESEL)	4.0
Light-duty vehicles with petrol engine (LDV_BENSIN_LO, LDV_BENSIN_HI)	-
Light-duty vehicles with petrol engine that can run on E85 blend (LDV_ETANOL_LO, LDV_ETANOL_HI)	-
Light-duty vehicles with diesel engine (LDV_DIESEL_LO, LDV_DIESEL_HI)	-
Light-duty vehicles with hybrid petrol and electric engine (LDV_PHEV)	4.0
Light-duty vehicles with electric engine (LDV_EV)	-

Note: No parameter value means that only a single fuel blend is used by the technology.

Table C.3A Substitution elasticity parameters in imports and exports

Symbol	Value	Description
σ^{A}_{pr}	See Table C.3B	Elasticity of substitution between imported and domestic products pr (Armington assumption)
σ^{IM}_{pr}	See Table C.3B	Elasticity of substitution between EU and ROW import product *pr* in aggregate imports of product *pr*
σ^{EX}_{pr}	See Table C.3B	Elasticity of substitution between EU and ROW export product *pr* in aggregate exports of product *pr*
σ^{E}_{EX}	0.5	Elasticity of substitution between energy products and the nest of non-energy products in exports
σ^{NE}_{EX}	2.0	Elasticity of substitution between products in the nest of non-energy products in exports

Table C.3B Substitution elasticity parameters in imports and exports ctd.

Product	σ^{A}	σ^{IM}	σ^{EX}
JORD	2.9	5.8	5.8
SKOG	2.9	5.8	5.8
BIO	2.9	5.8	5.8
KOL	3.1	6.2	6.2
RAOLJA	5.2	10.4	10.4
GAS	0.1	0.2	0.2
GRUV	3.0	6.0	6.0
LIVS	3.2	6.4	6.4
TRAV	3.0	6.0	6.0
MASSA	3.0	6.0	6.0
PETRO	2.1	4.2	4.2
TORV	2.9	5.8	5.8
BENSIN	2.1	4.2	4.2
DIESEL	2.1	4.2	4.2
BIODIESEL	3.0	6.0	6.0
BRANS	2.1	4.2	4.2
KEMI	3.3	6.6	6.6
ETANOL	3.0	6.0	6.0
GUMMI	3.3	6.6	6.6
JSTEN	1.9	3.8	3.8
JSTAL	3.0	6.0	6.0
METALL	4.0	8.0	8.0
METLTILL	3.9	7.8	7.8
VERKTILL	4.1	8.2	8.2
FORDTILL	3.6	7.2	7.2
ANTILL	3.6	7.2	7.2
EL	2.8	5.6	5.6
FJ	0.1	0.2	0.2
VA	0.1	0.2	0.2
AVFL	0.1	0.2	0.2
BYGG	0.1	0.2	0.2
HAND	0.9	1.8	1.8
JVAG	0.9	1.8	1.8
PASSTP	0.9	1.8	1.8
LASTBTP	0.9	1.8	1.8
SJOTP	1.9	3.8	3.8
LUFTTP	1.9	3.8	3.8
OTHERTP	0.9	1.8	1.8
HHTJ	1.9	3.8	3.8
KOMU	2.0	4.0	4.0
BANK	0.9	1.8	1.8
BOST	0.1	0.2	0.2
FTTJ	2.0	4.0	4.0

Note: We assume twice the value of the Armington substitution elasticities for the substitution elasticities between EU and Rest of World import products. See Table A.3 for product definitions.

Table C.4 Substitution elasticity parameters in government consumption of final consumption products

Symbol	Value	Description
σ^{G}	0.2	Elasticity of substitution between consumption bundles in the aggregate consumption bundle of the government
σ^{GDS}_{G}	0.2	Elasticity of substitution between goods products in the goods bundle of final consumption by the government
σ^{SER}_{G}	0.2	Elasticity of substitution between service products in the services bundle of final consumption by the government
σ^{BLD}_{G}	0.2	Elasticity of substitution between housing-related products in the housing bundle of final consumption by the government
σ^{TR}_{G}	0.5	Elasticity of substitution between transport products in the transports bundle of final consumption of the government

Table C.5A Substitution elasticity parameters in household utility and consumption

Symbol	Value	Description
σ^{U}_{h}	See Table C.5B	Elasticity of substitution between leisure hours and aggregate consumption in utility of household *h*
σ^{C}_{h}	0.5	Elasticity of substitution between consumption bundles in aggregate consumption of household *h*
$\sigma^{GDS}_{C,h}$	0.9	Elasticity of substitution between consumption bundles in the goods bundle of household *h*
$\sigma^{SER}_{C,h}$	0.9	Elasticity of substitution between consumption bundles in the services bundle of household *h*
$\sigma^{BLD}_{C,h}$	0.1	Elasticity of substitution between non-energy and energy bundles in the housing bundle of household *h*
$\sigma^{BLD\_E}_{C,h}$	0.3	Elasticity of substitution between non-fuels and fuels bundles in the energy-in-housing bundle of household *h*
$\sigma^{BLD\_EF}_{C,h}$	0.5	Elasticity of substitution between fuel bundles in the fuels-in-housing bundle of household *h*
$\sigma^{TR}_{C,h}$	0.5	Elasticity of substitution between consumption bundles in the transports bundle of household *h*
σ^{CT}_{h}	0.5	Elasticity of substitution between purchased and own road transports in the road transports bundle of household *h*
$\sigma^{OWN}_{CT,h}$	0.2	Elasticity of substitution between own road transports with used and new vehicles in the own road transports bundle of household *h*
$\sigma^{NEW}_{CT,OWN,h}$	4.0	Elasticity of substitution between own road transports with new vehicle technologies in the own road transports with new vehicles bundle of household *h*
$\sigma^{FE}_{CT,NEW,h}$	0.2	Elasticity of substitution between fuel and engine inputs in the own road transports with new vehicle technologies bundle of household *h*
σ^{C}_{fn}	See Table C.5C	Elasticity of substitution between final consumption products in consumption bundle *fn* of the households
σ^{CF}_{te}	See Table C.2	Elasticity of substitution between fuel blends when used with technology *te* by households

Table C.5B Substitution elasticity parameters in household utility

Households	σ^{U}
Large urban area, low income	1.2
Large urban area, high income	1.8
Smaller urban area , low income	1.7
Smaller urban area , high income	1.9
Rural area, low income	1.8
Rural area, high income	2.0

Table C.5C Substitution elasticity parameters in household consumption bundles

Consumption bundles	σ_{FN}
Food and beverages	0.1
Clothing & Footwear	0.1
Actual and imputed rents for housing	0.1
Electricity	-
Gas	-
Liquid fuels	0.1
Biofuels	0.1
Heat energy	0.1
Furniture and furnishings, and household textiles	0.1
Household appliances and tools	0.3
Purchase and operation of vehicles	0.1
Fuels and lubricants for personal vehicles	0.1
Maintenance of vehicles	0.1
Passenger transport by railway	-
Passenger transport by road	0.3
Passenger transport by air & package holidays	0.1
Passenger transport by sea	0.1
Recreational items, equipment and services	0.5
Other services	0.5
Other goods	0.5

Note: No parameter value means that the consumption bundle contains only a single final consumption product. See Table A.6 for consumption bundle classifications.

Table C.6 Benchmark value parameters used to calibrate the model to the National Accounts

Symbol	Description
v	Benchmark values (in constant prices)
θ	Benchmark value shares

Table C.7 Endowment parameters

Symbol	Description
$l_{h,t}$	Hours available for work and leisure of household *h* in period *t*
$k_{h,t}$	Supply of fixed capital by household *h* in period *t*
la_t	Non-fixed capital demand (inventories) in period *t*
g_t	Final consumption by the government in period *t*
$ct_{h,t}$	Non-discretionary consumption of road transports by household *h* in period *t*

Table C.8 Policy parameters

Symbol	Description
$\tau_{i,t}^{K}$	capital tax rate in sector *i* in period *t*
τ_{t}^{LS}	Rate of social security contributions in period *t*
$\tau_{h,t}^{L}$	Labour income tax rate for household *h* in period *t*
$\tau_{pr,t}^{IM}$	Import tarfiff rate for product *pr* in period *t*
$\tau_{M,pr,i,t}^{VA}$	Value added tax rate for product *pr* used to meet intermediate demand in sector *i* in period *t*
$\tau_{d,pr,t}^{VA}$	Value added tax rate for product *pr* used to meet final demand d in period *t*
$\tau_{BM,bl,i,t}^{VA}$	Value added tax rate for fuel blend *bl* used as intermediate input in sector *i* in period *t*
$\tau_{BC,bl,t}^{VA}$	Value added tax rate for fuel blend *bl* used for final consumption by households in period *t*
τ_{t}^{FLYG}	Target rate for aviation taxes in period *t*
$\tau_{te,i,t}^{MALUS}$	Target rate for malus taxes of technology *te* in sector *i* in period *t*
$\tau_{te,h,t}^{MALUS}$	Target rate for malus taxes of technology *te* for household *h* in period *t*
$s_{te,i,t}^{BONUS}$	Subsidy rate for bonusses on new vehicles of technology *te* in sector *i* in period *t*
$s_{te,h,t}^{BONUS}$	Subsidy rate for bonusses on new vehicles of technology *te* for household *h* in period *t*
$\tau_{pr,t}^{E}$	Target rate for energy taxes levied on energy product *pr* in period *t*
$s_{pr,i,t}^{E}$	Target rate for rebates from energy taxes levied on energy product *pr* in sector *i* in period *t*
$\tau_{bl,pr,t}^{CO2}$	Target rate for CO_2 taxes levied on product *pr* in blend *bl* in period *t*
$\tau_{pr,t}^{CO2}$	Target rate for CO_2 taxes levied on product *pr* in period *t*
$s_{pr,i,t}^{CO2}$	Target rate for rebates from CO_2 taxes levied on energy product *pr* in sector *i* in period *t*
$\tau_{pr,t}^{OTH}$	Target rate for other excise taxes levied on product *pr* in period *t*
$s_{i,t}^{industriklivet}$	Subsidy rate for industriklivet in sector *i* in period *t*
$s_{i,t}^{klimatklivet}$	Subsidy rate for klimatklivet in sector *i* in period *t*

ρ_t^{ETS}	Target price of an EU emission allowance under the EU ETS in period *t*
ρ_t^{ESR}	Target price of an emission allowance under the EU ESR in period *t*
ρ_t^{FLEX}	Target price of an emission allowance under other flexible mechanisms in period *t*

$emsh_{po,bl,pr,t}^{TCO2}$	Share of emissions of pollutant *po* associated with the use of product *pr* in blend *bl* in period *t* that is subject to the CO_2 tax
$emsh_{po,pr,t}^{TCO2}$	Share of emissions of pollutant *po* associated with the use of product *pr* in period *t* that is subject to the CO_2 tax
$emsh_{po,pr,i,t}^{TCO2}$	Share of emissions of pollutant *po* associated with the use of product *pr* in sector *i* in period *t* that is subject to the CO_2 tax
$emsh_{TR,po,bl,pr,t}^{TCO2}$	Share of emissions of pollutant *po* associated with the use of product *pr* in blend *bl* in period *t* that is subject to the additional CO_2 tax levied to reach interim targets on GHG emission reductions from domestic transports
$emsh_{TR,po,pr,i,t}^{TCO2}$	Share of emissions of pollutant *po* associated with the use of product *pr* in sector *i* in period *t* that is subject to the additional CO_2 tax levied to reach interim targets on GHG emission reduction from domestic transports
$emsh_{po,bl,pr,t}^{GHG}$	Share of emissions of pollutant *po* associated with the use of product *pr* in blend *bl* in period *t* that is subject to the GHG emission reduction target
$emsh_{po,pr,i,t}^{GHG}$	Share of emissions of pollutant *po* associated with the use of product *pr* in sector *i* in period *t* that is subject to the GHG emission reduction target
$emsh_{po,i,t}^{GHG}$	Share of process emissions of pollutant *po* in sector *i* in period *t* that is subject to the GHG emission reduction target
$emsh_{po,pr,t}^{GHG}$	Share of emissions of pollutant *po* associated with the use of product *pr* in period *t* that is subject to the GHG emission reduction target
$emsh_{po,fn,h,t}^{GHG}$	Share of emissions of pollutant *po* associated with the use of consumption bundle *fn* by household *h* in period *t* that is subject to the GHG emission reduction target
$emsh_{po,bl,pr,t}^{TGHG}$	Share of emissions of pollutant *po* associated with the use of product *pr* in blend *bl* in period *t* that is subject to the additional GHG tax levied to reach reduction targets on GHG emissions
$emsh_{po,pr,i,t}^{TGHG}$	Share of emissions of pollutant *po* associated with the use of product *pr* in sector *i* in period *t* that is subject to the additional GHG tax levied to reach reduction targets on GHG emissions
$emsh_{po,i,t}^{TGHG}$	Share of process emissions of pollutant *po* in sector *i* in period *t* that is subject to the additional GHG tax levied to reach reduction targets on GHG emissions
$emsh_{po,pr,t}^{TGHG}$	Share of emissions of pollutant *po* associated with the use of product *pr* in period *t* that is subject to the additional GHG tax levied to reach reduction targets on GHG emissions
$emsh_{po,fn,h,t}^{TGHG}$	Share of emissions of pollutant *po* associated with the use of consumption bundle *fn* by household *h* in period *t* that is subject to the additional GHG tax levied to reach reduction targets on GHG emissions
$emsh_{po,pr,i,t}^{ETS}$	Share of emissions of pollutant *po* associated with the use of product *pr* in sector *i* in period *t* that is subject to the EU ETS
$emsh_{po,i,t}^{ETS}$	Share of process emissions of pollutant *po* in sector *i* in period *t* that is subject to the EU ETS
$emsh_{po,bl,pr,t}^{ESR}$	Share of emissions of pollutant *po* associated with the use of product *pr* in blend *bl* in period *t* that is subject to the EU ESR
$emsh_{po,pr,i,t}^{ESR}$	Share of emissions of pollutant *po* associated with the use of product *pr* in sector *i* in period *t* that is subject to the EU ESR
$emsh_{po,i,t}^{ESR}$	Share of process emissions of pollutant *po* in sector *i* in period *t* that is subject to the EU ESR
$emsh_{po,pr,t}^{ESR}$	Share of emissions of pollutant *po* associated with the use of product *pr* in period *t* that is subject to the EU ESR
$emsh_{po,fn,h,t}^{ESR}$	Share of emissions of pollutant *po* associated with the use of consumption bundle *fn* by household *h* in period *t* that is subject to the EU ESR
$rfs_{bl,t}$	Renewable fuel standard (fraction between 0 and 1) on the use of liquid fuel products in fuel blend *bl* in period *t* and where the fuel standard is uniform between multiple blends
$rfs\_b_{bl,t}$	Renewable fuel standard (fraction between 0 and 1) on the use of liquid fuel products in fuel blend *bl* in period *t* and where the fuel standard is specific to the blend
$ffs\_b_{bl,t}$	Fossil fuel norm (fraction between 0 and 1) on the use of liquid fuel products in fuel blend *bl* in period *t* and where the fuel norm is specific to the blend

$fl_{bl,pr,t}^{RFS}$	Flag (binary parameter taking on value 0 or 1) rewarding the use of liquid bio fuel product *pr* in fuel blend *bl* in period *t* with the uniform renewable fuel norm or not
$fl_{bl,pr,t}^{RFS\_B}$	Flag (binary parameter taking on value 0 or 1) rewarding the use of liquid bio fuel product *pr* in fuel blend *bl* in period *t* with a specific renewable fuel norm or not
$fl_{bl,pr,t}^{FFS\_B}$	Flag (binary parameter taking on value 0 or 1) rewarding the use of liquid fossil fuel product *pr* in fuel blend *bl* in period *t* with a specific fossil fuel norm or not
$rev_{TAX,t}^{SE}$	Domestic tax revenue target in period *t*
$rev_{EUETS,t}^{SE}$	Revenue accruing to Sweden from auctioning under the EU ETS in period *t*
$rev_{EUETS,t}^{EU}$	Revenue accruing to the EU from auctioning under the EU ETS in period *t*
$em_{ETS,i,t}^{free}$	EU emission allowances under the EU ETS allocated for free whose value accrues to the income balance of firms in sector *i* in period *t*
$em_{ETS,h,t}^{free}$	EU emission allowances under the EU ETS allocated for free whose value accrues to the income balance of household *h* (as ultimate owner of the firms) in period *t*
$em_{EUESR,t}^{SE}$	Sweden's emission allocation under the EU ESR in period *t*
$em_{FLEX,t}^{SE}$	Number of emission allowances that Sweden can trade internationally under flexible mechanisms in period *t*
$cap_{TR,t}^{GHG}$	Reduction target (cap) for greenhouse gas emissions from domestic transports in period *t*
cap_{t}^{GHG}	Reduction target (cap) for greenhouse gas emissions in period *t*
ei_{t}^{target}	Energy intensity target in period *t*

Table C.9 Other parameters used to govern changes between time periods

Symbol	Description
δ^{K}	Annual depreciation rate of fixed capital
r	Annual rate of fixed-capital financing cost
$stock_{t}^{K}$	Stock of fixed capital in period *t*
$gr_{h,t}^{L}$	Growth rate of the hours available for work and leisure of household *h* in period *t*
gr_{t}^{LA}	Growth rate of inventories in period *t*
gr_{t}^{g}	Growth rate of final consumption by the government in period *t*
$gr_{i,t}^{EM_{ETS}^{free}}$	Growth rate of the endowment of EU emission allowances allocated for free in sector *i* period *t*
$lprod_{i,t}^{target}$	Targeted labour productivity increase in sector *i* in period *t*
$\pi_{i,t}^{VA}$	Total factor productivity increase in sector *i* in period *t*
$\pi_{i,t}^{K}$	Capital-augmenting technical change in sector *i* in period *t*
$\pi_{i,t}^{LS}$	Labour-augmenting technical change in sector *i* in period *t*
$\pi_{te,t}^{BAT}$	Efficiency increase of using batteries of technology *te* in period *t*
$\pi_{pr,i,t}^{E}$	Energy efficiency increase of using energy product *pr* in sector *i* in period *t*
$\pi_{pr,fn,t}^{E}$	Energy efficiency increase of using energy product *pr* in consumption bundle *fn* in period *t*

$\pi^{E}_{te,t}$	Energy efficiency increase for vehicle technology *te* in period *t*
$\rho_{pr,t}$	Target price index for product *pr* in period *t*
ρ^{FX}_{t}	Target price index for foreign exchange in period *t*
$\rho^{EU}_{pr,t}$	Market price index for product *pr* from the EU in period *t*
$\rho^{ROW}_{pr,t}$	Market price index for product *pr* from the rest of world in period *t*
$q^{EU}_{pr,t}$	Market demand index for product *pr* from the EU in period *t*
$q^{ROW}_{pr,t}$	Market demand index for product *pr* from the rest of the world in period *t*
$netexport^{target}_{t}$	Target level for net exports in period *t*
inv^{target}_{t}	Target level for investments (summed over products) in period *t*
gdp^{target}_{t}	Target level for gross domestic product (in constant prices) in period *t*
$fl^{YF}_{te,t}$	Flag (binary parameter taking on value 0 or 1) governing whether different fuel blends are perfect substitutes or imperfect substitutes to each other when used with technology *te* for own road transports in period *t*
$fl^{CF}_{te,t}$	Flag (binary parameter taking on value 0 or 1) governing whether different fuel blends are perfect substitutes or imperfect substitutes to each other when used with technology *te* for own road transports in period *t*
$fl^{vt}_{v,t}$	Flag (binary parameter taking on value 0 or 1) governing which used vehicles of annual vintage *vt* match to aggregate vintage *v* in period *t*
δ^{DV}	Annual depreciation rate for duty vehicles
$scrap_{te,i}$	Number of years after which a used vehicle of technology *te* is being scrapped by firms in sector *i*
$scrap_{te,h}$	Number of years after which a used vehicle of technology *te* is being scrapped by household *h*
$stock^{CHS}_{te,v,i,t}$	Stock of used vehicle chassis of technology *te* and vintage v used by firms in sector *i* in period *t* (in constant prices)
$stock^{CHS}_{te,v,h,t}$	Stock of used vehicle chassis of technology *te* and vintage v used by household *h* in period *t* (in constant prices)
$cost^{EX}_{te,v,t}$	Transaction cost incurred by households when exporting used vehicles of technology *te* and vintage *v* in period *t*
ef^{MWh}_{pr}	Energy factor converting benchmark values of energy use of product *pr* into its energy content in MWh in the benchmark
cpi_{t}	Index of relative price changes for consumer products in period *t* (in market prices)

Appendix D: Model equations

This appendix provides the algebraic specification of the model. In this specification, the orthogonality symbol $\perp$ points to the unknown variable being determined by the condition and the notation Π^{z} denotes the zero-profit condition for activity z. Sections D.1 through D.3. list the zero-profit conditions, market-clearing conditions and income balance condition holding in any given time period. Sections D.4 lists any additional or auxiliary conditions that may be required to hold in any given time period. Section D.5. lists the conditions holding between any two time periods.

D.1. Zero-profit (Z) conditions

Firms producing products:

$$\begin{aligned}
\Pi_{i,t}^{Y} \equiv\ & v_{i,t}^{Y}\left(\theta_{i,t}^{KLEM}\cdot {P_{i,t}^{KLEM}}^{1-\sigma_i^{EM}} + \theta_{i,t}^{EM}\cdot {P_{i,t}^{EM}}^{1-\sigma_i^{EM}}\right)^{\frac{1}{1-\sigma_i^{EM}}} \qquad \perp Y_{i,t} \qquad \begin{matrix} i\in I \\ t\in T \end{matrix} \qquad \text{(Z.01)}\\
& - v_i^{Y}\left(\begin{matrix} \theta_i^{S} S_{ETS,i,t}^{free} \\ +\left(1-\theta_i^{S}\right)\left(\begin{matrix} \sum_{pr}\theta_{pr,i}^{EA} {P_{pr,t}^{EA}}^{1+\omega_i} \\ +\sum_{pr}\theta_{pr,i}^{Y}\left(\left(1-P_{pr,t}^{ADJ}\right)P_{pr,t}\right)^{1+\omega_i}\end{matrix}\right)^{\frac{1}{1+\omega_i}}\end{matrix}\right) \\
& \geq 0
\end{aligned}$$

where:

$$P_{i,t}^{EM} \leq \sum_{po}\theta_{EM,i}^{po}\frac{PEM_{i,t}^{po}}{PEM_{i0}^{po}}$$

$$P_{i,t}^{KLEM} \leq \left(\theta_{KLEM,i,t}^{KLE}\, {P_{i,t}^{KLE}}^{1-\sigma_i^{KLEM}} + \theta_{KLEM,i,t}^{M}\, {P_{i,t}^{M}}^{1-\sigma_i^{KLEM}}\right)^{\frac{1}{1-\sigma_i^{KLEM}}}$$

$$P_{i,t}^{KLE} \leq \left(\theta_{KLE,i,t}^{KL}\, {PVA_{i,t}}^{1-\sigma_i^{KLE}} + \theta_{KLE,i,t}^{E}\, {P_{i,t}^{E}}^{1-\sigma_i^{KLE}}\right)^{\frac{1}{1-\sigma_i^{KLE}}}$$

$$P_{i,t}^{E} \leq \left(\sum_{pr}\theta_{E,i,t}^{pr}\, {PM_{pr,i,t}}^{1-\sigma_i^{E}} + \theta_{E,i,t}^{F}\, {P_{i,t}^{F}}^{1-\sigma_i^{E}}\right)^{\frac{1}{1-\sigma_i^{E}}}$$

$$P_{i,t}^{F} \leq \left(\theta_{F,i,t}^{SF} {P_{i,t}^{SF}}^{1-\sigma_i^{F}} + \theta_{F,i,t}^{LF} {P_{i,t}^{LF}}^{1-\sigma_i^{F}}\right)^{\frac{1}{1-\sigma_i^{F}}}$$

$$P_{i,t}^{SF} \leq \left(\sum_{pr} \theta_{SF,pr,i}^{M} {PM_{pr,i,t}}^{1-\sigma_i^{SF}} \right)^{\frac{1}{1-\sigma_i^{SF}}}$$

$$P_{i,t}^{LF} \leq \left(\sum_{pr} \theta_{LF,pr,i}^{M} {PM_{pr,i,t}}^{1-\sigma_i^{LF}} + \sum_{te \in TE\_M} \theta_{LF,te,pr,i}^{F} {PF_{te,i,t}}^{1-\sigma_i^{LF}} \right)^{\frac{1}{1-\sigma_i^{LF}}}$$

$$P_{i,t}^{M} \leq \left(\theta_{M,i,t}^{MAT} {P_{i,t}^{MAT}}^{1-\sigma_i^{M}} + \theta_{M,i,t}^{TR} {P_{i,t}^{TR}}^{1-\sigma_i^{M}} \right)^{\frac{1}{1-\sigma_i^{M}}}$$

$$P_{i,t}^{MAT} \leq \left(\sum_{pr} \theta_{MAT,i}^{pr} {PM_{pr,i,t}}^{1-\sigma_i^{MAT}} \right)^{\frac{1}{1-\sigma_i^{MAT}}}$$

$$P_{i,t}^{TR} \leq \left(\sum_{pr} \theta_{TR,i,t}^{pr} {PM_{pr,i,t}}^{1-\sigma_i^{TR}} + \theta_{TR,i,t}^{TRL} {P_{i,t}^{TRL}}^{1-\sigma_i^{TR}} + \theta_{TR,i,t}^{TRP} {P_{i,t}^{TRP}}^{1-\sigma_i^{TR}} \right)^{\frac{1}{1-\sigma_i^{TR}}}$$

$$P_{i,t}^{TRL} \leq \left(\sum_{\text{lastbtp} \in PR} \theta_{TRL,i,t}^{PUR} {PM_{pr,i,t}}^{1-\sigma_i^{TRL}} + \theta_{TRL,i,t}^{OWN} {P_{i,t}^{TRL\_OWN}}^{1-\sigma_i^{TRL}} \right)^{\frac{1}{1-\sigma_i^{TRL}}}$$

$$P_{i,t}^{TRL\_OWN} \leq \left(\theta_{TRL\_OWN,i,t}^{NEW} {P_{i,t}^{TRL\_NEW}}^{1-\sigma_i^{TRL\_OWN}} + \sum_{te,v} \theta_{TRL\_OWN,te,v,i,t}^{USED} {PTU_{te,v,i,t}}^{1-\sigma_i^{TRL\_OWN}} \right)^{\frac{1}{1-\sigma_i^{TRL\_OWN}}}$$

$$P_{i,t}^{TRL\_NEW} \leq \left(\sum_{te} \theta_{TRL\_NEW,i}^{te} {PTN_{te,i,t}}^{1-\sigma_i^{TRL\_NEW}} \right)^{\frac{1}{1-\sigma_i^{TRL\_NEW}}}$$

$$P_{i,t}^{TRP} \leq \left(\sum_{\text{passtp} \in PR} \theta_{TRP,i,t}^{PUR} {PM_{pr,i,t}}^{1-\sigma_i^{TRP}} + \theta_{TRP,i,t}^{OWN} {P_{i,t}^{TRP\_OWN}}^{1-\sigma_i^{TRP}} \right)^{\frac{1}{1-\sigma_i^{TRP}}}$$

$$P_{i,t}^{TRP\_OWN} \leq \left(\begin{array}{c} \theta_{TRP\_OWN,i,t}^{NEW} {P_{i,t}^{TRP\_NEW}}^{1-\sigma_i^{TRP\_OWN}} \\ + \sum_{te \in TE\_DV} \sum_{v} \theta_{TRP\_OWN,te,v,i,t}^{USED} {PTU_{te,v,i,t}}^{1-\sigma_i^{TRP\_OWN}} \end{array} \right)^{\frac{1}{1-\sigma_i^{TRP\_OWN}}}$$

$$P_{i,t}^{TRP\_NEW} \leq \left(\sum_{te \in TE\_DV} \theta_{TRP\_NEW,i,t}^{te} {PTN_{te,i,t}}^{1-\sigma_i^{TRP\_NEW}} \right)^{\frac{1}{1-\sigma_i^{TRP\_NEW}}}$$

and where:

$$PTN_{te,i,t} \leq \begin{pmatrix} \sum\limits_{\text{fttj} \in PR} \theta^{MAINT}_{NEW,te,i,t}\, PM_{pr,i,t} \\ +\ \theta^{CHS}_{NEW,te,i,t} \left(\left(1 - s^{BONUS}_{te,i,t}\right) PV^{NEW\_CHS}_{te,i,t} + T^{MALUS}_{te,i,t} \right) \\ +\ \theta^{BAT}_{NEW,te,i,t}\, PV^{NEW\_BAT}_{te,i,t} \\ +\ \theta^{FE}_{NEW,te,i,t}\ PTN^{FE}_{te,i,t} \end{pmatrix}$$

$$PTN^{FE}_{te,i,t} \leq \left(\theta^{ENG}_{FE,te,i,t}\, PV^{NEW\_ENG\ 1-\sigma^{FE}_{YTN,i}}_{te,i,t} + \theta^{F}_{FE,te,i,t}\, PF_{te,i,t}^{\ 1-\sigma^{FE}_{YTN,i}} \right)^{\frac{1}{1-\sigma^{FE}_{YTN,i}}}$$

$$PV^{NEW\_CHS}_{te,i,t} \leq \left(1 + \tau^{K}_{i,t}\right) \Big/ \left(1 + \tau^{K}_{i0}\right) \cdot PK_t$$

$$PV^{NEW\_BAT}_{te,i,t} \leq \left(1 + \tau^{K}_{i,t}\right) \Big/ \left(1 + \tau^{K}_{i0}\right) \cdot PK_t$$

$$PV^{NEW\_ENG}_{te,i,t} \leq \left(1 + \tau^{K}_{i,t}\right) \Big/ \left(1 + \tau^{K}_{i0}\right) \cdot PK_t$$

and where:

$$PTU_{te,v,i,t} \leq \begin{pmatrix} \sum\limits_{\text{fttj} \in PR} \theta^{MAINT}_{USED,te,v,i,t}\, PM_{pr,i,t} \\ +\ \theta^{VEHICLE}_{USED,te,v,i,t} \dfrac{\left(1 + \tau^{K}_{i,t}\right)}{\left(1 + \tau^{K}_{i0}\right)} PV^{USED}_{te,v,t} \\ +\ \theta^{F}_{USED,te,v,i,t}\, PF_{te,i,t} \end{pmatrix}$$

Firms using fuel blends in production:

$$\begin{aligned} \Pi^{YF}_{te,i,t} \equiv\ & v^{YF}_{te,i} \left(fl^{YF}_{te,t}\, PF^{CES}_{te,i,t} + \left(1 - fl^{YF}_{te,t}\right) PF^{NCES}_{te,i,t} \right) \\ & - v^{YF}_{te,i}\, PF_{te,i,t} \geq 0 \end{aligned} \qquad \perp YF_{te,i,t} \qquad \begin{array}{l} te \in TE \\ i \in I \\ t \in T \end{array} \qquad \text{(Z.02)}$$

$$\begin{aligned} \Pi^{YF\_CES}_{te,i,t} \equiv\ & v^{YF}_{te,i} \left(\sum_{bl} \theta^{bl}_{YF,te,i}\, PBM_{bl,i,t}^{\ 1-\sigma^{YF}_{te,i}} \right)^{\frac{1}{1-\sigma^{YF}_{te,i}}} \\ & - v^{YF}_{te,i}\, PF^{CES}_{te,i,t} \geq 0 \end{aligned} \qquad \perp YF^{CES}_{te,i,t} \qquad \begin{array}{l} te \in TE\_DV\_CES \\ i \in I \\ t \in T \end{array} \qquad \text{(Z.03)}$$

$$\begin{aligned} \Pi^{YF\_NCES}_{te,bl,i,t} \equiv\ & v^{YF}_{te,bl,i}\, PBM_{bl,i,t} \\ & - v^{YF}_{te,bl,i}\, PF^{NCES}_{te,i,t} \geq 0 \end{aligned} \qquad \perp YF^{NCES}_{te,bl,i,t} \qquad \begin{array}{l} te \in TE \\ te \notin TE\_DV\_CES \\ bl \in BL \\ i \in I \\ t \in T \end{array} \qquad \text{(Z.04)}$$

Firms using fixed capital and labour (value added) in production:

$$\begin{aligned}\Pi^{VA}_{i,t} \equiv v^{KL}_{i,t} & \left(\begin{array}{l} \theta^{K}_{i,t} \left(\dfrac{\left(1+\tau^{K}_{VA,i,t}\right)}{\left(1+\tau^{K}_{VA,i0}\right)} PK_t \right)^{1-\sigma^{KL}_i} + \\ \theta^{LS}_{i,t} \left(\dfrac{\left(1+T^{LS}_{t}\right)}{\left(1+\tau^{LS}_{0}\right)} PLS_{i,t} \right)^{1-\sigma^{KL}_i} \end{array} \right)^{\frac{1}{1-\sigma^{KL}_i}} \\ & - v^{VA}_{i,t} \cdot \left(1+P^{ADJ}_{VA,i,t}\right) \cdot PVA_{i,t} \geq 0 \end{aligned} \qquad \perp VA_{i,t} \qquad \begin{array}{l} i \in I \\ t \in T \end{array} \qquad \text{(Z.05)}$$

$$\begin{aligned}\Pi^{LS}_{i,t} & \equiv v^{LS}_{i} \, PLS_t \\ & - v^{LS}_{i} PLS_{i,t} \geq 0 \end{aligned} \qquad \perp LS_{i,t} \qquad \begin{array}{l} i \in I \\ t \in T \end{array} \qquad \text{(Z.06)}$$

Firms selling trade and merchant trade services:

$$\begin{aligned}\Pi^{HM}_{t} & \equiv \sum_{\text{hand} \in PR} v^{HM} \, P_{pr,t} \\ & - \quad v^{HM} PHM_t \geq 0 \end{aligned} \qquad \perp HM_t \qquad t \in T \qquad \text{(Z.07)}$$

Firms importing products:

$$\begin{aligned}\Pi^{IM}_{pr,t} \equiv v^{IM}_{pr} & \left(\begin{array}{l} \theta^{EU}_{IM,pr,t} PIM^{EU}_{pr,t}{}^{1-\sigma^{IM}_{pr}} + \\ \theta^{ROW}_{IM,pr,t} \left(\dfrac{\left(1+\tau^{IM}_{pr,t}\right)}{\left(1+\tau^{IM}_{pr0}\right)} PIM^{ROW}_{pr,t} \right)^{1-\sigma^{IM}_{pr}} \end{array} \right)^{\frac{1}{1-\sigma^{IM}_{pr}}} \\ & - v^{IM}_{pr} PIM_{pr,t} \geq 0 \end{aligned} \qquad \perp IM_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \qquad \text{(Z.08)}$$

where:

$$PIM^{EU}_{pr,t} \leq \rho^{EU}_{pr,t} \, PFX_t$$

$$PIM^{ROW}_{pr,t} \leq \rho^{ROW}_{pr,t} \, PFX_t$$

Firms distributing imported and domestically-produced products:

$$\begin{aligned}\Pi^{A}_{pr,t} & \equiv v^{A}_{pr} \left(\theta^{Y}_{A,pr} P_{pr,t}{}^{1-\sigma^{A}_{pr}} + \theta^{IM}_{A,pr} PIM_{pr,t}{}^{1-\sigma^{A}_{pr}} \right)^{\frac{1}{1-\sigma^{A}_{pr}}} \\ & - v^{A}_{pr} PA_{pr,t} \geq 0 \end{aligned} \qquad \perp A_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \qquad \text{(Z.09)}$$

Firms selling fuel blends:

$$\begin{aligned}
\Pi^{B}_{bl,pr,t} \equiv v^{B}_{bl,pr} & \begin{pmatrix}
\theta^{A}_{B,bl,pr}\, PA_{pr,t} \\
+\, \theta^{TOTH}_{B,bl,pr}\, T^{OTH}_{pr,t} \\
+\, \theta^{TE}_{B,bl,pr}\, T^{E}_{pr,t} + \theta^{TEI}_{B,bl,pr,t}\, T^{EI}_{t} \\
+\sum_{po} \theta^{po}_{B,bl,pr} \dfrac{PEM^{po}_{bl,pr,t}}{PEM^{po}_{bl,pr0}} \\
+\, \theta^{A}_{B,bl,pr,t}\, PRFS_{t} \cdot \left(rfs_{bl,t} - fl^{RFS}_{bl,pr,t} \right) \\
+\, \theta^{A}_{B,bl,pr,t}\, PRFS\_B_{bl,t} \cdot \left(rfs\_b_{bl,t} - fl^{RFS\_B}_{bl,pr,t} \right) \\
+\, \theta^{A}_{B,bl,pr,t}\, PFFS\_B_{bl,t} \cdot \left(ffs\_b_{bl,t} - fl^{FFS\_B}_{bl,pr,t} \right)
\end{pmatrix} \\
- v^{B}_{bl,pr}\, PB_{bl,t} \geq 0 &
\end{aligned}
\qquad \perp B_{bl,pr,t} \qquad
\begin{aligned} & bl \in BL \\ & pr \in PR\_B \\ & t \in T \end{aligned}
\qquad (Z.10)$$

Firms selling fuel blends for intermediate use by firms in production sectors:

$$\begin{aligned}
\Pi^{BM}_{bl,i,t} \equiv v^{BM}_{bl,i} \cdot & \frac{\left(1+\tau^{VA}_{BM,bl,i,t}\right)}{\left(1+\tau^{VA}_{BM,bl,i0}\right)} \cdot PBM^{pp}_{bl,i,t} \\
- v^{BM}_{bl,i}\, PBM_{bl,i,t} \geq 0 &
\end{aligned}
\qquad \perp BM_{bl,i,t} \qquad
\begin{aligned} & bl \in BL \\ & i \in I \\ & t \in T \end{aligned}
\qquad (Z.11)$$

where:

$$\begin{aligned}
PBM^{pp}_{bl,i,t} \leq\ & \theta^{B}_{BM,bl,i} \frac{\left(1 - S^{E}_{bl,i,t} - S^{CO2}_{bl,i,t}\right)}{\left(1 - S^{E}_{bl,i0} - S^{CO2}_{bl,i0}\right)} PB_{bl,t} \\
& + \theta^{TCO2\_TR}_{BM,bl,i,t}\ T^{CO2}_{TR,t} \\
& + \theta^{HM}_{BM,bl,i} PHM_{t}
\end{aligned}$$

Firms selling fuel blends for final consumption by households:

$$\begin{aligned}
\Pi^{BC}_{bl,t} \equiv v^{BC}_{bl} \cdot & \frac{\left(1+\tau^{VA}_{BC,bl,t}\right)}{\left(1+\tau^{VA}_{BC,bl0}\right)} \cdot PBC^{pp}_{bl,t} \\
- v^{BC}_{bl}\, PBC_{bl,t} \geq 0 &
\end{aligned}
\qquad \perp BC_{bl,t} \qquad
\begin{aligned} & bl \in BL \\ & t \in T \end{aligned}
\qquad (Z.12)$$

where:

$$\begin{aligned}
PBC^{pp}_{bl,t} \leq\ & PB_{bl,t} \\
& + \theta^{TCO2\_TR}_{BC,bl,t}\ T^{CO2}_{TR,t} \\
& + \theta^{HM}_{BC,bl} PHM_{t}
\end{aligned}$$

Firms selling products for intermediate use by firms in production sectors:

$$\begin{aligned}\Pi^{M}_{pr,i,t} \equiv v^{M}_{pr,i} & \left(\theta^{M}_{M,pr,i} \frac{\left(1+\tau^{VA}_{M,pr,i,t}\right)}{\left(1+\tau^{VA}_{M,pr,i0}\right)} PM^{pp}_{pr,i,t} + \sum_{po} \theta^{po}_{M,pr,i} \frac{PEM^{po}_{pr,i,t}}{PEM^{po}_{pr,i0}} \right) \\ & - v^{M}_{pr,i} PM_{pr,i,t} \geq 0 \end{aligned} \qquad \perp M_{pr,i,t} \qquad \begin{matrix} pr \in PR \\ i \in I \\ t \in T \end{matrix} \tag{Z.13}$$

where:

$$\begin{aligned} PM^{pp}_{pr,i,t} \leq\ & \theta^{A}_{M,pr,i} PA_{pr,t} \\ & + \theta^{HM}_{M,pr,i} PHM_{t} \\ & + \theta^{TOTH}_{M,pr,i} T^{OTH}_{pr,t} \\ & + \theta^{TE}_{M,pr,i} \frac{\left(1-s^{E}_{pr,i,t}\right)}{\left(1-s^{E}_{pr,i0}\right)} T^{E}_{pr,t} + \theta^{TEI}_{M,pr,i,t} T^{EI}_{t} \\ & + \theta^{TFLYG}_{M,pr,i,t} T^{FLYG}_{t} \end{aligned}$$

Firms selling products for final consumption by households:

$$\begin{aligned}\Pi^{C}_{pr,t} \equiv v^{C}_{pr} & \left(\theta^{EA}_{C,pr} P^{EA}_{pr,t} + \theta^{C}_{C,pr} \frac{\left(1+\tau^{VA}_{C,pr,t}\right)}{\left(1+\tau^{VA}_{C,pr0}\right)} PC^{pp}_{pr,t} + \sum_{po} \theta^{po}_{C,pr} \frac{PEM^{po}_{pr,t}}{PEM^{po}_{pr0}} \right) \\ & - v^{C}_{pr} PC_{pr,t} \geq 0 \end{aligned} \qquad \perp C_{pr,t} \qquad \begin{matrix} pr \in PR \\ t \in T \end{matrix} \tag{Z.14}$$

where:

$$\begin{aligned} PC^{pp}_{pr,t} \leq\ & \theta^{A}_{C,pr} PA_{pr,t} \\ & + \theta^{HM}_{C,pr} PHM_{t} \\ & + \theta^{TOTH}_{C,pr} T^{OTH}_{pr,t} \\ & + \theta^{TE}_{C,pr} T^{E}_{pr,t} + \theta^{TEI}_{C,pr,t} T^{EI}_{t} \\ & + \theta^{TFLYG}_{C,pr,t} T^{FLYG}_{t} \end{aligned}$$

Firms selling products for final consumption by the government:

$$\Pi^{G}_{pr,t} \equiv v^{G}_{pr} \begin{pmatrix} \theta^{EA}_{G,pr} P^{EA}_{pr,t} \\ + \dfrac{\left(1+\tau^{VA}_{G,pr,t}\right)}{\left(1+\tau^{VA}_{G,pr0}\right)} \cdot PG^{pp}_{pr,t} \end{pmatrix} - v^{G}_{pr}\, PG_{pr,t} \geq 0 \qquad \perp G_{pr,t} \qquad \begin{matrix} pr \in PR \\ t \in T \end{matrix} \qquad \text{(Z.15)}$$

where:

$$\begin{aligned} PG^{pp}_{pr,t} \leq\ & \theta^{A}_{G,pr} PA_{pr,t} \\ & + \theta^{HM}_{G,pr} PHM_{t} \\ & + \theta^{TOTH}_{G,pr}\, T^{OTH}_{pr,t} \end{aligned}$$

Firm exporting products:

$$\Pi^{EX}_{t} \equiv v^{EX}_{t} \begin{pmatrix} \sum\limits_{pr \in PR\_EX\_E} \theta^{EX}_{pr} PEX^{TOT\ 1-\sigma^{E}_{EX}}_{pr,t} \\ + \quad \theta^{EX}_{NE} PEX^{NE\ \ 1-\sigma^{E}_{EX}}_{t} \end{pmatrix}^{\frac{1}{1-\sigma^{E}_{EX}}} - v^{EX}_{t} \cdot PFX_{t} \geq 0 \qquad \perp EX_{t} \qquad t \in T \qquad \text{(Z.16)}$$

where:

$$PEX^{NE}_{t} \leq \left(\sum_{pr \notin PR\_EX\_E} \theta^{EX}_{pr} PEX^{TOT\ 1-\sigma^{NE}_{EX}}_{pr,t} \right)^{\frac{1}{1-\sigma^{NE}_{EX}}}$$

and where:

$$PEX^{TOT}_{pr,t} \leq \begin{pmatrix} \theta^{EX}_{pr} PEX^{EU\ \ 1-\sigma^{EX}_{pr}}_{pr,t} \\ + \theta^{EX}_{NE} PEX^{ROW\ 1-\sigma^{EX}_{pr}}_{pr,t} \end{pmatrix}^{\frac{1}{1-\sigma^{EX}_{pr}}}$$

$$\Pi^{EX\_EU}_{pr,t} \equiv v^{EX\_EU}_{pr}\, PEX_{pr,t} - v^{EX\_EU}_{pr,t}\, PEX^{EU}_{pr,t} \geq 0 \qquad \perp EX^{EU}_{pr,t} \qquad \begin{matrix} pr \in PR \\ t \in T \end{matrix} \qquad \text{(Z.17)}$$

$$\Pi^{EX\_ROW}_{pr,t} \equiv v^{EX\_ROW}_{pr}\, PEX_{pr,t} - v^{EX\_ROW}_{pr,t}\, PEX^{ROW}_{pr,t} \geq 0 \qquad \perp EX^{ROW}_{pr,t} \qquad \begin{matrix} pr \in PR \\ t \in T \end{matrix} \qquad \text{(Z.18)}$$

$$\begin{aligned}\Pi^{EX}_{pr,t} \equiv v^{EX}_{pr}&\begin{pmatrix}\theta^{A}_{EX,pr}PA_{pr,t}\\ +\theta^{HM}_{EX,pr}PHM_{t}\\ +\theta^{TOTH}_{EX,pr}T^{OTH}_{pr,t}\\ +\theta^{TE}_{EX,pr}T^{E}_{pr,t}\end{pmatrix}\\ &- v^{EX}_{pr}\cdot PEX_{pr,t} \geq 0\end{aligned} \qquad \perp EX_{pr,t} \qquad \begin{aligned}&pr \in PR\\ &t \in T\end{aligned} \qquad (Z.19)$$

Firms exporting used vehicles:

$$\begin{aligned}\Pi^{EXYV}_{te,v,t} &\equiv PV^{USED}_{te,v,t}\\ &- \left(1-cost^{EX}_{te,v,t}\right)PFX_{t} \geq 0\end{aligned} \qquad \perp EXYV_{te,v,t} \qquad \begin{aligned}&te \in TE\_DV\\ &v \in V\\ &t \in T\end{aligned} \qquad (Z.20)$$

$$\begin{aligned}\Pi^{EXCV}_{te,v,t} &\equiv PCV^{USED}_{te,v,t}\\ &- \left(1-cost^{EX}_{te,v,t}\right)PFX_{t} \geq 0\end{aligned} \qquad \perp EXCV_{te,v,t} \qquad \begin{aligned}&te \in TE\_LDV\\ &v \in V\\ &t \in T\end{aligned} \qquad (Z.21)$$

Firms forming non-fixed capital (inventories):

$$\begin{aligned}\Pi^{LA}_{t} &\equiv v^{LA}\prod_{pr} PLA_{pr,t}^{\theta^{LA}_{pr}}\\ &- v^{LA}PLA_{t} \geq 0\end{aligned} \qquad \perp LA_{t} \qquad t \in T \qquad (Z.22)$$

$$\begin{aligned}\Pi^{LA}_{pr,t} &\equiv v^{LA}_{pr}\cdot\frac{\left(1+\tau^{VA}_{LA,pr,t}\right)}{\left(1+\tau^{VA}_{LA,pr0}\right)}\cdot PLA^{pp}_{pr,t}\\ &- v^{LA}_{pr}PLA_{pr,t} \geq 0\end{aligned} \qquad \perp LA_{pr,t} \qquad \begin{aligned}&pr \in PR\\ &t \in T\end{aligned} \qquad (Z.23)$$

where:

$$PLA^{pp}_{pr,t} \leq \theta^{A}_{LA,pr}PA_{pr,t} + \theta^{HM}_{LA,pr}PHM_{t}$$

Firms forming fixed capital:

$$\begin{aligned}\Pi^{I}_{t} &\equiv v^{I}\left(\prod_{pr} PI_{pr,t}^{\theta^{I}_{pr}}\right)\\ &- v^{I}PI_{t} \geq 0\end{aligned} \qquad \perp I_{t} \qquad t \in T \qquad (Z.24)$$

$$\begin{aligned}\Pi^{I}_{pr,t} \equiv{}& v^{I}_{pr} \cdot \frac{\left(1+\tau^{VA}_{I,pr,t}\right)}{\left(1+\tau^{VA}_{I,pr0}\right)} \cdot PI^{pp}_{pr,t} \\ & - v^{I}_{pr} PI_{pr,t} \geq 0\end{aligned} \qquad \perp I_{pr,t} \qquad \begin{matrix} pr \in PR \\ t \in T \end{matrix} \qquad \text{(Z.25)}$$

where:

$$\begin{aligned} PI^{pp}_{pr,t} \leq{}& \theta^{A}_{I,pr} PA_{pr,t} \\ & + \theta^{HM}_{I,pr} PHM_{t} \\ & + \theta^{TOTH}_{I,pr} T^{OTH}_{pr,t} \end{aligned}$$

Firms selling working hours:

$$\begin{aligned}\Pi^{LS}_{t} \equiv{}& v^{LS} \left(\prod_{h} \left(\frac{\left(1+\tau^{L}_{h,t}\right)}{\left(1+\tau^{L}_{h0}\right)} PL_{h,t} \right)^{\theta^{LS}_{h}} \right) \\ & - v^{LS} PLS_{t} \geq 0 \end{aligned} \qquad \perp LS_{t} \qquad t \in T \qquad \text{(Z.26)}$$

Government consuming final consumption products:

$$\begin{aligned}\Pi^{G}_{t} \equiv{}& v^{G} \begin{pmatrix} \theta^{GDS}_{G} PG^{GDS\,1-\sigma^{G}}_{t} \\ +\theta^{SER}_{G} PG^{SER\,1-\sigma^{G}}_{t} \\ +\theta^{BLD}_{G} PG^{BLD\,1-\sigma^{G}}_{t} \\ +\theta^{TR}_{G} \; PG^{TR\,1-\sigma^{G}}_{t} \end{pmatrix}^{\frac{1}{1-\sigma^{G}}} \\ & - v^{G} PG_{t} \geq 0 \end{aligned} \qquad \perp G_{t} \qquad t \in T \qquad \text{(Z.27)}$$

where:

$$PG^{GDS}_{t} \leq \left(\sum_{pr \in PR\_G\_GDS} \theta^{GDS}_{G,pr} \, PG_{pr,t}{}^{1-\sigma^{GDS}_{G}} \right)^{\frac{1}{1-\sigma^{GDS}_{G}}}$$

$$PG^{SER}_{t} \leq \left(\sum_{pr \in PR\_G\_SER} \theta^{SER}_{G,pr} \, PG_{pr,t}{}^{1-\sigma^{SER}_{G}} \right)^{\frac{1}{1-\sigma^{SER}_{G}}}$$

$$PG^{BLD}_{t} \leq \left(\sum_{pr \in PR\_G\_BLD} \theta^{BLD}_{G,pr} \, PG_{pr,t}{}^{1-\sigma^{BLD}_{G}} \right)^{\frac{1}{1-\sigma^{BLD}_{G}}}$$

$$PG_t^{TR} \le \left(\sum_{pr \in PR\_G\_TR} \theta_{G,pr}^{TR} \, PG_{pr,t}{}^{1-\sigma_G^{TR}} \right)^{\frac{1}{1-\sigma_G^{TR}}}$$

Households bundling final consumption products into consumption bundles:

$$\begin{aligned} \Pi_{fn,t}^{C} \equiv v_{fn,t}^{C} & \left(\sum_{pr} \theta_{fn,t}^{pr} \, PC_{pr,t}{}^{1-\sigma_{fn}^{C}} \right)^{\frac{1}{1-\sigma_{fn}^{C}}} \\ & - v_{fn}^{C} PC_{fn,t} \ge 0 \end{aligned} \qquad \perp C_{fn,t} \qquad \begin{aligned} & fn \in FN \\ & t \in T \end{aligned} \qquad \text{(Z.28)}$$

Households consuming bundles:

$$\begin{aligned} \Pi_{h,t}^{C} \equiv v_{h,t}^{C} & \begin{pmatrix} \theta_{C,h,t}^{GDS} \, PC_{h,t}^{GDS\,1-\sigma_h^C} \\ +\theta_{C,h,t}^{SER} \, PC_{h,t}^{SER\,1-\sigma_h^C} \\ +\theta_{C,h,t}^{BLD} \, PC_{h,t}^{BLD\,1-\sigma_h^C} \\ +\theta_{C,h,t}^{TR} \, PC_{h,t}^{TR\,1-\sigma_h^C} \end{pmatrix}^{\frac{1}{1-\sigma_h^C}} \\ & - v_{h,t}^{C} PC_{h,t} \ge 0 \end{aligned} \qquad \perp C_{h,t} \qquad \begin{aligned} & h \in H \\ & t \in T \end{aligned} \qquad \text{(Z.29)}$$

where:

$$PC_{h,t}^{GDS} \le \left(\sum_{fn \in FN\_GDS} \theta_{C,GDS,h}^{fn} \, PC_{fn,t}{}^{1-\sigma_{C,h}^{GDS}} \right)^{\frac{1}{1-\sigma_{C,h}^{GDS}}}$$

$$PC_{h,t}^{SER} \le \left(\sum_{fn \in FN\_SER} \theta_{C,SER,h}^{fn} \, PC_{fn,t}{}^{1-\sigma_{C,h}^{SER}} \right)^{\frac{1}{1-\sigma_{C,h}^{SER}}}$$

$$PC_{h,t}^{BLD} \le \begin{pmatrix} \sum_{rent \in FN} \theta_{C,BLD,h}^{fn} \, PC_{fn,t}{}^{1-\sigma_{C,h}^{BLD}} \\ + \quad \theta_{C,BLD,h}^{E} \, PC_{h,t}^{BLD\_E\;\;1-\sigma_{C,h}^{BLD}} \end{pmatrix}^{\frac{1}{1-\sigma_{C,h}^{BLD}}}$$

$$PC_{h,t}^{BLD\_E} \le \begin{pmatrix} \sum_{\mathrm{el,fj} \in FN} \theta_{C,BLD\_E,h}^{fn} PC_{fn,t}{}^{1-\sigma_{C,h}^{BLD\_E}} \\ + \quad \theta_{C,BLD\_E,h}^{F} PC_{h,t}^{BLD\_EF\;1-\sigma_{C,h}^{BLD\_E}} \end{pmatrix}^{\frac{1}{1-\sigma_{C,h}^{BLD\_E}}}$$

$$PC_{h,t}^{BLD\_EF} \leq \left(\sum_{fn \in FN\_HF} \theta_{C,BLD\_EF,h}^{fn} \begin{pmatrix} \theta_{C,BLD\_EFF,h}^{fn} \quad PC_{fn,t} \\ + \sum_{po} \theta_{C,BLD\_EFF,fn,h}^{po} \dfrac{PEM_{fn,h,t}^{po}}{PEM_{fn,h0}^{po}} \end{pmatrix}^{1-\sigma_{C,h}^{BLD\_EF}} \right)^{\frac{1}{1-\sigma_{C,h}^{BLD\_EF}}}$$

$$PC_{h,t}^{TR} \quad \leq \begin{pmatrix} \sum_{fn \in FN\_TR} \theta_{C,TR,h,t}^{fn} PC_{fn,t}^{\ 1-\sigma_{C,h}^{TR}} \\ + \quad \theta_{C,TR,h,t}^{RD} PCT_{h,t}^{\ 1-\sigma_{C,h}^{TR}} \end{pmatrix}^{\frac{1}{1-\sigma_{C,h}^{TR}}}$$

Households consuming a bundle of road transports:

$$\Pi_{h,t}^{CT} \equiv v_{h,t}^{CT} \begin{pmatrix} \sum_{\text{road} \in FN} \theta_{CT,h,t}^{PUR} PC_{fn,t}^{\ 1-\sigma_{h}^{CT}} \\ + \quad \theta_{CT,h,t}^{OWN} PCT_{h,t}^{OWN\ 1-\sigma_{h}^{CT}} \end{pmatrix}^{\frac{1}{1-\sigma_{h}^{CT}}} - v_{h}^{CT} PCT_{h,t} \geq 0 \qquad \perp CT_{h,t} \qquad \begin{matrix} h \in H \\ t \in T \end{matrix} \qquad (Z.30)$$

where:

$$PCT_{h,t}^{OWN} \quad \leq \begin{pmatrix} \theta_{CT,OWN,h,t}^{LDV\_NEW} \quad PCT_{h,t}^{LDV\_NEW\ 1-\sigma_{CT,h}^{OWN}} \\ + \sum_{te \in TE\_LDV} \sum_{v} \theta_{CT,OWN,te,v,h,t}^{LDV\_USED} PCT_{te,v,h,t}^{LDV\_USED\ 1-\sigma_{CT,h}^{OWN}} \end{pmatrix}^{\frac{1}{1-\sigma_{CT,h}^{OWN}}}$$

and where

$$PCT_{h,t}^{LDV\_NEW} \leq \left(\sum_{te \in TE\_LDV} \theta_{CT,NEW,h,t}^{te} PCT_{te,h,t}^{LDV\_NEW\ 1-\sigma_{CT,OWN,h}^{NEW}} \right)^{\frac{1}{1-\sigma_{CT,OWN,h}^{NEW}}}$$

$$\begin{aligned} PCT_{te,h,t}^{LDV\_NEW} \leq & \sum_{\text{main} \in FN} \theta_{CT,NEW,te,h,t}^{MAINT} PC_{fn,t} \\ & + \theta_{CT,NEW,te,h,t}^{CHS} \left(\left(1 - s_{te,h,t}^{BONUS}\right) PCV_{te,t}^{NEW\_CHS} + T_{te,h,t}^{MALUS} \right) \\ & + \theta_{CT,NEW,te,h,t}^{BAT} PCV_{te,t}^{NEW\_BAT} \\ & + \theta_{CT,NEW,te,h,t}^{FE} \begin{pmatrix} \theta_{CT,FE,te,h,t}^{ENG} PCV_{te,t}^{NEW\_ENG\ 1-\sigma_{CT,NEW,h}^{FE}} \\ + \theta_{CT,FE,te,h,t}^{F} PCF_{te,t}^{\ 1-\sigma_{CT,NEW,h}^{FE}} \end{pmatrix}^{\frac{1}{1-\sigma_{CT,NEW,h}^{FE}}} \end{aligned}$$

$$PCV_{te,t}^{NEW\_CHS} \leq \sum_{\text{transeq} \in FN} PC_{fn,t}$$

$$PCV_{te,t}^{NEW\_BAT} \leq \sum_{\text{transeq} \in FN} PC_{fn,t}$$

$$PCV_{te,t}^{NEW\_ENG} \leq \sum_{\text{transeq} \in FN} PC_{fn,t}$$

and where:

$$\begin{aligned} PCT_{te,v,h,t}^{LDV\_USED} \leq & \sum_{\text{main} \in FN} \theta_{CT,USED,te,v,h,t}^{MAINT} PC_{fn,t} \\ + & \quad \theta_{CT,USED,te,v,h,t}^{VEHICLE} PCV_{te,v,t}^{USED} \\ + & \quad \theta_{CT,USED,te,v,h,t}^{F} PCF_{te,t} \end{aligned}$$

Households consuming fuel blends associated with road transports:

$$\begin{aligned} \Pi_{te,t}^{CF} \equiv v_{te}^{CF} & \begin{pmatrix} fl_{te,t}^{CF} \; PCF_{te,t}^{CES} \\ +\left(1 - fl_{te,t}^{CF}\right) PCF_{te,t}^{NCES} \end{pmatrix} \\ - v_{te}^{CF} & \; PCF_{te,t} \geq 0 \end{aligned} \qquad \perp CF_{te,t} \qquad \begin{aligned} & te \in TE\_LDV \\ & t \in T \end{aligned} \qquad (Z.31)$$

$$\begin{aligned} \Pi_{te,t}^{CF\_CES} \equiv v_{te}^{CF} & \left(\sum_{bl} \theta_{CF,te}^{bl} PBC_{bl,t}^{\;1-\sigma_{te}^{CF}} \right)^{\frac{1}{1-\sigma_{te}^{CF}}} \\ -v_{te}^{CF} & \; PCF_{te,t}^{CES} \geq 0 \end{aligned} \qquad \perp CF_{te,t}^{CES} \qquad \begin{aligned} & te \in TE\_LDV \\ & te = \text{ldv\_phev} \\ & t \in T \end{aligned} \qquad (Z.32)$$

$$\begin{aligned} \Pi_{te,bl,t}^{CF\_NCES} & \equiv v_{te,bl}^{CF} \, PBC_{bl,t} \\ & -v_{te,bl}^{CF} \, PCF_{te,t}^{NCES} \geq 0 \end{aligned} \qquad \perp CF_{te,bl,t}^{NCES} \qquad \begin{aligned} & te \in TE\_LDV \\ & te \neq \text{ldv\_phev} \\ & bl \in BL \\ & t \in T \end{aligned} \qquad (Z.33)$$

Households deriving utility from consumption and leisure:

$$\begin{aligned} \Pi_{h,t}^{U} \equiv v_{h,t}^{U} & \begin{pmatrix} \theta_{U,h,t}^{C} \, PC_{h,t}^{\;1-\sigma_{h}^{U}} \\ +\theta_{U,h,t}^{L} PL_{h,t}^{\;1-\sigma_{h}^{U}} \end{pmatrix}^{\frac{1}{1-\sigma_{h}^{U}}} \\ - v_{h,t}^{U} & PU_{h,t} \geq 0 \end{aligned} \qquad \perp U_{h,t} \qquad \begin{aligned} & h \in H \\ & t \in T \end{aligned} \qquad (Z.34)$$

Households saving a fixed part of their budget for investments in fixed capital:

$$\begin{aligned} \Pi_{h,t}^{BU} \equiv v_{h,t}^{BU} & \begin{pmatrix} \theta_{BU,h,t}^{SAV} \, PI_{t} \\ +\theta_{BU,h,t}^{U} \, PU_{h,t} \end{pmatrix} \\ - v_{h,t}^{BU} & PBU_{h,t} \geq 0 \end{aligned} \qquad \perp BU_{h,t} \qquad \begin{aligned} & h \in H \\ & t \in T \end{aligned} \qquad (Z.35)$$

Emission accounting:

$$\begin{aligned}\Pi^{po}_{bl,pr,t} \equiv\ & emsh^{TCO2}_{po,bl,pr,t}\cdot T^{CO2}_{bl,pr,t}\\ &+ emsh^{TGHG}_{po,bl,pr,t}\cdot T^{GHG}_{t}\\ &- PEM^{po}_{bl,pr,t} \geq 0\end{aligned} \qquad \perp EM^{po}_{bl,pr,t} \qquad \begin{array}{l} po\in PO\\ bl\in BL\\ pr\in PR\\ t\in T\end{array} \qquad \text{(Z.36)}$$

$$\begin{aligned}\Pi^{po}_{pr,t} \equiv\ & emsh^{TCO2}_{po,pr,t}\cdot\left(\frac{1+\tau^{VA}_{C,pr,t}}{1+\tau^{VA}_{C,pr0}}\right)T^{CO2}_{pr,t}\\ &+ emsh^{TGHG}_{po,pr,t}\cdot\left(1+\tau^{VA}_{C,pr,t}\right)T^{GHG}_{t}\\ &- PEM^{po}_{pr,t} \geq 0\end{aligned} \qquad \perp EM^{po}_{pr,t} \qquad \begin{array}{l} po\in PO\\ pr\in PR\\ t\in T\end{array} \qquad \text{(Z.37)}$$

$$\begin{aligned}\Pi^{po}_{pr,i,t} \equiv\ & emsh^{ETS}_{po,pr,i,t}\cdot PETS_{t}\\ &+ emsh^{TCO2}_{po,pr,i,t}\cdot\frac{\left(1-s^{CO2}_{pr,i,t}+\tau^{VA}_{M,pr,i,t}\right)}{\left(1-s^{CO2}_{pr,i0}+\tau^{VA}_{M,pr,i0}\right)}T^{CO2}_{pr,t}\\ &+ emsh^{TCO2}_{TR,po,pr,i,t}\cdot\left(1+\tau^{VA}_{M,pr,i,t}\right)T^{CO2}_{TR,t}\\ &+ emsh^{TGHG}_{po,pr,i,t}\cdot\left(1+\tau^{VA}_{M,pr,i,t}\right)T^{GHG}_{t}\\ &- PEM^{po}_{pr,i,t} \geq 0\end{aligned} \qquad \perp EM^{po}_{pr,i,t} \qquad \begin{array}{l} po\in PO\\ pr\in PR\\ i\in I\\ t\in T\end{array} \qquad \text{(Z.38)}$$

$$\begin{aligned}\Pi^{po}_{i,t} \equiv\ & emsh^{ETS}_{po,i,t}\cdot PETS_{t}\\ &+ emsh^{TGHG}_{po,i,t}\cdot T^{GHG}_{t}\\ &- PEM^{po}_{i,t} \geq 0\end{aligned} \qquad \perp EM^{po}_{i,t} \qquad \begin{array}{l} po\in PO\\ i\in I\\ t\in T\end{array} \qquad \text{(Z.39)}$$

$$\begin{aligned}\Pi^{po}_{fn,h,t} \equiv\ & emsh^{TGHG}_{po,fn,h,t}\cdot T^{GHG}_{t}\\ &- PEM^{po}_{fn,h,t} \geq 0\end{aligned} \qquad \perp EM^{po}_{fn,h,t} \qquad \begin{array}{l} po\in PO\\ fn\in FN\\ h\in H\\ t\in T\end{array} \qquad \text{(Z.40)}$$

D.2. Market-clearing (M) conditions

Domestically-produced products:

$$\begin{aligned}\sum_{i}\frac{\partial\Pi^{Y}_{i,t}}{\partial\left(1-P^{ADJ}_{pr,t}\right)P_{pr,t}}Y_{i,t} \geq\ & \frac{\partial\Pi^{A}_{pr,t}}{\partial P_{pr,t}}A_{pr,t}\\ &+\frac{\partial\Pi^{HM}_{t}}{\partial P_{pr,t}}HM_{t}\end{aligned} \qquad \perp P_{pr,t} \qquad \begin{array}{l} pr\in PR\\ pr=\text{hand}\\ t\in T\end{array} \qquad \text{(M.01)}$$

$$\sum_{i}\frac{\partial\Pi^{Y}_{i,t}}{\partial\left(1-P^{ADJ}_{pr,t}\right)P_{pr,t}}Y_{i,t} \geq \frac{\partial\Pi^{A}_{pr,t}}{\partial P_{pr,t}}A_{pr,t} \qquad pr\neq\text{hand}$$

Domestically-produced products for own non-commercial use:

$$\begin{aligned}\sum_{gov\in I}\frac{\partial\Pi^{Y}_{i,t}}{\partial P^{EA}_{pr,t}}Y_{i,t}\geq{}&\frac{\partial\Pi^{G}_{pr,t}}{\partial P^{EA}_{pr,t}}G_{pr,t}\\&+\frac{\partial\Pi^{C}_{pr,t}}{\partial P^{EA}_{pr,t}}C_{pr,t}\end{aligned}\qquad\perp P^{EA}_{pr,t}\qquad\begin{aligned}&pr\in PR\\&t\in T\end{aligned}\qquad\text{(M.02)}$$

Trade and merchant trade services:

$$\begin{aligned}v^{HM}HM_{t}\geq{}&\sum_{bl,i}\frac{\partial\Pi^{BM}_{bl,i,t}}{\partial\left(1+\tau^{VA}_{BM,bl,i,t}\right)PHM_{t}}BM_{bl,i,t}\\&+\sum_{pr,i}\frac{\partial\Pi^{M}_{pr,i,t}}{\partial\left(1+\tau^{VA}_{M,pr,t}\right)PHM_{t}}M_{pr,i,t}\\&+\sum_{bl}\frac{\partial\Pi^{BC}_{bl,t}}{\partial\left(1+\tau^{VA}_{BC,bl,t}\right)PHM_{t}}BC_{bl,t}\\&+\sum_{pr}\frac{\partial\Pi^{C}_{pr,t}}{\partial\left(1+\tau^{VA}_{C,pr,t}\right)PHM_{t}}C_{pr,t}\\&+\sum_{pr}\frac{\partial\Pi^{G}_{pr,t}}{\partial\left(1+\tau^{VA}_{G,pr,t}\right)PHM_{t}}G_{pr,t}\\&+\sum_{pr}\frac{\partial\Pi^{LA}_{pr,t}}{\partial\left(1+\tau^{VA}_{LA,pr,t}\right)PHM_{t}}LA_{pr,t}\\&+\sum_{pr}\frac{\partial\Pi^{I}_{pr,t}}{\partial\left(1+\tau^{VA}_{I,pr,t}\right)PHM_{t}}I_{pr,t}\\&+\sum_{pr}\frac{\partial\Pi^{EX}_{pr,t}}{\partial PHM_{t}}EX_{pr,t}\end{aligned}\qquad\perp PHM_{t}\qquad t\in T\qquad\text{(M.03)}$$

Fuel blends bundled per vehicle technology and used in production:

$$v^{YF}_{te,i}\,YF_{te,i,t}\geq\frac{\partial\Pi^{Y}_{i,t}}{\partial PF_{te,i,t}}Y_{i,t}\qquad\perp PF_{te,i,t}\qquad\begin{aligned}&te\in TE\\&i\in I\\&t\in T\end{aligned}\qquad\text{(M.04)}$$

$$v^{YF}_{te,i}\,YF^{CES}_{te,i,t}\geq\frac{\partial\Pi^{YF}_{te,i,t}}{\partial PF^{CES}_{te,i,t}}YF_{te,i,t}\qquad\perp PF^{CES}_{te,i,t}\qquad\begin{aligned}&te\in TE\_DV\_CES\\&i\in I\\&t\in T\end{aligned}\qquad\text{(M.05)}$$

$$\sum_{bl}v^{YF}_{te,bl,i}\,YF^{NCES}_{te,bl,i,t}\geq\frac{\partial\Pi^{YF}_{te,i,t}}{\partial PF^{NCES}_{te,i,t}}YF_{te,i,t}\qquad\perp PF^{NCES}_{te,i,t}\qquad\begin{aligned}&te\in TE\\&te\notin TE\_DV\_CES\\&i\in I\quad t\in T\end{aligned}\qquad\text{(M.06)}$$

Used vehicles used in production:

$$v_{te,v,t}^{YV\_USED} \geq \sum_{i} \frac{\partial \Pi_{i,t}^{Y}}{\partial \left(1+\tau_{i,t}^{K}\right) PV_{te,v,t}^{USED}} Y_{i,t} + EXYV_{te,v,t} \qquad \perp PV_{te,v,t}^{USED} \qquad te \in TE\_DV,\; v \in V,\; t \in T \qquad \text{(M.07)}$$

Value added in production:

$$v_{i,t}^{VA}\, VA_{i,t} + v_{i0}^{VA}\, VA_{i,t}^{ADJ} \geq \frac{\partial \Pi_{i,t}^{Y}}{\partial PVA_{i,t}} Y_{i,t} \qquad \perp PVA_{i,t} \qquad i \in I,\; t \in T \qquad \text{(M.08)}$$

Labour use in production sectors (hours worked):

$$v_{i}^{LS} LS_{i,t} \geq \frac{\partial \Pi_{i,t}^{VA}}{\partial (1+T_{t}^{LS}) PLS_{i,t}} VA_{i,t} \qquad \perp PLS_{i,t} \qquad i \in I,\; t \in T \qquad \text{(M.09)}$$

Imported products:

$$v_{pr}^{IM} IM_{pr,t} \geq \frac{\partial \Pi_{pr,t}^{A}}{\partial PIM_{pr,t}} A_{pr,t} \qquad \perp PIM_{pr,t} \qquad pr \in PR,\; t \in T \qquad \text{(M.10)}$$

Distributed products (‘Armington’ bundles of domestically-produced and imported products):

$$\begin{aligned} v_{pr}^{A} A_{pr,t} \geq {} & \sum_{bl} \frac{\partial \Pi_{bl,pr,t}^{B}}{\partial PA_{pr,t}} B_{bl,pr,t} \\ & + \sum_{i} \frac{\partial \Pi_{pr,i,t}^{M}}{\partial \left(1+\tau_{M,pr,i,t}^{VA}\right) PA_{pr,t}} M_{pr,i,t} \\ & + \frac{\partial \Pi_{pr,t}^{C}}{\partial \left(1+\tau_{C,pr,t}^{VA}\right) PA_{pr,t}} C_{pr,t} \\ & + \frac{\partial \Pi_{pr,t}^{G}}{\partial \left(1+\tau_{G,pr,t}^{VA}\right) PA_{pr,t}} G_{pr,t} \\ & + \frac{\partial \Pi_{pr,t}^{LA}}{\partial \left(1+\tau_{LA,pr,t}^{VA}\right) PA_{pr,t}} LA_{pr,t} \\ & + \frac{\partial \Pi_{pr,t}^{I}}{\partial \left(1+\tau_{I,pr,t}^{VA}\right) PA_{pr,t}} I_{pr,t} \\ & + \frac{\partial \Pi_{pr,t}^{EX}}{\partial PA_{pr,t}} EX_{pr,t} \end{aligned} \qquad \perp PA_{pr,t} \qquad pr \in PR,\; t \in T \qquad \text{(M.11)}$$

Fuel blends (in producer prices):

$$\begin{aligned}&\sum_{pr\in PR\_B} v^{B}_{bl,pr} B_{bl,pr,t}\\ \geq\ &\sum_{i} \frac{\partial \Pi^{BM}_{bl,i,t}}{\partial\left(1-S^{E}_{bl,i,t}-S^{CO2}_{bl,i,t}+\tau^{VA}_{BM,bl,i,t}\right)PB_{bl,t}} BM_{bl,i,t}\\ &+\frac{\partial \Pi^{BC}_{bl,t}}{\partial\left(1+\tau^{VA}_{BC,bl,t}\right)PB_{bl,t}} BC_{bl,t}\end{aligned} \qquad \perp PB_{bl,t} \qquad \begin{aligned}&bl\in BL\\ &t\in T\end{aligned} \qquad \text{(M.12)}$$

Fuel blends used for intermediate consumption in production (in market prices):

$$v^{BM}_{bl,i} BM_{bl,i,t} \geq \sum_{te} \left(\begin{aligned} &\frac{\partial \Pi^{YF\_CES}_{te,i,t}}{\partial PBM_{bl,i,t}} YF^{CES}_{te,i,t}\\ &+\frac{\partial \Pi^{YF\_NCES}_{te,bl,i,t}}{\partial PBM_{bl,i,t}} YF^{NCES}_{te,bl,i,t} \end{aligned} \right) \qquad \perp PBM_{bl,i,t} \qquad \begin{aligned}&bl\in BL\\ &i\in I\\ &t\in T\end{aligned} \qquad \text{(M.13)}$$

Fuel blends used for final consumption by households (in market prices):

$$v^{BC}_{bl} BC_{bl,t} \geq \sum_{te\in TE\_LDV} \left(\begin{aligned} &\frac{\partial \Pi^{CF\_CES}_{te,t}}{\partial PBC_{bl,t}} CF^{CES}_{te,t}\\ &+\frac{\partial \Pi^{CF\_NCES}_{te,bl,t}}{\partial PBC_{bl,t}} CF^{NCES}_{te,bl,t} \end{aligned} \right) \qquad \perp PBC_{bl,t} \qquad \begin{aligned}&bl\in BL\\ &t\in T\end{aligned} \qquad \text{(M.14)}$$

Renewable-fuel standard that is uniform between multiple fuel blends:

$$\begin{aligned}&\sum_{bl,pr} v^{B}_{bl,pr}\theta^{A}_{B,bl,pr,t}\ fl^{RFS}_{bl,pr,t} B_{bl,pr,t}\\ \geq &\sum_{bl,pr} v^{B}_{bl,pr}\theta^{A}_{B,bl,pr,t}\ rfs_{bl,t}\ B_{bl,pr,t}\end{aligned} \qquad \perp PRFS_{t} \qquad t\in T \qquad \text{(M.15)}$$

Renewable-fuel standards that are specific to fuel blends:

$$\begin{aligned}&\sum_{pr} v^{B}_{bl,pr}\theta^{A}_{B,bl,pr,t}\ fl^{RFS\_B}_{bl,pr,t}\ B_{bl,pr,t}\\ \geq &\sum_{pr} v^{B}_{bl,pr}\theta^{A}_{B,bl,pr,t}\ rfs\_b_{bl,t}\ B_{bl,pr,t}\end{aligned} \qquad \perp PRFS\_B_{bl,t} \qquad \begin{aligned}&bl\in BL\\ &t\in T\end{aligned} \qquad \text{(M.16)}$$

Fossil-fuel standards that are specific to fuel blends:

$$\begin{aligned}&\sum_{pr} v^{B}_{bl,pr}\theta^{A}_{B,bl,pr,t}\; fl^{FFS\_B}_{bl,pr,t}\; B_{bl,pr,t}\\ &\geq \sum_{pr} v^{B}_{bl,pr}\theta^{A}_{B,bl,pr,t}\; ffs\_b_{bl,t}\; B_{bl,pr,t}\end{aligned} \qquad \perp PFFS\_B_{bl,t} \qquad \begin{array}{l} bl \in BL \\ t \in T \end{array} \tag{M.17}$$

Products used for intermediate consumption in production (in market prices):

$$v^{M}_{pr,i} M_{pr,i,t} \geq \frac{\partial \Pi^{Y}_{i,t}}{\partial PM_{pr,i,t}} Y_{i,t} \qquad \perp PM_{pr,i,t} \qquad \begin{array}{l} pr \in PR \\ i \in I \\ t \in T \end{array} \tag{M.18}$$

Products used for final consumption by the government (in market prices):

$$v^{G}_{pr} G_{pr,t} \geq \frac{\partial \Pi^{G}_{t}}{\partial PG_{pr,t}} G_{t} \qquad \perp PG_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.19}$$

$$v^{G} G_{t} \geq g_{t} \qquad \perp PG_{t} \qquad t \in T \tag{M.20}$$

Products used for final consumption by households (in market prices):

$$v^{C}_{pr} C_{pr,t} \geq \sum_{fn} \frac{\partial \Pi^{C}_{fn,t}}{\partial PC_{pr,t}} C_{fn,t} \qquad \perp PC_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.21}$$

Products used for export:

$$\begin{aligned} v^{EX}_{pr}\; EX_{pr,t} \geq\; & \frac{\partial \Pi^{EX\_EU}_{pr,t}}{\partial PEX_{pr,t}} EX^{EU}_{pr,t} \\ & + \frac{\partial \Pi^{EX\_ROW}_{pr,t}}{\partial PEX_{pr,t}} EX^{ROW}_{pr,t} \end{aligned} \qquad \perp PEX_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.22}$$

$$v^{EX\_EU}_{pr,t}\; EX^{EU}_{pr,t} \geq \frac{\partial \Pi^{EX}_{t}}{\partial PEX^{EU}_{pr,t}} EX_{t} \qquad \perp PEX^{EU}_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.23}$$

$$v^{EX\_ROW}_{pr,t}\; EX^{ROW}_{pr,t} \geq \frac{\partial \Pi^{EX}_{t}}{\partial PEX^{ROW}_{pr,t}} EX_{t} \qquad \perp PEX^{EU}_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.24}$$

Products used for non-fixed capital formation (inventories):

$$v^{LA}_{pr} LA_{pr,t} \geq \frac{\partial \Pi^{LA}_{t}}{\partial PLA_{pr,t}} LA_{t} \qquad \perp PLA_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.25}$$

$$v^{LA} LA_{t} \geq la_{t} \qquad \perp PLA_{t} \qquad t \in T \tag{M.26}$$

Products used for fixed-capital formation:

$$v^{I}_{pr} I_{pr,t} \geq \frac{\partial \Pi^{I}_{t}}{\partial PI_{pr,t}} I_{t} \qquad \perp PI_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \tag{M.27}$$

$$\begin{aligned} v^{I} I_{t} \geq & \sum_{h} \frac{\partial \Pi^{BU}_{h,t}}{\partial PI_{t}} BU_{h,t} \\ & + \theta^{K}_{h} \, SAV^{ADJ}_{t} \end{aligned} \qquad \perp PI_{t} \qquad t \in T \tag{M.28}$$

Aggregate labour use in production (hours worked):

$$v^{LS} LS_{t} \geq \sum_{i} \frac{\partial \Pi^{LS}_{i,t}}{\partial PLS_{t}} LS_{t} \qquad \perp PLS_{t} \qquad t \in T \tag{M.29}$$

Bundles of products used for final consumption by households:

$$\begin{aligned} v^{C}_{fn} C_{fn,t} \geq & \sum_{h} \frac{\partial \Pi^{C}_{h,t}}{\partial PC_{fn,t}} C_{h,t} \\ & + \sum_{h} \frac{\partial \Pi^{CT}_{h,t}}{\partial PC_{fn,t}} CT_{h,t} \\ & + \sum_{te \in TE\_LDV} \sum_{v} \frac{CV^{USED}_{te,v,t}}{PC_{fn,t}} \end{aligned} \qquad \perp PC_{fn,t} \qquad \begin{array}{l} fn \in FN \\ fn = \text{transeq} \\ t \in T \end{array} \tag{M.30}$$

$$\begin{aligned} v^{C}_{fn} C_{fn,t} \geq & \sum_{h} \frac{\partial \Pi^{C}_{h,t}}{\partial PC_{fn,t}} C_{h,t} \\ & + \sum_{h} \frac{\partial \Pi^{CT}_{h,t}}{\partial PC_{fn,t}} CT_{h,t} \end{aligned} \qquad fn \neq \text{transeq}$$

Fuel blends bundled per vehicle technology and used for final consumption by households:

$$v_{te}^{CF}\, CF_{te,t} \geq \sum_{h} \frac{\partial \Pi_{h,t}^{CT}}{\partial PCF_{te,t}} CT_{h,t} \qquad \perp PCF_{te,t} \qquad \begin{array}{l} te \in TE\_LDV \\ t \in T \end{array} \tag{M.31}$$

$$v_{te}^{CF}\, CF_{te,t}^{CES} \geq \frac{\partial \Pi_{te,t}^{CF}}{\partial PCF_{te,t}^{CES}} CF_{te,t} \qquad \perp PCF_{te,t}^{CES} \qquad \begin{array}{l} te \in TE\_DV\_CES \\ t \in T \end{array} \tag{M.32}$$

$$\sum_{bl} v_{te,bl}^{CF}\, CF_{te,bl,t}^{NCES} \geq \frac{\partial \Pi_{te,t}^{CF}}{\partial PCF_{te,t}^{NCES}} CF_{te,t} \qquad \perp PCF_{te,t}^{NCES} \qquad \begin{array}{l} te \in TE\_LDV \\ te \notin TE\_DV\_CES \\ t \in T \end{array} \tag{M.33}$$

Used vehicles used for final consumption by households:

$$\begin{aligned} v_{te,v,t}^{CV\_USED} \geq & \sum_{h} \frac{\partial \Pi_{h,t}^{CT}}{\partial PCV_{te,v,t}^{USED}} CT_{h,t} \\ & + EXCV_{te,v,t} \end{aligned} \qquad \perp PCV_{te,v,t}^{USED} \qquad \begin{array}{l} te \in TE\_LDV \\ v \in V \\ t \in T \end{array} \tag{M.34}$$

Road transport services used for final consumption by households:

$$v_{h}^{CT} CT_{h,t} \geq \frac{\partial \Pi_{h,t}^{C}}{\partial PCT_{h,t}} C_{h,t} + ct_{h,t} \qquad \perp PCT_{h,t} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{M.35}$$

Final consumption by households:

$$v_{h,t}^{C} C_{h,t} \geq \frac{\partial \Pi_{h,t}^{U}}{\partial PC_{h,t}} U_{h,t} \qquad \perp PC_{h,t} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{M.36}$$

Utility of households:

$$v_{h,t}^{U} U_{h,t} \geq \frac{\partial \Pi_{h,t}^{BU}}{\partial PU_{h,t}} BU_{h,t} \qquad \perp PU_{h,t} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{M.37}$$

Budget of households:

$$v_{h,t}^{BU} BU_{h,t} \geq \frac{INC_{h,t}^{H}}{PBU_{h,t}} \qquad \perp PBU_{h,t} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{M.38}$$

Hours available for work and leisure:

$$l_{h,t} \geq \frac{\partial \Pi_{t}^{LS}}{\partial\left(1+\tau_{h,t}^{L}\right) PL_{h,t}} LS_{t} + \frac{\partial \Pi_{h,t}^{U}}{\partial PL_{h,t}} U_{h,t} \qquad \perp PL_{h,t} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{M.39}$$

Capital use:

$$\sum_{h} \theta_{h}^{K} k_{t} \geq \sum_{i} \frac{\partial \Pi_{i,t}^{VA}}{\partial\left(1+\tau_{VA,i,t}^{K}\right) PK_{t}} VA_{i,t} + \sum_{i} \frac{\partial \Pi_{i,t}^{Y}}{\partial\left(1+\tau_{i,t}^{K}\right) PK_{t}} Y_{i,t} + \sum_{te \in TE\_DV} \sum_{v} \frac{YV_{te,v,t}^{USED}}{PK_{t}} \qquad \perp PK_{t} \qquad t \in T \tag{M.40}$$

Emissions of pollutants:

$$EM_{bl,pr,t}^{po} \geq \sum_{bl} \frac{\partial \Pi_{bl,pr,t}^{B}}{\partial PEM_{bl,pr,t}^{po}} B_{bl,pr,t} \qquad \perp PEM_{bl,pr,t}^{po} \qquad \begin{array}{l} po \in PO \\ bl \in BL \\ pr \in PR \\ t \in T \end{array} \tag{M.41}$$

$$EM_{pr,t}^{po} \geq \frac{\partial \Pi_{pr,t}^{C}}{\partial PEM_{pr,t}^{po}} C_{pr,t} \qquad \perp PEM_{pr,t}^{po} \qquad \begin{array}{l} po \in PO \\ pr \in PR \\ t \in T \end{array} \tag{M.42}$$

$$EM_{pr,i,t}^{po} \geq \frac{\partial \Pi_{pr,i,t}^{M}}{\partial PEM_{pr,i,t}^{po}} M_{pr,i,t} \qquad \perp PEM_{pr,i,t}^{po} \qquad \begin{array}{l} po \in PO \\ pr \in PR \\ i \in I \\ t \in T \end{array} \tag{M.43}$$

$$EM_{i,t}^{po} \geq \frac{\partial \Pi_{i,t}^{Y}}{\partial PEM_{i,t}^{po}} Y_{i,t} \qquad \perp PEM_{i,t}^{po} \qquad \begin{array}{l} po \in PO \\ i \in I \\ t \in T \end{array} \tag{M.44}$$

$$EM_{fn,h,t}^{po} \geq \frac{\partial \Pi_{h,t}^{C}}{\partial PEM_{fn,h,t}^{po}} C_{h,t} \qquad \perp PEM_{fn,h,t}^{po} \qquad \begin{array}{l} po \in PO \\ fn \in FN \\ h \in H \\ t \in T \end{array} \tag{M.45}$$

Emission allowances under the EU ETS:

$$\begin{aligned} & EM_{ETS,t}^{auct} + \sum_{i} em_{ETS,i,t}^{free} + \sum_{h} em_{ETS,h,t}^{free} \qquad \perp PETS_t \qquad t \in T \qquad \text{(M.46)} \\ & \geq \\ & \sum_{po,pr,i} emsh_{po,pr,i,t}^{ETS} EM_{pr,i,t}^{po} + \sum_{po,i} emsh_{po,i,t}^{ETS} \; EM_{i,t}^{po} \end{aligned}$$

CO$_2$ taxes:

$$EM_{bl,pr,t}^{TCO2} \geq \sum_{po} emsh_{po,bl,pr,t}^{TCO2} EM_{bl,pr,t}^{po} \qquad \perp T_{bl,pr,t}^{CO2} \qquad \begin{array}{l} bl \in BL \\ pr \in PR \\ t \in T \end{array} \qquad \text{(M.47)}$$

$$\begin{aligned} EM_{pr,t}^{TCO2} \geq & \sum_{po} emsh_{po,pr,t}^{TCO2} \; EM_{pr,t}^{po} \qquad \perp T_{pr,t}^{CO2} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \qquad \text{(M.48)} \\ & + \sum_{po,i} emsh_{po,pr,i,t}^{TCO2} EM_{pr,i,t}^{po} \end{aligned}$$

Additional CO$_2$ tax needed to reach the interim target on reducing GHG emissions from domestic transports:

$$\begin{aligned} EM_{TR,t}^{TCO2} \geq & \sum_{pr,i,po} emsh_{TR,po,pr,i,t}^{TCO2} EM_{pr,i,t}^{po} \qquad \perp T_{TR,t}^{CO2} \qquad t \in T \qquad \text{(M.49)} \\ & + \sum_{bl,i} \frac{\partial \Pi_{bl,i,t}^{BM}}{\partial \left(1 + \tau_{BM,bl,i,t}^{VA}\right) T_{TR,t}^{CO2}} BM_{bl,i,t} \\ & + \sum_{bl} \frac{\partial \Pi_{bl,t}^{BC}}{\partial \left(1 + \tau_{BC,bl,t}^{VA}\right) T_{TR,t}^{CO2}} BC_{bl,t} \end{aligned}$$

Additional GHG tax needed to reach a reduction target for aggregate GHG emissions:

$$\begin{aligned} EM_{t}^{TGHG} \geq & \sum_{bl,pr,po} emsh_{po,bl,pr,t}^{TGHG} EM_{bl,pr,t}^{po} \qquad \perp T_{t}^{GHG} \qquad t \in T \qquad \text{(M.50)} \\ & + \sum_{pr,po} emsh_{po,pr,t}^{TGHG} \; EM_{pr,t}^{po} \\ & + \sum_{pr,i,po} emsh_{po,pr,i,t}^{TGHG} \; EM_{pr,i,t}^{po} \\ & + \sum_{i,po} emsh_{po,i,t}^{TGHG} \; EM_{i,t}^{po} \\ & + \sum_{fn,h,po} emsh_{po,fn,h,t}^{TGHG} EM_{fn,h,t}^{po} \end{aligned}$$

Energy taxes:

$$\begin{aligned} REV^{TE}_{pr,t} \geq {} & \sum_{bl} \frac{\partial \Pi^{B}_{bl,pr,t}}{\partial T^{E}_{pr,t}} B_{bl,pr,t} + \\ & + \sum_{i} \frac{\partial \Pi^{M}_{pr,i,t}}{\partial \left(1 - s^{E}_{pr,i,t} + \tau^{VA}_{M,pr,i,t}\right) T^{E}_{pr,t}} M_{pr,i,t} \\ & + \frac{\partial \Pi^{C}_{pr,t}}{\partial \left(1 + \tau^{VA}_{C,pr,t}\right) T^{E}_{pr,t}} C_{pr,t} \\ & + \frac{\partial \Pi^{EX}_{pr,t}}{\partial T^{E}_{pr,t}} EX_{pr,t} \end{aligned} \qquad \perp T^{E}_{pr,t} \qquad \begin{aligned} & pr \in PR\_TE \\ & t \in T \end{aligned} \qquad \text{(M.51)}$$

Additional energy tax needed to reach the energy intensity target:

$$\begin{aligned} REV^{TEI}_{t} \geq {} & \sum_{bl,pr} \frac{\partial \Pi^{B}_{bl,pr,t}}{\partial T^{EI}_{t}} B_{bl,pr,t} \\ & + \sum_{pr,i} \frac{\partial \Pi^{M}_{pr,i,t}}{\partial \left(1 + \tau^{VA}_{M,pr,i,t}\right) T^{EI}_{t}} M_{pr,i,t} \\ & + \sum_{pr} \frac{\partial \Pi^{C}_{pr,t}}{\partial \left(1 + \tau^{VA}_{C,pr,t}\right) T^{EI}_{t}} C_{pr,t} \end{aligned} \qquad \perp T^{EI}_{t} \qquad t \in T \qquad \text{(M.52)}$$

Aviation tax:

$$\begin{aligned} REV^{TFLYG}_{t} \geq {} & \sum_{\text{lufttp} \in PR} \sum_{i} \frac{\partial \Pi^{M}_{pr,i,t}}{\partial \left(1 + \tau^{VA}_{M,pr,i,t}\right) T^{FLYG}_{t}} M_{pr,i,t} \\ & + \sum_{\text{lufttp} \in PR} \frac{\partial \Pi^{C}_{pr,t}}{\partial \left(1 + \tau^{VA}_{C,pr,t}\right) T^{FLYG}_{t}} C_{pr,t} \end{aligned} \qquad \perp T^{FLYG}_{t} \qquad t \in T \qquad \text{(M.53)}$$

Malus tax on vehicles:

$$REV^{MALUS}_{te,i,t} \geq \frac{\partial \Pi^{Y}_{i,t}}{\partial T^{MALUS}_{te,i,t}} Y_{i,t} \qquad \perp T^{MALUS}_{te,i,t} \qquad \begin{aligned} & te \in TE\_LDV \\ & i \in I \\ & t \in T \end{aligned} \qquad \text{(M.54)}$$

$$REV^{MALUS}_{te,h,t} \geq \frac{\partial \Pi^{CT}_{h,t}}{\partial T^{MALUS}_{te,h,t}} CT_{h,t} \qquad \perp T^{MALUS}_{te,h,t} \qquad \begin{aligned} & te \in TE\_LDV \\ & h \in H \\ & t \in T \end{aligned} \qquad \text{(M.55)}$$

Other excise taxes:

$$\begin{aligned}
REV^{TOTH}_{pr,t} \geq & \sum_{bl} \frac{\partial \Pi^{B}_{bl,pr,t}}{\partial T^{OTH}_{pr,t}} B_{bl,pr,t} && \perp T^{OTH}_{pr,t} \qquad pr \in PR \qquad \text{(M.56)} \\
& && \qquad\qquad\quad t \in T \\
& + \sum_{i} \frac{\partial \Pi^{M}_{pr,i,t}}{\partial \left(1+\tau^{VA}_{M,pr,i,t}\right) T^{OTH}_{pr,t}} M_{pr,i,t} \\
& + \frac{\partial \Pi^{C}_{pr,t}}{\partial \left(1+\tau^{VA}_{C,pr,t}\right) T^{OTH}_{pr,t}} C_{pr,t} \\
& + \frac{\partial \Pi^{G}_{pr,t}}{\partial \left(1+\tau^{VA}_{G,pr,t}\right) T^{OTH}_{pr,t}} G_{pr,t} \\
& + \frac{\partial \Pi^{I}_{pr,t}}{\partial \left(1+\tau^{VA}_{I,pr,t}\right) T^{OTH}_{pr,t}} I_{pr,t} \\
& + \frac{\partial \Pi^{EX}_{pr,t}}{\partial T^{OTH}_{pr,t}} EX_{pr,t}
\end{aligned}$$

Subsidy of EU emission allowances being allocated for free under the EU ETS:

$$\begin{aligned}
\frac{\partial \Pi^{Y}_{i,t}}{\partial S^{free}_{ETS,i,t}} Y_{i,t} \geq em^{free}_{ETS,i0} \cdot PETS_{0} && \perp S^{free}_{ETS,i,t} \qquad i \in I \qquad \text{(M.57)} \\
&& \qquad\qquad\quad t \in T
\end{aligned}$$

Foreign exchange:

$$\begin{aligned}
& v^{EX}_{t} EX_{t} && \perp PFX_{t} \qquad t \in T \qquad \text{(M.58)} \\
& - \sum_{pr} \frac{\partial \Pi^{IM}_{pr,t}}{\partial PFX_{t}} IM_{pr,t} \\
& + \sum_{te \in TE\_DV} \sum_{v} \left(1 - cost^{EX}_{te,v,t}\right) EXYV_{te,v,t} \\
& + \sum_{te \in TE\_LDV} \sum_{v} \left(1 - cost^{EX}_{te,v,t}\right) EXCV_{te,v,t} \\
& + rev^{SE}_{EUETS,t} \\
& + EX^{SE}_{EUESR,t} \\
& + \rho^{FLEX}_{t} em^{SE}_{FLEX,t} \\
& - IM^{auct}_{ETS,t} \\
& - BOP_{t} \\
& \geq 0
\end{aligned}$$

D.3. Income balance (I) conditions

Households:

$$\begin{aligned} INC_{h,t} = {} & PL_{h,t} \cdot l_{h,t} \\ & + \theta_h^K \cdot PK_t \cdot k_t \\ & + \theta_h^K \cdot R_t \\ & + \theta_h^{TR} \cdot PETS_t \cdot em_{ETS,h,t}^{free} \\ & - \theta_h^K \cdot PI_t \cdot SAV_t^{ADJ} \\ & - \theta_h^{LA} \cdot PLA_t \cdot la_t \\ & - PCT_{h,t} \cdot ct_{h,t} \\ & + \theta_h^{TR} \cdot INC_t^G \end{aligned} \qquad \perp INC_{h,t}^H \qquad \begin{aligned} & h \in H \\ & t \in T \end{aligned} \qquad \text{(I.01)}$$

where:

$$R_t = \sum_{pr} \frac{\partial \Pi_{i,t}^Y}{\partial \left(1 - P_{pr,t}^{ADJ}\right) P_{pr,t}} Y_{i,t} \cdot P_{pr,t} \cdot P_{pr,t}^{ADJ}$$

Government:

$$\begin{aligned} INC_t^G = {} & PFX_t \cdot BOP_t \\ & - PG_t \cdot g_t \\ & + TAX_t \\ & + PETS_t \cdot EM_{ETS,t}^{auct} \\ & - PFX_t \cdot IM_{ETS,t}^{auct} \\ & + PFX_t \cdot rev_{EUETS,t}^{SE} \\ & + PFX_t \cdot EX_{EUESR,t}^{SE} \\ & - PFX_t \cdot \rho_t^{FLEX} \cdot em_{FLEX,t}^{SE} \end{aligned} \qquad \perp INC_t^G \qquad t \in T \qquad \text{(I.02)}$$

where:

$$\begin{aligned} TAX_t = {} & TAX_t^K + TAX_t^{LS} + TAX_t^L + TAX_t^{IM} + TAX_t^{VA} + TAX_t^E \\ & + TAX_t^{CO2} + TAX_t^{GHG} + TAX_t^{FLYG} + TAX_t^{MALUS} - SUB_t^{BONUS} + TAX_t^{OTH} \end{aligned}$$

and where:

$$TAX_t^{LS} = \sum_i \frac{\partial \Pi_{i,t}^{VA}}{\partial \left(1 + T_t^{LS}\right) PLS_{i,t}} VA_{i,t} \cdot PLS_{i,t} \cdot T_t^{LS}$$

$$TAX_t^{L} = \sum_{h} \frac{\partial \Pi_t^{LS}}{\partial\left(1+\tau_{h,t}^{L}\right) PL_{h,t}} LS_t \cdot PL_{h,t} \cdot \tau_{h,t}^{L}$$

$$\begin{aligned}
TAX_t^{K} = & \sum_{i} \frac{\partial \Pi_{i,t}^{VA}}{\partial\left(1+\tau_{VA,i,t}^{K}\right) PK_t} VA_{i,t} \cdot PK_t \cdot \tau_{VA,i,t}^{K} \\
& + \sum_{i} \frac{\partial \Pi_{i,t}^{Y}}{\partial\left(1+\tau_{i,t}^{K}\right) PK_t} Y_{i,t} \cdot PK_t \cdot \tau_{i,t}^{K} \\
& + \sum_{i} \sum_{te \in TE\_DV} \sum_{v} \frac{\partial \Pi_{i,t}^{Y}}{\partial\left(1+\tau_{i,t}^{K}\right) PV_{te,v,t}^{USED}} Y_{i,t} \cdot PV_{te,v,t}^{USED} \cdot \tau_{i,t}^{K}
\end{aligned}$$

$$TAX_t^{IM} = \sum_{pr} \frac{\partial \Pi_{pr,t}^{IM}}{\partial\left(1+\tau_{pr,t}^{IM}\right) PIM_{pr,t}^{ROW}} IM_{pr,t} \cdot PIM_{pr,t}^{ROW} \cdot \tau_{pr,t}^{IM}$$

$$\begin{aligned}
TAX_t^{VA} = & \sum_{bl,i} \frac{\partial \Pi_{bl,i,t}^{BM}}{\partial\left(1+\tau_{BM,bl,i,t}^{VA}\right) PBM_{bl,i,t}^{pp}} \cdot BM_{bl,i,t} PBM_{bl,i,t}^{pp} \cdot \tau_{BM,bl,i,t}^{VA} \\
& + \sum_{bl} \frac{\partial \Pi_{bl,t}^{BC}}{\partial\left(1+\tau_{BC,bl,t}^{VA}\right) PBC_{bl,t}^{pp}} \cdot BC_{bl,t} PBC_{bl,t}^{pp} \cdot \tau_{BC,bl,t}^{VA} \\
& + \sum_{pr,i} \frac{\partial \Pi_{pr,i,t}^{M}}{\partial\left(1+\tau_{M,pr,i,t}^{VA}\right) PM_{pr,i,t}^{pp}} \cdot M_{pr,i,t} PM_{pr,i,t}^{pp} \cdot \tau_{M,pr,i,t}^{VA} \\
& + \sum_{pr} \frac{\partial \Pi_{pr,t}^{C}}{\partial\left(1+\tau_{C,pr,t}^{VA}\right) PC_{pr,t}^{pp}} \cdot C_{pr,t} PC_{pr,t}^{pp} \cdot \tau_{C,pr,t}^{VA} \\
& + \sum_{pr} \frac{\partial \Pi_{pr,t}^{G}}{\partial\left(1+\tau_{G,pr,t}^{VA}\right) PG_{pr,t}^{pp}} \cdot G_{pr,t} PG_{pr,t}^{pp} \cdot \tau_{G,pr,t}^{VA} \\
& + \sum_{pr} \frac{\partial \Pi_{pr,t}^{LA}}{\partial\left(1+\tau_{LA,pr,t}^{VA}\right) PLA_{pr,t}^{pp}} \cdot LA_{pr,t} PLA_{pr,t}^{pp} \cdot \tau_{LA,pr,t}^{VA} \\
& + \sum_{pr} \frac{\partial \Pi_{pr,t}^{I}}{\partial\left(1+\tau_{I,pr,t}^{VA}\right) PI_{pr,t}^{pp}} \cdot I_{pr,t} PI_{pr,t}^{pp} \cdot \tau_{I,pr,t}^{VA} \\
& + \sum_{po,pr,i} \frac{\partial \Pi_{pr,i,t}^{po}}{\partial\left(1-s_{pr,i,t}^{CO2}+\tau_{M,pr,i,t}^{VA}\right) T_{pr,t}^{CO2}} \cdot EM_{pr,i,t}^{po} T_{pr,t}^{CO2} \cdot \tau_{M,pr,i,t}^{VA} \\
& + \sum_{po,pr,i} \frac{\partial \Pi_{pr,i,t}^{po}}{\partial\left(1+\tau_{M,pr,i,t}^{VA}\right) T_{TR,t}^{CO2}} \cdot EM_{pr,i,t}^{po} T_{TR,t}^{CO2} \cdot \tau_{M,pr,i,t}^{VA} \\
& + \sum_{po,pr,i} \frac{\partial \Pi_{pr,i,t}^{po}}{\partial\left(1+\tau_{M,pr,i,t}^{VA}\right) T_{t}^{GHG}} \cdot EM_{pr,i,t}^{po} T_{t}^{GHG} \cdot \tau_{M,pr,i,t}^{VA} \\
& + \sum_{po,pr} \frac{\partial \Pi_{pr,t}^{po}}{\partial\left(1+\tau_{C,pr,t}^{VA}\right) T_{pr,t}^{CO2}} \cdot EM_{pr,t}^{po} T_{pr,t}^{CO2} \cdot \tau_{C,pr,t}^{VA} \\
& + \sum_{po,pr} \frac{\partial \Pi_{pr,t}^{po}}{\partial\left(1+\tau_{C,pr,t}^{VA}\right) T_{t}^{GHG}} \cdot EM_{pr,t}^{po} T_{t}^{GHG} \cdot \tau_{C,pr,t}^{VA}
\end{aligned}$$

$$
\begin{aligned}
TAX_t^E \quad &= \sum_{pr} REV_{pr,t}^{TE} \cdot T_{pr,t}^E \\
&+ \sum_{pr,i} \frac{\partial \Pi_{pr,i,t}^M}{\partial\left(1 - s_{pr,i,t}^E + \tau_{M,pr,i,t}^{VA}\right) T_{pr,t}^E} M_{pr,i,t} \cdot T_{pr,t}^E \cdot s_{pr,i,t}^E \\
&+ \sum_{bl,i} \frac{\partial \Pi_{bl,i,t}^{BM}}{\partial\left(1 - S_{bl,i,t}^E - S_{bl,i,t}^{CO2} + \tau_{BM,bl,i,t}^{VA}\right) PB_{bl,t}} BM_{bl,i,t} \cdot PB_{bl,t} \cdot S_{bl,i,t}^E \\
&+ REV_t^{TEI} \cdot T_t^{EI}
\end{aligned}
$$

$$
\begin{aligned}
TAX_t^{CO2} \quad &= \sum_{bl,pr} EM_{bl,pr,t}^{TCO2} \cdot T_{bl,pr,t}^{CO2} + \sum_{pr} EM_{pr,t}^{TCO2} \cdot T_{pr,t}^{CO2} \\
&+ \sum_{pr,i,po} \frac{\partial \Pi_{pr,i,t}^{po}}{\partial\left(1 - s_{pr,i,t}^{CO2} + \tau_{M,pr,i,t}^{VA}\right) T_{pr,t}^{CO2}} EM_{pr,i,t}^{po} \cdot T_{pr,t}^{CO2} \cdot s_{pr,i,t}^{CO2} \\
&+ \sum_{bl,i} \frac{\partial \Pi_{bl,i,t}^{BM}}{\partial\left(1 - S_{bl,i,t}^E - S_{bl,i,t}^{CO2} + \tau_{BM,bl,i,t}^{VA}\right) PB_{bl,t}} BM_{bl,i,t} \cdot PB_{bl,t} \cdot S_{bl,i,t}^{CO2} \\
&+ EM_{TR,t}^{TCO2} \cdot T_{TR,t}^{CO2}
\end{aligned}
$$

$$
TAX_t^{GHG} = EM_t^{TGHG} \cdot T_t^{GHG}
$$

$$
TAX_t^{FLYG} = REV_t^{TFLYG} \cdot T_t^{FLYG}
$$

$$
\begin{aligned}
TAX_t^{MALUS} &= \sum_{te \in TE\_LDV} \sum_i REV_{te,i,t}^{MALUS} \cdot T_{te,i,t}^{MALUS} \\
&+ \sum_{te \in TE\_LDV} \sum_h REV_{te,h,t}^{MALUS} \cdot T_{te,h,t}^{MALUS}
\end{aligned}
$$

$$
\begin{aligned}
SUB_t^{BONUS} &= \sum_{te \in TE\_DV} \sum_i \frac{\partial \Pi_{i,t}^Y}{\partial\left(1 - s_{te,i,t}^{BONUS}\right) PV_{te,i,t}^{NEW\_CHS}} Y_{i,t} \cdot PV_{te,i,t}^{NEW\_CHS} \cdot s_{te,i,t}^{BONUS} \\
&+ \sum_{te \in TE\_LDV} \sum_h \frac{\partial \Pi_{h,t}^{CT}}{\partial\left(1 - s_{te,h,t}^{BONUS}\right) PCV_{te,t}^{NEW\_CHS}} CT_{h,t} \cdot PCV_{te,t}^{NEW\_CHS} \cdot s_{te,h,t}^{BONUS}
\end{aligned}
$$

$$
TAX_t^{OTH} = \sum_{pr} REV_{pr,t}^{TOTH} \cdot T_{pr,t}^{OTH}
$$

Firm income from EU emission allowances being allocated for free under the EU ETS:

$$
\begin{aligned}
& em_{ETS,i0}^{free} \cdot PETS_0 \cdot S_{ETS,i,t}^{free} && \perp INC_{ETS,i,t}^F \quad i \in I \\
&= em_{ETS,i,t}^{free} \cdot PETS_t && \qquad\qquad\qquad\; t \in T
\end{aligned}
\tag{I.03}
$$

Value of the price and quantity adjustments of value added in production:

$$\begin{array}{lllr} \dfrac{\partial \Pi^{VA}_{i,t}}{\partial \left(1+P^{ADJ}_{VA,i,t}\right) PVA_{i,t}} VA_{i,t} \cdot PVA_{i,t} \cdot P^{ADJ}_{VA,i,t} & \perp INC^{VA}_{i,t} & i \in I & \text{(I.04)} \\ = v^{VA}_{i0} \cdot VA^{ADJ}_{i,t} \cdot PVA_{i,t} & & t \in T & \end{array}$$

Supply of used vehicles:

$$\begin{array}{lllr} YV^{USED}_{te,v,t} = PV^{USED}_{te,v,t} \cdot v^{YV\_USED}_{te,v,t} & \perp YV^{USED}_{te,v,t} & te \in TE\_DV & \text{(I.05)} \\ & & v \in V & \\ & & t \in T & \end{array}$$

$$\begin{array}{lllr} CV^{USED}_{te,v,t} = PCV^{USED}_{te,v,t} \cdot v^{CV\_USED}_{te,v,t} & \perp CV^{USED}_{te,v,t} & te \in TE\_LDV & \text{(I.06)} \\ & & v \in V & \\ & & t \in T & \end{array}$$

D.4. Auxiliary (X) conditions

Targeting increases in sectoral labour productivity and GDP (in constant prices):

$$\begin{array}{lllr} \dfrac{\dfrac{\left(\begin{array}{l} v^{Y}_{i,t} Y_{i,t} - \sum\limits_{po} EM^{po}_{i,t} - \sum\limits_{po,pr} EM^{po}_{pr,i,t} \\ \quad - \sum\limits_{te} v^{YF}_{te,i} YF_{te,i,t} - \sum\limits_{pr} v^{M}_{pr,i} M_{pr,i,t} \end{array}\right)}{\left(\begin{array}{l} v^{Y}_{i,t} Y_{i0} - \sum\limits_{po} EM^{po}_{i0} - \sum\limits_{po,pr} EM^{po}_{pr,i0} \\ \quad - \sum\limits_{te} v^{YF}_{te,i} YF_{te,i0} - \sum\limits_{pr} v^{M}_{pr,i} M_{pr,i0} \end{array}\right)}}{\dfrac{v^{LS}_{i}\ LS_{i,t}}{v^{LS}_{i}\ LS_{i0}}} = lprod^{target}_{i,t} & \perp VA^{ADJ}_{i,t} & i \in I,\ i \neq fttj & \text{(X.01)} \\ & & t \in T & \end{array}$$

$$\begin{array}{lll} \dfrac{GDP_t}{GDP_0} = gdp^{target}_{t} & & i = fttj \end{array}$$

$$\begin{array}{lllr} P^{ADJ}_{VA,i,t} = \dfrac{VA^{ADJ}_{i,t}}{VA_{i,t}} & \perp P^{ADJ}_{VA,i,t} & i \in I & \text{(X.02)} \\ & & t \in T & \end{array}$$

$$
\begin{aligned}
GDP_t = & \sum_h v^C_{h,t}\, C_{h,t} + ct_{h,t} \\
& + \sum_{pr} v^G_{pr}\, G_{pr,t} \\
& + \sum_{pr} v^I_{pr}\, I_{pr,t} \\
& + \sum_{pr} v^{LA}_{pr}\, LA_{pr,t} \\
& - \sum_{pr} v^{IM}_{pr,t}\, IM_{pr,t} \\
& + \sum_{pr} q^{EU}_{pr,t}\; v^{EX\_EU}_{pr}\; EX^{EU}_{pr,t} \\
& + \sum_{pr} q^{ROW}_{pr,t}\; v^{EX\_ROW}_{pr}\; EX^{ROW}_{pr,t} \\
& + \sum_{te,v} \left(1 - cost^{EX}_{te,v,t}\right) \cdot \left(EXYV_{te,v,t} + EXCV_{te,v,t}\right)
\end{aligned}
\qquad \perp GDP_t \qquad t \in T \qquad \text{(X.03)}
$$

Targeting prices for domestically-produced products:

$$
PA_{pr,t} = \rho_{pr,t} \qquad \perp P^{ADJ}_{pr,t} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \qquad \text{(X.04)}
$$

Targeting investments in fixed capital (in constant prices) over time:

$$
\frac{\sum_{pr} v^I_{pr}\, I_{pr,t}}{\sum_{pr} v^I_{pr}} = inv^{target}_t \qquad \perp SAV^{ADJ}_t \qquad t \in T \qquad \text{(X.05)}
$$

Targeting development of exports relative to development of imports (in constant prices) over time:

$$\frac{\left(\begin{array}{l} \sum_{te\in TE\_DV}\sum_{v}\left(1-cost_{te,v,t}^{EX}\right)EXYV_{te,v,t} \\ +\sum_{te\in TE\_LDV}\sum_{v}\left(1-cost_{te,v,t}^{EX}\right)EXCV_{te,v,t} \\ +\quad \sum_{pr} v_{pr}^{EX\_EU}\ q_{pr,t}^{EU}\ EX_{pr,t}^{EU} \\ +\quad \sum_{pr} v_{pr}^{EX\_ROW}\ q_{pr,t}^{ROW}\ EX_{pr,t}^{ROW} \end{array}\right)}{\sum_{pr} v_{pr}^{EX}} - \frac{\sum_{pr} v_{pr}^{IM}\ IM_{pr,t}}{\sum_{pr} v_{pr}^{IM}} = netexport_t^{target} \qquad \perp BOP_t \qquad t\in T \qquad \text{(X.06)}$$

$$PFX_t = \rho_t^{FX} \qquad \perp BOP_t \qquad t\in T \qquad \text{(X.07)}$$

Adjusting the rate of social security contributions to keep overall tax revenues fixed:

$$TAX_t = rev_{TAX,t}^{SE} \qquad \perp T_t^{LS} \qquad t\in T \qquad \text{(X.08)}$$

Targeting malus tax rates:

$$T_{te,i,t}^{MALUS} = \tau_{te,i,t}^{MALUS} \qquad \perp REV_{te,i,t}^{MALUS} \qquad \begin{array}{l} te\in TE\_LDV \\ i\in I \\ t\in T \end{array} \qquad \text{(X.09)}$$

$$T_{te,h,t}^{MALUS} = \tau_{te,h,t}^{MALUS} \qquad \perp REV_{te,h,t}^{MALUS} \qquad \begin{array}{l} te\in TE\_LDV \\ h\in H \\ t\in T \end{array} \qquad \text{(X.10)}$$

Targeting aviation tax rates:

$$T_t^{FLYG} = \tau_t^{FLYG} \qquad \perp REV_t^{TFLYG} \qquad t\in T \qquad \text{(X.11)}$$

Targeting energy tax rates:

$$T^{E}_{pr,t} = \tau^{E}_{pr,t} \qquad \perp REV^{TE}_{pr,t} \qquad \begin{array}{l} pr \in PR\_TE \\ t \in T \end{array} \qquad \text{(X.12)}$$

Targeting rebates from the energy tax:

$$\frac{\partial \Pi^{BM}_{bl,i,t}}{\partial \left(1 - S^{E}_{bl,i,t} - S^{CO2}_{bl,i,t} + \tau^{VA}_{BM,bl,i,t}\right) PB_{bl,t}} BM_{bl,i,t} \cdot PB_{bl,t} \cdot S^{E}_{bl,i,t} = \sum_{pr} \frac{\partial \Pi^{B}_{bl,pr,t}}{\partial T^{E}_{pr,t}} B_{bl,pr,t} T^{E}_{pr,t} s^{E}_{pr,i,t} \qquad \perp S^{E}_{bl,i,t} \qquad \begin{array}{l} bl \in BL \\ i \in I \\ t \in T \end{array} \qquad \text{(X.13)}$$

Targeting energy intensities of the economy:

$$ei^{target}_{t} \cdot \frac{\sum_{pr} \left(\begin{array}{l} \sum_{bl} \frac{\partial \Pi^{B}_{bl,pr0}}{\partial PA_{pr0}} B_{bl,pr0} \\ + \sum_{i} \frac{\partial \Pi^{M}_{pr,i0}}{\partial PA_{pr0}} M_{pr,i0} \\ + \quad \frac{\partial \Pi^{C}_{pr0}}{\partial PA_{pr0}} C_{pr0} \end{array} \right) \cdot ef^{MWh}_{pr}}{GDP_{0}} \geq \frac{\sum_{pr} \left(\begin{array}{l} \sum_{bl} \frac{\partial \Pi^{B}_{bl,pr,t}}{\partial PA_{pr,t}} B_{bl,pr,t} \\ + \sum_{i} \frac{\partial \Pi^{M}_{pr,i,t}}{\partial PA_{pr,t}} M_{pr,i,t} \\ + \quad \frac{\partial \Pi^{C}_{pr,t}}{\partial PA_{pr,t}} C_{pr,t} \end{array} \right) \cdot ef^{MWh}_{pr}}{GDP_{t}} \qquad \perp REV^{TEI}_{t} \qquad t \in T \qquad \text{(X.14)}$$

Targeting CO$_2$ tax rates:

$$T^{CO2}_{pr,t} = \tau^{CO2}_{pr,t} \qquad \perp EM^{TCO2}_{pr,t} \qquad \begin{array}{l} pr \in PR\_TCO2 \\ t \in T \end{array} \qquad (X.15)$$

$$T^{CO2}_{bl,pr,t} = \tau^{CO2}_{bl,pr,t} \qquad \perp EM^{TCO2}_{bl,pr,t} \qquad \begin{array}{l} bl \in BL \\ pr \in pr\_BL \\ t \in T \end{array} \qquad (X.16)$$

Targeting rebates from the CO$_2$ tax:

$$\begin{array}{l} \dfrac{\partial \Pi^{BM}_{bl,i,t}}{\partial\left(1 - S^{E}_{bl,i,t} - S^{CO2}_{bl,i,t} + \tau^{VA}_{BM,bl,i,t}\right) PB_{bl,t}} BM_{bl,i,t} \cdot PB_{bl,t} \cdot S^{CO2}_{bl,i,t} \\ = \\ \displaystyle\sum_{pr} \frac{\partial \Pi^{B}_{bl,pr,t}}{\partial T^{CO2}_{pr,t}} B_{bl,pr,t} T^{CO2}_{pr,t} s^{CO2}_{pr,i,t} \end{array} \qquad \perp S^{CO2}_{bl,i,t} \qquad \begin{array}{l} bl \in BL \\ i \in I \qquad t \in T \end{array} \qquad (X.17)$$

Targeting reductions of GHG emissions from domestic transports:

$$\begin{array}{l} cap^{GHG}_{TR,t} \cdot \left(\begin{array}{l} \displaystyle\sum_{po,bl,pr} EM^{po}_{bl,pr0} \cdot emsh^{TCO2}_{TR,po,bl,pr0} \cdot SH^{TR}_{bl0} \\ \displaystyle + \sum_{po,pr,i} EM^{po}_{pr,i0} \cdot emsh^{TCO2}_{TR,po,pr,i0} \end{array} \right) \\ \geq \\ \left(\begin{array}{l} \displaystyle\sum_{po,bl,pr} EM^{po}_{bl,pr,t} \cdot emsh^{TCO2}_{TR,po,bl,pr0} \cdot SH^{TR}_{bl,t} \\ \displaystyle + \sum_{po,pr,i} EM^{po}_{pr,i,t} \cdot emsh^{TCO2}_{TR,po,pr,i0} \end{array} \right) \end{array} \qquad \perp EM^{TCO2}_{TR,t} \qquad t \in T \qquad (X.18)$$

Computing share of fuel blends (in constant prices) used in road transports (as opposed to machines):

$$SH^{TR}_{bl,t} = \frac{\displaystyle\sum_{te \in TE\_DV} \sum_{i} \left(\begin{array}{l} \dfrac{\partial \Pi^{YF\_CES}_{te,i,t}}{\partial PBM_{bl,i,t}} YF^{CES}_{te,i,t} \\ + \dfrac{\partial \Pi^{YF\_NCES}_{te,bl,i,t}}{\partial PBM_{bl,i,t}} YF^{NCES}_{te,bl,i,t} \end{array} \right)}{\displaystyle\sum_{te,i} \left(\begin{array}{l} \dfrac{\partial \Pi^{YF\_CES}_{te,i,t}}{\partial PBM_{bl,i,t}} YF^{CES}_{te,i,t} \\ + \dfrac{\partial \Pi^{YF\_NCES}_{te,bl,i,t}}{\partial PBM_{bl,i,t}} YF^{NCES}_{te,bl,i,t} \end{array} \right)} \qquad \perp SH^{TR}_{bl,t} \qquad \begin{array}{l} bl \in BL \\ t \in T \end{array} \qquad (X.19)$$

Targeting reductions of GHG emissions:

$$cap_t^{GHG} \cdot \left(\begin{array}{l} \sum\limits_{po,bl,pr} EM_{bl,pr0}^{po} \cdot emsh_{po,bl,pr0}^{GHG} \\ + \sum\limits_{po,pr,i} EM_{pr,i0}^{po} \cdot emsh_{po,pr,i0}^{GHG} \\ + \sum\limits_{po,pr} EM_{pr0}^{po} \cdot emsh_{po,pr0}^{GHG} \\ + \sum\limits_{po,i} EM_{i0}^{po} \cdot emsh_{po,i0}^{GHG} \\ + \sum\limits_{po,fn,h} EM_{fn,h0}^{po} \cdot emsh_{po,fn,h0}^{GHG} \end{array} \right) \qquad \perp EM_t^{TGHG} \qquad t \in T \qquad \text{(X.20)}$$

$$\geq$$

$$\left(\begin{array}{l} \sum\limits_{po,bl,pr} EM_{bl,pr,t}^{po} \cdot emsh_{po,bl,pr0}^{GHG} \\ + \sum\limits_{po,pr,i} EM_{pr,i,t}^{po} \cdot emsh_{po,pr,i0}^{GHG} \\ + \sum\limits_{po,pr} EM_{pr,t}^{po} \cdot emsh_{po,pr0}^{GHG} \\ + \sum\limits_{po,i} EM_{i,t}^{po} \cdot emsh_{po,i0}^{GHG} \\ + \sum\limits_{po,fn,h} EM_{fn,h,t}^{po} \cdot emsh_{po,fn,h0}^{GHG} \end{array} \right)$$

Targeting rates for other excise taxes:

$$T_{pr,t}^{OTH} = \tau_{pr,t}^{OTH} \qquad \perp REV_{pr,t}^{TOTH} \qquad \begin{array}{l} pr \in PR \\ t \in T \end{array} \qquad \text{(X.21)}$$

Targeting EU emission allowance prices under the EU ETS:

$$PETS_t = \rho_t^{ETS} \qquad \perp EM_{ETS,t}^{auct} \qquad t \in T \qquad \text{(X.22)}$$

$$PETS_t = T_t^{GHG} \qquad \perp EM_{ETS,t}^{auct} \qquad t \in T \qquad \text{(X.23)}$$

Equaling value of EU emission allowances and foreign exchange when im/exporting the allowances:

$$PETS_t \cdot EM_{ETS,t}^{auct} = PFX_t \cdot IM_{ETS,t}^{auct} \qquad \perp IM_{ETS,t}^{auct} \qquad t \in T \qquad \text{(X.24)}$$

Computing net exports of the national allocation under the EU ESR:

$$EX^{SE}_{EUESR,t} = \rho^{ESR}_t \cdot \left(em^{SE}_{EUESR,t} - \left(\begin{array}{l} \sum_{po,bl,pr} EM^{po}_{bl,pr,t} \cdot emsh^{ESR}_{po,bl,pr,t} \\ + \sum_{po,pr,i} EM^{po}_{pr,i,t} \cdot emsh^{ESR}_{po,pr,i,t} \\ + \sum_{po,pr} EM^{po}_{pr,t} \cdot emsh^{ESR}_{po,pr,t} \\ + \sum_{po,i} EM^{po}_{i,t} \cdot emsh^{ESR}_{po,i,t} \\ + \sum_{po,fn,h} EM^{po}_{fn,h,t} \cdot emsh^{ESR}_{po,fn,h,t} \end{array} \right) \right) \quad \perp EX^{SE}_{EUESR,t} \quad t \in T \qquad \text{(X.25)}$$

D.5. Equations governing changes between time periods (D)

Changes in hours available for work and leisure:

$$l_{h,t} = l_{h0} \qquad h \in H \qquad \text{(D.01)}$$
$$t \in T,\ t = 2019$$

$$l_{h,t} = \left(1 + gr^{L}_{h,t-1}\right) \cdot l_{h,t-1} \qquad t \neq 2019$$

Changes in the use of fixed capital:

$$k_t = \left(\delta^K + r\right) \cdot stock^K_t \qquad t \in T \qquad \text{(D.02)}$$

Changes in the stock of fixed-capital:

$$stock^K_t = stock^K_0 \qquad t = 2015 \qquad \text{(D.03)}$$

$$stock^K_t = \left(1 - \delta^K\right) stock^K_{t\text{-}1} + v^I I_{t-1} \qquad t = 2016,...,T$$

Changes in investment demand for non-fixed capital (inventories):

$$la_t = la_0 \qquad t \in T,\ t = 2019 \tag{D.04}$$

$$la_t = \left(1 + gr_{t-1}^{LA}\right) \cdot la_{t-1} \qquad t \neq 2019$$

Changes in public consumption:

$$g_t = g_0 \qquad t \in T,\ t = 2019 \tag{D.05}$$

$$g_t = \left(1 + gr_{t-1}^{g}\right) \cdot g_{t-1} \qquad t \neq 2019$$

Changes in discretionary consumption of road transports:

$$\theta_{C,TR,h,t}^{RD} = \frac{v_{C,TR,h}^{RD} - ct_{h,t}}{\sum_{fn \in FN\_TR} v_{C,TR,h}^{fn} + v_{C,TR,h}^{RD} - ct_{h,t}} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{D.06}$$

$$\theta_{U,h,t}^{C} = \frac{v_h^{C} - ct_{h,t}}{v_{U,h}^{L} + v_h^{C} - ct_{h,t}} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{D.07}$$

$$\theta_{B,h,t}^{U} = \frac{v_h^{U} - ct_{h,t}}{v_{B,h}^{S} + v_h^{U} - ct_{h,t}} \qquad \begin{array}{l} h \in H \\ t \in T \end{array} \tag{D.08}$$

Changes in consumption of own road transports with used light-duty vehicles:

$$v_{te,v,t}^{CV\_USED} = \sum_h v_{CT,USED,te,v,h,t}^{VEHICLE} \qquad \begin{array}{l} te \in TE\_LDV \\ v \in V \\ t \in T \end{array} \tag{D.09}$$

where:

$$v_{CT,USED,te,v,h,t}^{VEHICLE} = v_{CT,USED,te,v,h,t}^{CHS} + v_{CT,USED,te,v,h,t}^{BAT} + v_{CT,USED,te,v,h,t}^{ENG}$$

$$\theta_{CT,USED,te,v,h,t}^{VEHICLE} = \frac{v_{CT,USED,te,v,h,t}^{VEHICLE}}{\sum_{dvcost} v_{CT,USED,te,v,h,t}^{dvcost}} \qquad \begin{array}{l} te \in TE\_LDV \\ v \in V \\ h \in H \\ t \in T \end{array} \tag{D.10}$$

$$\theta^{dvcost}_{CT,USED,te,v,h,t} = \frac{v^{dvcost}_{CT,USED,te,v,h,t}}{\sum_{dvcost} v^{dvcost}_{CT,USED,te,v,h,t}} \qquad (D.11)$$

maint,f $\in DVCOST$
$te \in TE\_LDV$
$v \in V$
$h \in H$
$t \in T$

$$v^{dvcost}_{CT,USED,te,v,h,t} = \sum_{vt} v^{dvcost}_{CT,USED,te,vt,h,t} \cdot fl^{vt}_{v,t} \qquad (D.12)$$

$dvcost \in DVCOST$
$te \in te\_ldv$
$v \in V$
$h \in H$
$t \in T$

where:

$$v^{dvcost}_{CT,USED,te,vt,h,t} = v^{dvcost}_{CT,USED,te,vt,h,0} \qquad t \in T\,, t = 2019$$

$$v^{CHS}_{CT,USED,te,vt,h,t} = \frac{\partial \Pi^{CT}_{h,t-1}}{\partial \left(1 - s^{BONUS}_{te,t-1}\right) PCV^{NEW\_CHS}_{te,t-1}} CT_{h,t-1} \qquad t \neq 2019\,,\ vt = t$$

$$v^{BAT}_{CT,USED,te,vt,h,t} = \frac{\partial \Pi^{CT}_{h,t-1}}{\partial PCV^{NEW\_BAT}_{te,t-1}} CT_{h,t-1} \qquad t \neq 2019\,,\ vt = t$$

$$v^{ENG}_{CT,USED,te,vt,h,t} = \frac{\partial \Pi^{CT}_{h,t-1}}{\partial PCV^{NEW\_ENG}_{te,t-1}} CT_{h,t-1} \qquad t \neq 2019\,,\ vt = t$$

$$v^{MAINT}_{CT,USED,te,vt,h,t} = \sum_{\text{main} \in FN} \frac{\partial \Pi^{CT}_{h,t-1}}{\partial PC_{fn,t-1}} CT_{h,t-1} \qquad t \neq 2019\,,\ vt = t$$

$$v^{F}_{CT,USED,te,vt,h,t} = \frac{\partial \Pi^{CT}_{h,t-1}}{\partial PCF_{te,t-1}} CT_{h,t-1} \qquad t \neq 2019\,,\ vt = t$$

$$v^{dvcost}_{CT,USED,te,vt,h,t} = \left(1 - \delta^{DV}\right) \cdot \left(1 - \theta^{EXCV}_{te,v,t\text{-}1} \cdot fl^{vt}_{v,t\text{-}1}\right) \cdot v^{dvcost}_{CT,USED,te,vt,h,t-1} \qquad t \neq 2019\,,\ vt < t$$

$$v^{dvcost}_{CT,USED,te,vt,h,t} = 0 \qquad t \neq 2019\,,\ vt \leq t - scrap_{te,h}$$

and where:

$$\theta^{EXCV}_{te,v,t\text{-}1} = EXCV_{te,v,t} \Big/ v^{CV\_USED}_{te,v,t} \qquad t \neq 2019$$

Changes in intermediate use of own road transports with used vehicles in production:

$$v_{te,v,t}^{YV\_USED} = \sum_{i} v_{Y,USED,te,v,i,t}^{VEHICLE} \qquad te \in TE\_DV \;\; v \in V \;\; t \in T \qquad \text{(D.13)}$$

where:

$$v_{Y,USED,te,v,i,t}^{VEHICLE} = v_{Y,USED,te,v,i,t}^{CHS} + v_{Y,USED,te,v,i,t}^{BAT} + v_{Y,USED,te,v,i,t}^{ENG}$$

$$\theta_{USED,te,v,i,t}^{VEHICLE} = \frac{v_{Y,USED,te,v,i,t}^{VEHICLE}}{\sum_{dvcost} v_{Y,USED,te,v,i,t}^{dvcost}} \qquad te \in TE\_DV \;\; v \in V \;\; i \in I \;\; t \in T \qquad \text{(D.14)}$$

$$\theta_{USED,te,v,i,t}^{dvcost} = \frac{v_{Y,USED,te,v,i,t}^{dvcost}}{\sum_{dvcost} v_{Y,USED,te,v,i,t}^{dvcost}} \qquad \text{maint,f} \in DVCOST \;\; te \in TE\_DV \;\; v \in V \;\; i \in I \;\; t \in T \qquad \text{(D.15)}$$

$$v_{Y,USED,te,v,i,t}^{dvcost} = \sum_{vt} v_{Y,USED,te,vt,i,t}^{dvcost} \cdot fl_{v,t}^{vt} \qquad dvcost \in DVCOST \;\; te \in TE\_DV \;\; v \in V \;\; i \in I \;\; t \in T \qquad \text{(D.16)}$$

where:

$$v_{Y,USED,te,vt,i,t}^{dvcost} = v_{Y,USED,te,vt,i0}^{dvcost} \qquad t = 2019$$

$$v_{Y,USED,te,vt,i,t}^{CHS} = \frac{\partial \Pi_{i,t-1}^{Y}}{\partial\left(1 - s_{te,t-1}^{BONUS}\right) PV_{te,i,t-1}^{NEW\_CHS}} Y_{i,t-1} \qquad t \neq 2019,\; vt = t$$

$$v_{Y,USED,te,vt,i,t}^{BAT} = \frac{\partial \Pi_{i,t-1}^{Y}}{\partial PV_{te,i,t-1}^{NEW\_BAT}} Y_{i,t-1} \qquad t \neq 2019,\; vt = t$$

$$v_{Y,USED,te,vt,i,t}^{ENG} = \frac{\partial \Pi_{i,t-1}^{Y}}{\partial PV_{te,i,t-1}^{NEW\_ENG}} Y_{i,t-1} \qquad t \neq 2019,\; vt = t$$

$$v_{Y,USED,te,vt,i,t}^{MAINT} = \sum_{\text{fttj} \in PR} \frac{\partial \Pi_{i,t-1}^{Y}}{\partial PM_{pr,i,t-1}} Y_{i,t-1} \qquad t \neq 2019,\; vt = t$$

$$v_{Y,USED,te,vt,i,t}^{F} = \frac{\partial \Pi_{i,t-1}^{Y}}{\partial PF_{te,i,t-1}} Y_{i,t-1} \qquad t \neq 2019,\; vt = t$$

$$v^{dvcost}_{Y,USED,te,vt,i,t} = \left(1-\delta^{DV}\right)\cdot\left(1-\theta^{EXYV}_{te,v,t\text{-}1}\cdot fl^{vt}_{v,t\text{-}1}\right)\cdot v^{dvcost}_{Y,USED,te,vt,i,t-1} \qquad t \neq 2019,\ vt < t$$

$$v^{dvcost}_{Y,USED,te,vt,i,t} = 0 \qquad t \neq 2019,\ vt \leq t - scrap_{te,i}$$

and where:

$$\theta^{EXYV}_{te,v,t\text{-}1} = EXYV_{te,v,t} \Big/ v^{YV\_USED}_{te,v,t} \qquad t \neq 2019$$

Changes in total factor productivity in production:

$$v^{VA}_{i,t} = \left(1+\pi^{VA}_{i,t}\right)v^{VA}_{i0} \qquad \begin{array}{l} i \in I \\ t \in T \end{array} \tag{D.17}$$

Capital-augmenting technical changes in production:

$$\theta^{K}_{i,t} = \frac{\theta^{K}_{i0}}{1+\pi^{K}_{i,t}} \qquad \begin{array}{l} i \in I \\ t \in T \end{array} \tag{D.18}$$

Labour-augmenting technical changes in production:

$$\theta^{LS}_{i,t} = \frac{\theta^{LS}_{i0}}{1+\pi^{LS}_{i,t}} \qquad \begin{array}{l} i \in I \\ t \in T \end{array} \tag{D.19}$$

Changes in the efficiency of energy use in production:

$$\theta^{NF}_{pr,i,t} = \frac{\theta^{NF}_{pr,i0}}{1+\pi^{E}_{pr,i,t}} \qquad \begin{array}{l} \text{el, fj} \in PR \\ i \in I \\ t \in T \end{array} \tag{D.20}$$

$$\theta^{SF}_{pr,i,t} = \frac{\theta^{SF}_{pr,i0}}{1+\pi^{E}_{pr,i,t}} \qquad \begin{array}{l} \text{kol, bio, torv} \in PR \\ i \in I \\ t \in T \end{array} \tag{D.21}$$

$$\theta^{LF}_{pr,i,t} = \frac{\theta^{LF}_{pr,i0}}{1+\pi^{E}_{pr,i,t}} \qquad \begin{array}{l} \text{raolja, brans,} \\ \text{gas} \in PR \\ i \in I \\ t \in T \end{array} \tag{D.22}$$

$$\theta^{F}_{FE,te,i,t} = \frac{\theta^{F}_{FE,te,i0}}{1+\pi^{E}_{te,t}} \qquad \begin{array}{l} te \in TE\_DV \\ i \in I \\ t \in T \end{array} \tag{D.23}$$

Changes in the efficiency of energy use in consumption:

$$\theta^{pr}_{fn,t} = \theta^{pr}_{fn0} \qquad pr \in PR,\; fn \in FN,\; t = 2019 \qquad \text{(D.24)}$$

$$\theta^{pr}_{fn,t} = \frac{\theta^{pr}_{fn0}}{1+\pi^{E}_{pr,t}} \qquad \text{el,f}j \in PR,\; t \neq 2019$$

$$\theta^{F}_{CT,FE,te,h,t} = \frac{\theta^{F}_{CT,FE,te,h0}}{1+\pi^{E}_{te,t}} \qquad te \in TE,\; h \in H,\; t \in T \qquad \text{(D.25)}$$

Changes in electric-vehicle battery productivity in production:

$$\theta^{BAT}_{NEW,te,i,t} = \frac{\theta^{BAT}_{NEW,te,i0}}{1+\pi^{BAT}_{te,t}} \qquad \text{phev,ev} \in TE,\; i \in I,\; t \in T \qquad \text{(D.26)}$$

Changes in electric-vehicle battery efficiency in consumption:

$$\theta^{BAT}_{CT,NEW,te,h,t} = \frac{\theta^{BAT}_{CT,NEW,te,h0}}{1+\pi^{BAT}_{te,t}} \qquad \text{phev,ev} \in TE,\; h \in H,\; t \in T \qquad \text{(D.27)}$$

Changes in world market prices and demands:

$$v^{EX\_EU}_{pr,t} = \rho^{EU}_{pr,t} \cdot q^{EU}_{pr,t} \cdot v^{EX\_EU}_{pr} \qquad pr \in PR,\; t \in T \qquad \text{(D.28)}$$

$$v^{EX\_ROW}_{pr,t} = \rho^{ROW}_{pr,t} \cdot q^{ROW}_{pr,t} \cdot v^{EX\_ROW}_{pr} \qquad pr \in PR,\; t \in T \qquad \text{(D.29)}$$

$$v^{EX}_{t} = \sum_{pr=1}^{PR} \rho^{EU}_{pr,t} \cdot q^{EU}_{pr,t} \cdot v^{EX\_EU}_{pr} + \sum_{pr=1}^{PR} \rho^{ROW}_{pr,t} \cdot q^{ROW}_{pr,t} \cdot v^{EX\_ROW}_{pr} \qquad t \in T \qquad \text{(D.30)}$$

Changes in relative prices of consumer products:

$$cpi_t = 1 \qquad t \in T,\; t = 2019 \qquad \text{(D.31)}$$

$$cpi_t = \frac{\sum_{pr} v_{pr}^{C} C_{pr0} PC_{pr,t-1} + \sum_{bl} v_{bl}^{BC} BC_{bl0} PBC_{bl,t-1}}{\sum_{pr} v_{pr}^{C} C_{pr0} + \sum_{bl} v_{bl}^{BC} BC_{bl0}} \qquad t \neq 2019$$

Changes in the number of EU emission allowances allocated for free:

$$em_{ETS,i,t}^{free} = em_{ETS,i0}^{free} \qquad i \in I \quad t \in T \quad t = 2019 \tag{D.32}$$

$$em_{ETS,i,t}^{free} = \left(1 + gr_{i,t-1}^{EM_{ETS}^{free}}\right) \cdot em_{ETS,i,t-1}^{free} \qquad t \neq 2019$$

Changes in Sweden’s revenue from auctioning EU emission allowances under the EU ETS:

$$rev_{EUETS,t}^{SE} = \theta_{EUETS,t}^{SE} \cdot rev_{EUETS,t}^{EU} \qquad t \in T \tag{D.33}$$

Changes in subsidy rates for industriklivet and klimatklivet:

$$\tau_{VA,i,t}^{K} = \tau_{VA,i0}^{K} - s_{i,t}^{industriklivet} - s_{i,t}^{klimatklivet} \qquad i \in I \quad t \in T \tag{D.34}$$

Appendix E: Calibration of model equations to the system of National and Environmental Accounts

In this appendix we describe in a general way how we calibrate the model equations to base-year (benchmark) data from the system of national- and environmental accounts. In the calibrated share form, the model equations explicitly incorporate benchmark data parameters next to the model variables, allowing for a straightforward calibration. If we take the upper nest of a firm's unit-cost function embedded in equation Z.01 as an example, we use the benchmark value parameter v and the benchmark value share parameters θ next to the price variables P and the elasticity of substitution parameter σ (see equation F.01).

The substitution elasticity governs the possibilities the firm has in substituting one input for another input when faced with changes in relative prices, but the substitution elasticity does not affect the calibration of the equation to the benchmark data. Stated differently, the equation holds under any choice of the substitution elasticity parameter.

The price variables enter the equation relative to their benchmark levels. Consequently, the precise price levels do not matter for the calibration and we follow the convention to normalize prices to one for most production factors and products. Doing so allows us to drop many benchmark prices in the denominators and allows us to readily interpret the price variables as price indices. Emission prices are the notable exception, in which case we want to readily interpret the price variables as price levels.

We obtain most benchmark value parameters directly from the National Acounts. To compute benchmark value parameters for the use of emission allowances, we obtain (process) emission levels em from the Environmental Accounts, assume benchmark price levels for the emission price variables PEM_0 and adjust the National Accounting data to match the Environmental Accounting data (e.g. deduct EU ETS allowance prices paid from other taxes paid on production). The benchmark value shares we simply deduce from the benchmark value parameters. Note that the benchmark value share parameters are specific to the nest in the functions in that the value share parameters represent the value of inputs as a share of all inputs in the particular nest in question (see e.g. the difference between $\theta_{i,t}^{EM}$ and $\theta_{EM,i}^{po}$). Note also that we benchmark most benchmark parameters to base-year data, but that for we adjust some benchmark value parameters and benchmark value share parameters in between time periods to account for e.g. productivity improvements.

$$c_{i,t}\left(P_{i,t}^{KLEM}, P_{i,t}^{EM}\right) = v_{i,t}^{Y}\left(\begin{array}{l}\theta_{i,t}^{KLEM}\left(\dfrac{P_{i,t}^{KLEM}}{P_{i0}^{KLEM}}\right)^{1-\sigma_i^{EM}} \\ +\theta_{i,t}^{EM}\left(\dfrac{P_{i,t}^{EM}}{P_{i0}^{EM}}\right)^{1-\sigma_i^{EM}}\end{array}\right)^{\frac{1}{1-\sigma_i^{EM}}} \qquad \text{(E.01)}$$

where:

$$P_{i,t}^{EM} \leq \sum_{po} \theta_{EM,i}^{po} \frac{PEM_{i,t}^{po}}{PEM_{i0}^{po}}$$

and where:

$$v_{i,t}^{Y} = v_{i,t}^{KLEM} + v_{i}^{EM}$$

$$\theta_{i,t}^{KLEM} = \frac{v_{i,t}^{KLEM}}{v_{i,t}^{KLEM} + v_{i}^{EM}}$$

$$\theta_{i,t}^{EM} = \frac{v_{i}^{EM}}{v_{i,t}^{KLEM} + v_{i}^{EM}}$$

$$v_{i}^{EM} = \sum_{po \in PO} PEM_{i0}^{po} \cdot em_{i}^{po}$$

$$\theta_{EM,i}^{po} = \frac{PEM_{i0}^{po} \cdot em_{i}^{po}}{\sum_{po \in PO} PEM_{i0}^{po} \cdot em_{i}^{po}}$$

Appendix F: Accounting for CO_2 emissions

Table F.1 CO_2 emissions in Mtonnes by source and environmental accounting classification

	Environmental accounting classifications		CO_2 emissions	
CO_2 emission source	**Activity**	**Fuel**	**Fossil**	**Biogenic**
Industry processes, diffuse sources	Diffust, IPPU, Jordbruk	Naturgas, Raffinaderigas, Kol, Koks, Övr. petroleum, ej bränslelag	4.58	-
	Stationärt	Raffinaderigas, deponi-/rötgas	1.91	0.04
	Mobilt	Biogas	-	0.23
	avfall	ej bränslelag	0.06	0.10
Combustion of coal and cokes	Stationärt	Kol, koks	1.73	-
Combustion of furnace gas in steel furnaces	IPPU, Stationärt	Koksugnsgas, Masugnsgas, LD-gas	4.78	-
Combustion of (other) gas	Stationärt	Stadsgas, Naturgas, Metan	2.35	-
	Mobilt	Naturgas	0.09	-
Combustion of diesel	Stationärt	Dieselolja	0.11	-
	mobilt	Dieselolja	12.52	-
Combustion of petrol	Mobilt	Bensin	7.80	-
Combustion of kerosene	Mobilt	Flygbensin, Flygfotogen	2.81	-
Combustion of other liquid fossil fuels	Stationary, mobilt	Eldningsolja 1 och 2-5, Brännolja, Övr. bränslen	8.57	-
Combustion of petro-chemical fuels	Stationary	Propan, Fotogen, Petroleumkoks, Övr. petroleum, Övr fasta fossila bränslen	1.25	-
	Mobilt	Gasol	0.01	-
Combustion of waste	Stationärt	Sopor	2.34	3.85
Combustion of peat	Stationärt	Torv	0.55	-
Combustion of black liquors	IPPU	Avlutar	-	17.22
Combustion of solid biomass	Stationärt	Trädbränsle, Tallolja, Träkol, Övr. biomassa	-	22.61
Combustion of biodiesel	Mobilt	FAME	-	2.76
Combustion of etanol	Mobilt	Etanol	-	0.40
	Stationärt	Etanol	-	<0.01
Total			**51.44**	**47.21**

Source: Statistics Sweden (2022b)