Februar 2022

RESEARCH PAPER NO. 19

Extensions of the Energy PUblic Policy Model for Austria and other European countries E-(PuMA)

Johannes Berger
Ludwig Strohner

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Contents

1 Introduction

This Research Paper contains a documentation of extensions of the dynamic computable general equilibrium model PuMA to implement energy and greenhouse gas emissions (GHG). The documentation of the PuMA model is published in EcoAustria Research Paper No. 11. Up to now, the model was applied to analyse economic, labour market and public finance effects of different policy reforms, structural changes and other important policy questions. PuMA is similar to the EU Labour Market Model (EU-LMM), which was also developed by the authors and is used by the Directorate General Employment, Social Affairs & Inclusion of the European Commission.[1] E-PuMA extends the model by implementing important channels of energy demand of private households and firms as well as GHG emissions.

E-PuMA implements additional demand nests for private households. This allows to model the impact of energy price changes on demand and various policy reforms like CO_2 related prices. In addition to final goods and investment goods firms additional types of firms are implemented. Electricity firms produce electricity by different kinds of energy inputs and corresponding capital stock and provide electricity to private households and the energy firms. Energy firms combine different energy inputs together with capital and electricity to produce energy provided to final goods firms. Final goods firms demand energy and decide about abatement effort with respect to non-energy-related emissions.

Section 2 describes extensions related to private households, Section 3 extensions related to firms, Section 4 describes changes related to functional forms, and Section 5 discusses relevant literature for the calibration of the model.

2 Extensions related to private households - Demand for varieties of goods

2.1 Consumption bundle of energy and non-energy consumption goods

Households consume different types of goods. The distinction is related to energy and non-energy-related consumption goods. The bundle consists of expenditures for indoor climate, traffic, other energy and non-energy-related consumption goods. In line with Varga et al. (2021), indoor climate and traffic equipment is leased from firms providing these services. Other energy is bought directly. The different consumption goods are denoted by *heat* for indoor climate expenditures, *tr* for traffic expenditures, *eo* for other energy expenditures and *ne* for all other non-energy private consumption goods. Other energy expenditures stands for electricity demand of private households not related to traffic and heating. A CES-utility function represents the preferences for the different goods, with *pe* as elasticity of substitution. The complete structure of nests implemented is shown in Figure 1.

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[1] See e.g. Berger et al. (2016) and European Commission (2017) for applications.

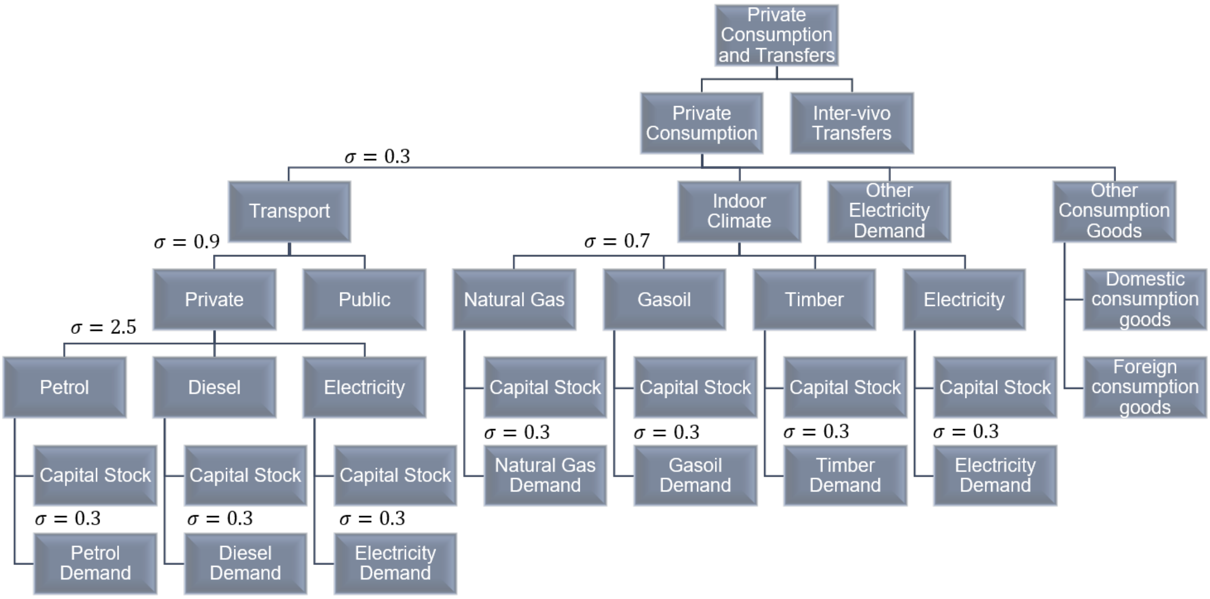

Figure 1: Nest-structure of the demand of private households

The consumption problem the household solves is given by:

$$
\begin{aligned}
pc &= \min_{c^{heat},c^{tr},c^{eo},c^{ne}} p^{heat}c^{heat} + p^{tr}c^{tr} + p^{eo}c^{eo} + pcc \cdot c^{ne} \\
\text{s.t. } U_t^e\left(c^{heat},c^{tr},c^{eo},c^{ne}\right) &= \left[\begin{array}{l} a_{e1}^{\frac{1}{pe}}\left(c^{heat}\right)^{\frac{pe-1}{pe}} + a_{e2}^{\frac{1}{pe}}\left(c^{tr}\right)^{\frac{pe-1}{pe}} + a_{e3}^{\frac{1}{pe}}\left(c^{eo}\right)^{\frac{pe-1}{pe}} + \\ +a_{e4}^{\frac{1}{pe}}\left(c^{ne}\right)^{\frac{pe-1}{pe}} \end{array}\right]^{\frac{pe}{pe-1}} \geq 1.
\end{aligned}
$$

Proposition 1 *Minimization of the price index pc leads to the following division of consumption upon energy and non-energy goods and price index:*

$$
\begin{aligned}
C_{e,j} &= a_{ej}\left(\frac{pc}{p^j}\right)^{pe} C^a, \ \textit{with } j \in \{heat{=}1,\ tr{=}2,\ eo{=}3,\ ne{=}4\} \\
pc &= \left[\sum_j a_{ej}\left(p^j\right)^{1-pe}\right]^{\frac{1}{1-pe}}.
\end{aligned}
$$

2.2 Traffic and Indoor climate demand

Traffic and indoor climate consumption of private households is characterized by renting capital stocks for traffic and indoor climate from leasing companies. Households gain utility by the consumption of the traffic and indoor climate capital in interaction with the corresponding energy source. The amount of energy source consumed reflects the intensity of consumption of the capital stock. To simplify the following representation the following notation is introduced:

$Y \in$ {traffic (tr), indoor climate (heat)}

$X \in$ {petrol, diesel, electricity, public transport} if Y = tr

$X \in$ {natural gas, gasoil, timber, electricity} if Y = heat

The sub-nest of traffic and indoor climate demand distinguishes between different energy sources, which further differentiate between rented capital and the energy source. The only exemption is public transport, for which no additional nest exists. Prices for public transport are determined by the government. More precisely, as above, cost minimization results in the following structure of consumption and price index:

$$\begin{aligned} C_{e,Y,X} &= a_{Y,X} \left(\frac{p^Y}{p^{Y,X}} \right)^{pe_Y} C_{e,Y} \\ p^Y &= \left[\sum_X a_{Y,X} \left(p^{Y,X} \right)^{1-pe_Y} \right]^{\frac{1}{1-pe_Y}} , \end{aligned}$$

and the following conditions in the lower nest:

$$\begin{aligned} C^{capital}_{e,Y,X} &= a^{capital}_{Y,X} \left(\frac{p^{Y,X}}{p^{Y,X,capital}} \right)^{pe_{Y,X}} C_{e,Y,X} \\ C^{energysource}_{e,Y,X} &= \left(1 - a^{capital}_{Y,X} \right) \left(\frac{p^{Y,X}}{p^{Y,X,energysource}} \right)^{pe_{Y,X}} C_{e,Y,X} \\ p^{Y,X} &= \left[a^{capital}_{Y,X} \left(p^{Y,X,capital} \right)^{1-pe_{Y,X}} + \left(1 - a^{capital}_{Y,X} \right) \left(p^{Y,X,energysource} \right)^{1-pe_{Y,X}} \right]^{\frac{1}{1-pe_{Y,X}}} . \end{aligned}$$

2.3 Foreign demand of energy sources

The export of energy sources as fuel for traffic plays an important role. For this reason we implement additional export demand for fuel. We implement separate demand functions for three different fuels, petrol, diesel and kerosene. The corresponding fuel is imported and directly exported such that there exists no link to the production sector. The export price differs from the import price by excise taxes. Foreign demand is given by:

$$e^{FuelX} = e^{0,FuelX} \left[\frac{p^{f,FuelX}}{p^{FuelX} + t^{excFuelX}} \right]^{p_{FuelX}} \quad \text{with FuelX} \in \{\text{petrol, diesel, kerosene}\} ,$$

where $p^{f,FuelX}$ is the foreign price for fuel, $t^{excFuelX}$ the excise tax on fuel and p_{FuelX} the armington elasticity.

3 Extensions on the Production Side

3.1 Final goods firms

Final goods firms produce output by means of capital, energy and labour input. The final goods sector is characterized by free entry, however firms have to bear fixed costs in each period they are in the market. Competition between producers of varieties and the free entry condition leads to zero profit of final goods firms in equilibrium. This condition determines the number of domestic final goods firms N^F active in the market. They face a downward sloping demand curve in their own price p_j. These firms hire workers from the labour market, fire a share of the labour force and rent capital from the capital goods firms. Offering v_i^a vacancies implies vacancy costs $\kappa_i^a\left(v_i^a\right)$ to the firm. The wage bill of firm j is given by:

$$\left(1+t^{sscF}\right) wL_j^D = \sum_{a,i} \left[\left(1+t_i^{sscF,a}\right) w_i^a L_{j,i}^{D,a} + z_i^{F,a} p^a_{man,j,i} L^{H,a}_{j,i}\right]. \tag{1}$$

t^{sscF} represents social security contributions and other wage-dependent taxes and contributions of the employer. The variable $z_i^{F,a}$ includes flat social security contributions or taxes of employers that are not related to wages, such as in Denmark. The model includes firing costs incurred by firms when dismissing workers. Firing costs consist of severance payments τ^S, firing taxes τ^{Fire} and administrative costs (like law suits; modelled as lost output) τ^C. For simplification we define $\tau^F = \tau^S + \tau^{Fire}$. Severance payments and firing taxes depend on the wage level and number of hours worked. This is not the case for administrative costs. In addition final goods firms bear labour adjustment costs. It is assumed that adjustment of employment compared to the previous period leads to costs $Ladj_i$, in form of lost output. Firms do not take into account that the employment decision in period t has an impact on the following periods. Also new firms bear adjustment costs. The nest structure of the production function is presented in Figure 2.

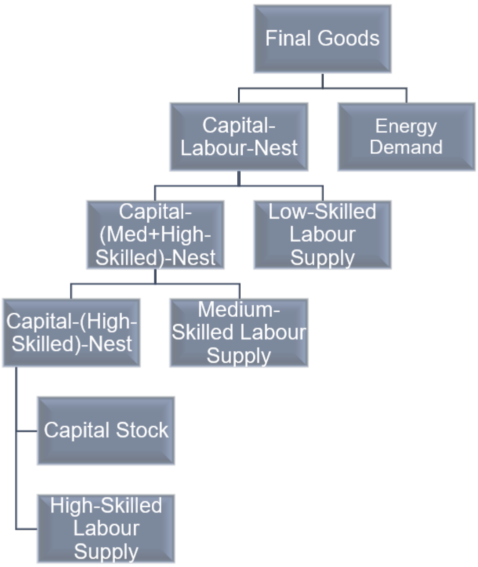

Figure 2: Nest-structure of the final goods production function

Firms have to pay taxes on profits t^{prof}. The assessment base is given by output deducted by capital costs, the wage-sum inclusive taxes and contributions paid by employers, the vacancy and managerial costs, firing taxes plus employment subsidies as well as expenditures for energy. To simplify notation we neglect index j of the firm:

$$
\begin{aligned}
&\chi = \qquad (2)\\
&p\bar{Y} - p^{k}K - p^{inv}K\left(\delta\left(u\right) - \bar{\delta}^{K}\right) - p^{E}E - \left(1 + t^{sscF}\right)wL^{D} - T^{F} + \\
&+\sum_{i,a}\left(sub^{L}p^{a}_{man,i} + sub^{T}e_{i}^{F,a}\right)L_{i}^{H,a} - \sum_{i,a}\tau_{i}^{F,a}fac_{i}^{a}\left(1 - p^{a}_{man,i}\right)w_{i}^{a}l_{i}^{a}\bar{\theta}_{i}^{a}L_{i}^{H,a} - \\
&-P_{Z}\left(1 - AB_{FG}\right)EMF_{FG}\bar{Y} + sub^{AB}AB_{FG}EMF_{FG}\bar{Y},\\
&\bar{Y} = Y - FC - \sum_{i,a}\kappa_{i}^{a}\left(v_{i}^{a}\right) - \sum_{i}Ladj_{i} - \sum_{i,a}\left(\varphi_{i}^{FS,a}\left(e_{i}^{F,a}\right) + \varphi_{i}^{F,a}\left(p^{a}_{man,i}\right)\right)L_{i}^{H,a} - \\
&-\sum_{i,a}\tau_{i}^{C,a}fac_{i}^{a}\left(1 - p^{a}_{man,i}\right)L_{i}^{H,a} - C_{FG} \qquad (3)\\
&T^{F} = \\
&t^{prof}\left(p\bar{Y} - p^{k}K - p^{inv}K\left(\delta\left(u\right) - \bar{\delta}^{K}\right) - p^{E}E - \left(1 + t^{sscF}\right)wL^{D}\right) + \\
&+t^{prof}\left(\sum_{i,a}\left(sub^{L}p^{a}_{man,i} + sub^{T}e_{i}^{F,a}\right)L_{i}^{H,a} - \sum_{i,a}\tau_{i}^{F,a}fac_{i}^{a}\left(1 - p^{a}_{man,i}\right)w_{i}^{a}l_{i}^{a}\bar{\theta}_{i}^{a}L_{i}^{H,a}\right) - \\
&-t^{prof}\left(P_{Z}\left(1 - AB_{FG}\right)EMF_{FG}\bar{Y} - sub^{AB}AB_{FG}EMF_{FG}\bar{Y}\right),\\
&C_{FG} = \varphi_{1}^{FG}AB_{FG}^{\varphi_{2}^{FG}}\bar{Y} + \frac{\gamma_{C_{FG}}}{2}\left(\frac{AB_{FG,t}}{AB_{FG,t-1}} - 1\right)^{2}\bar{Y} = \bar{A}B_{FG}\bar{Y},
\end{aligned}
$$

where $sub_{i}^{L,a}$ is a government employment subsidy and FC the fixed costs of the firm in terms of lost output. In addition, firms may get a subsidy of sub^{T} per unit of firm-sponsored training and pay $p^{E}E$ for energy whereas excise taxes for resources are paid by the energy firm. Final goods firms are responsible for non-energy GHG emissions. They decide about abatement efforts AB_{FG} to reduce emissions EMF_{FG}, measured in output terms. Emissions are priced by a price P_{Z}. Costs for higher abatement efforts are reflected in C_{FG} and are also measured in output terms.

Firms maximize dividend payments χ by optimally choosing the number of vacancies v_{i}^{a}, capital K, the firing rate $(1 - p^{a}_{man,i})$, the level of capital utilization u, firm-sponsored training $e_{i}^{F,a}$, energy demand E, and abatement effort AB_{FG}. The problem of final goods firms is

$$\max_{v,K,p,e^{F},u,E,AB_{FG}} \chi \text{ s.t.} \tag{4a}$$

$$\bar{Y} = D(p) \tag{4b}$$

$$D\left(p\right) = d_{0}\cdot\left(\frac{p^{H}\left(p\right)}{p}\right)^{\sigma}, \tag{4c}$$

where p^{H} is the price level of firms producing in the Home country and taken as given by a single firm, i.e. single firms cannot influence the average price level across all domestic firms p^{H}. The optimality conditions are given by:

$$
\begin{aligned}
v_i^a \quad : \quad & q_i^a \left\{ \begin{array}{l} \bar{\lambda}\left(F_{L,i}^{Y,a} l_i^a \bar{\theta}_i^a p_{man,i}^a - \varphi_i^{F,a}\left(p_{man,i}^a\right) - \varphi_i^{FS,a}\left(e_i^{F,a}\right) - \tau_i^{C,a} fac_i^a \left(1-p_{man,i}^a\right) - Ladj_{N_{t,i}^W} p_{man,i}^a\right) + \\ + \left(1-t^{prof}\right)\left[-\left(1+t_i^{sscF,a}\right) p_{man,i}^a w_i^a \bar{\theta}_i^a l_i^a + \left(sub^L - z_i^{F,a}\right) p_{man,i}^a + sub^T e_i^{F,a}\right] + \\ + \left(1-t^{prof}\right)\left[-\tau_i^{F,a} fac_i^a \left(1-p_{man,i}^a\right) w_i^a l_i^a \bar{\theta}_i^a\right] \end{array} \right\} \\
& = \kappa_i^{a\prime} \bar{\lambda}, \qquad (5) \\
p_{man,i}^a \quad : \quad & \bar{\lambda}\left(F_{L,i}^{Y,a} l_i^a \bar{\theta}_i^a + \tau_i^{C,a} fac_i^a - Ladj_{N_{t,i}^W}\right) - \left(1-t^{prof}\right)\left\{\left(1+t_i^{sscF,a}\right) w_i^a l_i^a \bar{\theta}_i^a + z_i^{F,a}\right\} - \\
& - \left(1-t^{prof}\right)\left\{-sub^L - \tau_i^{F,a} fac_i^a w_i^a l_i^a \bar{\theta}_i^a\right\} = \left(\varphi_i^F\left(p_{man,i}^a\right)\right)' \bar{\lambda}, \qquad (6) \\
e_i^{F,a} \quad : \quad & \left(\theta_i^{F,a}\left(e_i^{F,a}\right)\right)' l_i^a \theta_i^{H,a} \left[\begin{array}{l} p_{man,i}^a \left(\bar{\lambda} F_{L,i}^{Y,a} - \left(1-t^{prof}\right)\left(1+t_i^{sscF,a}\right) w_i^a\right) - \\ - \left(1-t^{prof}\right)\left(1-p_{man,i}^a\right) \tau_i^{F,a} fac_i^a w_i^a \end{array} \right] + \qquad (7) \\
& + \left(1-t^{prof}\right) sub^T = \left(\varphi_i^{FS}\left(e_i^{F,a}\right)\right)' \bar{\lambda},
\end{aligned}
$$

$$
\begin{aligned}
K \quad : \quad & \left(p^k + p^{inv}\left(\delta\left(u\right) - \bar{\delta}^K\right)\right)\left(1-t^{prof}\right) = \bar{\lambda} F_K^Y, \qquad (8) \\
u \quad : \quad & p^{inv} K \delta'\left(u\right)\left(1-t^{prof}\right) = \bar{\lambda} F_u^Y, \qquad (9) \\
E \quad : \quad & p^E\left(1-t^{prof}\right) = \bar{\lambda} F_E^Y, \qquad (10) \\
AB_{FG} \quad : \quad & \left(P_Z + sub^{AB}\right) EMF_{FG} = \frac{\partial \bar{AB}_{FG}}{\partial AB_{FG}} \left(\frac{1}{1+\bar{AB}_{FG}}\right)\left(p - \left(P_Z\left(1-AB_{FG}\right) - sub^{AB} AB_{FG}\right) EMF_{FG}\right), \qquad (11) \\
& \frac{\partial \bar{AB}_{FG}}{\partial AB_{FG}} = \varphi_1^{FG} \varphi_2^{FG} AB_{FG}^{\varphi_2^{FG}-1} + \gamma_{C_{FG}} \left(\frac{AB_{FG,t}}{AB_{FG,t-1}} - 1\right) \frac{1}{AB_{FG,t-1}}, \qquad (12) \\
p \quad : \quad & \bar{Y}\left(1-t^{prof}\right) = \lambda \sigma D\left(p\right) \frac{1}{p}\left(1 - \frac{p^\sigma}{N^F}\right), \qquad (13) \\
\lambda \quad : \quad & \bar{Y} = D\left(p\right) \qquad (14)
\end{aligned}
$$

Optimization with respect to the price of the firm implies that:

$$
\begin{aligned}
& p = \lambda\sigma \frac{D\left(p\right)}{\bar{Y}\left(1-t^{prof}\right)}\left(1 - \frac{p^\sigma}{N^F}\right) = \frac{\lambda\sigma}{1-t^{prof}}\left(1 - \frac{p^\sigma}{N^F}\right) \Rightarrow \\
& \underbrace{\left(\left(1-t^{prof}\right) p - \lambda\right)}_{\hat{\lambda}} = \left(1-t^{prof}\right) p \left(1 - \frac{1}{\sigma\left(1-\frac{1}{N^F}\right)}\right), \\
& \bar{\lambda} = \hat{\lambda} - \left(1-t^{prof}\right)\left(P_Z\left(1-AB_{FG}\right) EMF_{FG} - sub^{AB} AB_{FG} EMF_{FG}\right).
\end{aligned}
$$

The firm's first order conditions (FOC) equate the marginal revenues and the marginal costs of providing one additional unit of vacancies, managerial effort, firm-sponsored training, capital, capital utilization, energy demand, and abatement effort.

3.2 Electricity sector

The electricity sector provides electricity to the energy sector (see below) and private households. It produces electricity from different energy sources for which separate capital stocks exist. Energy sources are coal, oil, gas, and renewable sources. In addition, electricity can be imported based on an internationally determined electricity price. It is assumed that the sector faces perfect competition. The representative firm in the electricity sector maximizes the following value function.

$$
\begin{aligned}
& V_t^{EL}\left(K_{ELCOAL,t}, K_{ELOIL,t}, K_{ELGAS,t}, K_{ELRES,t}\right) = \\
& \max\left\{\chi_{EL,t} + \frac{GV_{t+1}^{EL}\left(K_{ELCOAL,t+1}, K_{ELOIL,t+1}, K_{ELGAS,t+1}, K_{ELRES,t+1}\right)}{R_{t+1}^{EL}}\right\}, \\
& \text{s.t. } GK_{ELX,t+1} = \left(1-\delta^{ELX}\right) K_{ELX,t} + I_{ELX,t},
\end{aligned}
$$

where RES stands for renewable sources of energy (wind, solar, biomass and hydrogen), $ELX \in \{ELRES, ELCOAL, ELOIL, ELGAS\}$ and δ^{ELX} for the depreciation rate. The representative firm produces electricity from transformation of fossil energy sources and renewable sources. Transformation based on fossils requires energy sources and a related capital stock, transformation based on renewables requires only a capital stock. Fossil energy sources are imported and not produced within the country. The structure of production for electricity firms is provided in Figure 3.

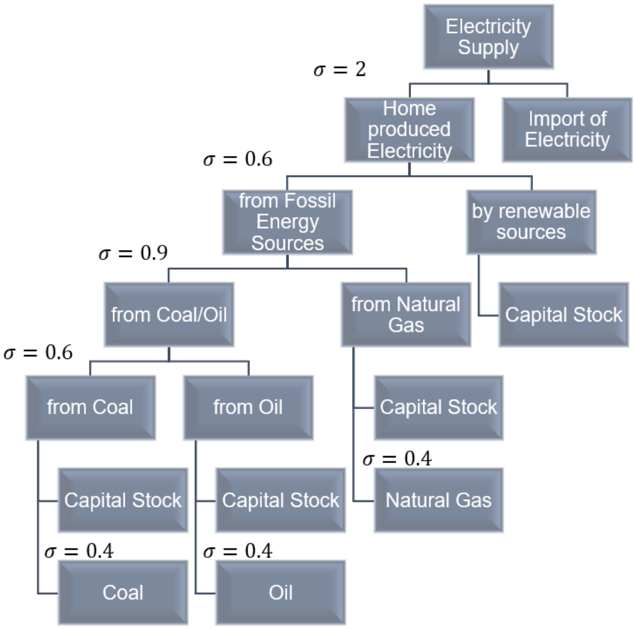

Figure 3: Nest-structure of electricity firms

Dividends $\chi_{EL,t}$ are given by

$$
\begin{aligned}
& \chi_{EL,t} = \\
& \left(1-t^{prof}\right)\left\{\begin{array}{c} P_{EL,t}EL_t^{net} - \sum_{ELX} p_t^{inv} ADJ_{I_{ELX,t}} - P_{Z,t}Z_{EL,t} - \sum_{ELX} t_{cap}^{ELX} p_t^{inv} K_{ELX,t} + \\ + \sum_{ELX} sub_t^{I,ELX} p_t^{inv} I_{ELX,t} - \sum_{ELX} PG_{ELX,t}ELX - P_{EL_{IMP,t}} EL_{IMP,t} \end{array}\right\} + \\
& + \sum_{ELX} t^{prof}\delta^{ELX} p_t^{inv} K_{ELX,t} - \sum_{ELX} p_t^{inv} I_{ELX,t}, \\
& EL_t^{net} = EL_t - C_{EL,t}.
\end{aligned}
$$

C_{EL} represents abatement costs for the electricity sector to avoid CO_2 emissions, $Z_{EL,t}$ are emissions related costs (like the emissions trading system) and $ADJ_{I_{ELX}}$ reflect adjustment costs for capital stock changes. The gross price for fossil energy PG includes ad valorem and excise taxes $PG_{ELX,t} = \left(1+t^{EL,ELX}\right) P_{ELX,t} + t^{EX,ELX}$. The same holds for the import price. Electricity EL is a nest of different energy sources as presented below.

$$\begin{aligned}
EL_t &= tf_{EL}\left[b_1 EL_{IMP,t}^{\theta_1} + (1-b_1)\, EL_{PROD,t}^{\theta_1}\right]^{\frac{1}{\theta_1}} \\
EL_{PROD,t} &= \left[b_2 EL_{FOS,t}^{\theta_2} + (1-b_2)\, EL_{ELRES,t}^{\theta_2}\right]^{\frac{1}{\theta_2}} \\
EL_{FOS,t} &= \left[b_3 EL_{COIL,t}^{\theta_3} + (1-b_3)\, EL_{ELGAS,t}^{\theta_3}\right]^{\frac{1}{\theta_3}} \\
EL_{COIL,t} &= \left[b_4 EL_{ELCOAL,t}^{\theta_4} + (1-b_4)\, EL_{ELOIL,t}^{\theta_4}\right]^{\frac{1}{\theta_4}},
\end{aligned}$$

where tf_{EL} is a transformation factor to adjust output to aggregate electricity production. The adjustment costs for fossil and renewable resources investment is given by

$$ADJ_{I_{ELX},t} = \frac{\psi_{ELX}}{2}\left(j_{ELX} - \delta^{ELX} - g\right)^2 K_{ELX,t}$$

where $j_{ELX} = \frac{I_{ELX}}{K_{ELX}}$. The production function for renewable resources and the transformation function for other energy sources are given by

$$\begin{aligned}
EL_{ELRES,t} &= tf_{ELRES}\left(K_{ELRES,t}\right)^{\alpha_{ELRES}}\left(F_{ELRES}\right)^{1-\alpha_{ELRES}}, \\
EL_{ELX,t} &= tf_{ELX}\left(a_{ELX} K_{ELX,t}^{\theta_{ELX}} + (1-a_{ELX})\, ELX^{\theta_{ELX}}\right)^{\frac{1}{\theta_{ELX}}}, \forall ELX \neq ELRES
\end{aligned}$$

where $K_{ELX,t}$ is the capital employed in production, tf_{ELX} the transformation factor scaling inputs to the produced amount of electricity and F_{ELRES} denotes the endowment of natural resources. The production of electricity from fossil fuels contributes to carbon emissions according to:

$$Z_{EL,t} = \left(1 - AB_{EL,t}\right)\sum_{ELX}\left[EMF_{ELX} ELX\right],$$

where $AB_{EL,t}$ is the abatement effort and EMF_{ELX} is the emission factor for the different CO$_2$-related energy resources. The abatement cost function C_{EL} is defined as

$$C_{EL,t} = \varphi_1^{EL} AB_{EL,t}^{\varphi_2^{EL}} \sum_{ELX \neq ELRES} ELX + \frac{\gamma_{C_{EL}}}{2}\left(\frac{AB_{EL,t}}{AB_{EL,t-1}} - 1\right)^2 \sum_{ELX \neq ELRES} ELX$$

The firm maximizes over

$$EL_{IMP,t}, I_{ELX,t}, ELX_t, AB_{EL,t}.$$

The first order and envelope conditions are given by:

$$\begin{aligned}
\frac{\partial V_t^{EL}}{\partial EL_{IMP,t}} &: \; P_{EL,t}\frac{\partial EL_t}{\partial EL_{IMP,t}} = P_{EL_{IMP},t}, \\
\frac{\partial V_t^{EL}}{\partial ELX_t \neq ELRES} &: \; P_{EL,t}\frac{\partial EL_t}{\partial ELX_t} = P_{EL,t}\frac{\partial C_{EL,t}}{\partial ELX_t} + P_{Z,t}\frac{\partial Z_{EL,t}}{\partial ELX_t} + PG_{ELX,t}, \\
\frac{\partial V_t^{EL}}{\partial AB_{EL,t}} &: \; P_{Z,t}\frac{\partial Z_{EL,t}}{\partial AB_{EL,t}} = -P_{EL,t}\frac{\partial C_{EL,t}}{\partial AB_{EL,t}}, \\
\frac{\partial V_t^{EL}}{\partial I_{ELX,t}} &: \; \frac{q_{t+1}^{ELX}}{R_{t+1}^{EL}} = p_t^{inv}\left[\left(1 - t^{prof}\right)\left(\frac{\partial ADJ_{ELX,t}}{\partial I_{ELX,t}} - sub^{I,ELX}\right) + 1\right], \\
\frac{\partial V_t^{EL}}{\partial K_{ELX,t}} &: \; q_t^{ELX} = \left(1 - t^{prof}\right)\left[P_{EL,t}\frac{\partial EL_t}{\partial K_{ELX,t}} - p_t^{inv}\frac{\partial ADJ_{ELX,t}}{\partial K_{ELX,t}} - p_t^{inv} t_{cap}^{ELX}\right] + t^{prof} p_t^{inv}\delta^{ELX} + \\
&\quad + \frac{q_{t+1}^{ELX}}{R_{t+1}^{EL}}\left(1 - \delta^{ELX}\right).
\end{aligned}$$

The partial derivatives of the energy nest are given by:

$$
\begin{aligned}
\frac{\partial EL_t}{\partial EL_{IMP,t}} &= tf_{EL}^{\theta_1} b_1 EL_{IMP,t}^{\theta_1-1} EL_t^{1-\theta_1}, \\
\frac{\partial EL_t}{\partial K_{ELRES,t}} &= tf_{EL}^{\theta_1}\left(1-b_1\right)\left(1-b_2\right) EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} \alpha_{ELRES} \frac{EL_{RES,t}^{\theta_2}}{K_{ELRES,t}}, \\
\frac{\partial EL_t}{\partial ELGAS_t} &= tf_{EL}^{\theta_1}\left(1-b_1\right) b_2\left(1-b_3\right)\left(1-a_{ELGAS}\right) tf_{ELGAS}^{\theta_{ELGAS}} ELGAS_t^{\theta_{ELGAS}-1} \cdot \\
&\quad \cdot EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} EL_{FOS,t}^{\theta_2-\theta_3} EL_{ELGAS,t}^{\theta_3-\theta_{ELGAS}}, \\
\frac{\partial EL_t}{\partial ELCOAL_t} &= tf_{EL}^{\theta_1}\left(1-b_1\right) b_2 b_3 b_4\left(1-a_{ELCOAL}\right) tf_{ELCOAL}^{\theta_{ELCOAL}} ELCOAL_t^{\theta_{ELCOAL}-1} EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} EL_{FOS,t}^{\theta_2-\theta_3} \cdot \\
&\quad \cdot EL_{COIL,t}^{\theta_3-\theta_4} EL_{ELCOAL}^{\theta_4-\theta_{ELCOAL}}, \\
\frac{\partial EL_t}{\partial ELOIL_t} &= tf_{EL}^{\theta_1}\left(1-b_1\right) b_2 b_3\left(1-b_4\right)\left(1-a_{ELOIL}\right) tf_{ELOIL}^{\theta_{ELOIL}} ELOIL_t^{\theta_{ELOIL}-1} EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} EL_{FOS,t}^{\theta_2-\theta_3} \cdot \\
&\quad \cdot EL_{COIL,t}^{\theta_3-\theta_4} EL_{ELOIL,t}^{\theta_4-\theta_{ELOIL}}, \\
\frac{\partial EL_t}{\partial K_{ELGAS,t}} &= tf_{EL}^{\theta_1}\left(1-b_1\right) b_2\left(1-b_3\right) a_{ELGAS} tf_{ELGAS}^{\theta_{ELGAS}} K_{ELGAS,t}^{\theta_{ELGAS}-1} EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} EL_{FOS,t}^{\theta_2-\theta_3} EL_{ELGAS,t}^{\theta_3-\theta_{ELGAS}}, \\
\frac{\partial EL_t}{\partial K_{ELCOAL,t}} &= tf_{EL}^{\theta_1}\left(1-b_1\right) b_2 b_3 b_4 a_{ELCOAL} tf_{ELCOAL}^{\theta_{ELCOAL}} K_{ELCOAL,t}^{\theta_{ELCOAL}-1} EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} EL_{FOS,t}^{\theta_2-\theta_3} \cdot \\
&\quad \cdot EL_{COIL,t}^{\theta_3-\theta_4} EL_{ELCOAL}^{\theta_4-\theta_{ELCOAL}}, \\
\frac{\partial EL_t}{\partial K_{ELOIL,t}} &= tf_{EL}^{\theta_1}\left(1-b_1\right) b_2 b_3\left(1-b_4\right) a_{ELOIL} tf_{ELOIL}^{\theta_{ELOIL}} K_{ELOIL,t}^{\theta_{ELOIL}-1} EL_t^{1-\theta_1} EL_{PROD,t}^{\theta_1-\theta_2} EL_{FOS,t}^{\theta_2-\theta_3} \cdot \\
&\quad \cdot EL_{COIL,t}^{\theta_3-\theta_4} EL_{ELOIL,t}^{\theta_4-\theta_{ELOIL}}.
\end{aligned}
$$

The partial derivatives of cost functions are given by:

$$
\begin{aligned}
\frac{\partial C_{EL,t}}{\partial ELX \neq ELRES} &= \left[\varphi_1^{EL} AB_{EL,t}^{\varphi_2^{EL}} + \frac{\gamma_{C_{EL}}}{2}\left(\frac{AB_{EL,t}}{AB_{EL,t-1}} - 1\right)^2\right], \\
\frac{\partial C_{EL,t}}{\partial AB_{EL,t}} &= \sum_{ELX \neq ELRES} ELX\left(\varphi_1^{EL}\varphi_2^{EL} AB_{EL,t}^{\varphi_2^{EL}-1} + \gamma_{C_{EL}}\left(\frac{AB_{EL,t}}{AB_{EL,t-1}} - 1\right)\frac{1}{AB_{EL,t-1}}\right), \\
\frac{\partial Z_{EL,t}}{\partial AB_{EL,t}} &= -\sum_{ELX} EMF_{ELX} ELX_t, \\
\frac{\partial Z_{EL,t}}{\partial ELX_t} &= \left(1 - AB_{EL,t}\right) EMF_{ELX}, \\
\frac{\partial ADJ_{I_{ELX},t}}{\partial I_{ELX,t}} &= \psi_{ELX}\left(\frac{I_{ELX,t}}{K_{ELX,t}} - \delta^{ELX} - g\right), \\
\frac{\partial ADJ_{I_{ELX},t}}{\partial K_{ELX,t}} &= -\frac{\psi_{ELX}}{2}\left(\frac{I_{ELX,t}}{K_{ELX,t}} - \delta^{ELX} - g\right)\left(\frac{I_{ELX,t}}{K_{ELX,t}} + \delta^{ELX} + g\right).
\end{aligned}
$$

The value of the energy firm is given by:

$$
V_t^{EL} = \sum_{ELX} \underbrace{q_t^{ELX} K_{ELX,t}}_{V_{K,t}^{ELX}} + V_{E,t}^{EL} = V_{K,t}^{EL} + V_{E,t}^{EL},
$$

where $V_{E,t}^{EL}$ reflects rents.

$$
\begin{aligned}
V_{E,t}^{EL} &= \text{rent}_t + \frac{GV_{E,t+1}^{EL}}{R_{t+1}^{EL}}, \\
V_{K,t}^{EL} &= \chi_{EL,t} - \text{rent}_t + \frac{GV_{K,t+1}^{EL}}{R_{t+1}^{EL}},
\end{aligned}
$$

where rent_t is defined as:

$$\text{rent}_t = \left(1 - t^{prof}\right) \left[\begin{array}{c} P_{EL} \left(EL_t^{net} - \sum_{ELX} \frac{\partial EL_t}{\partial K_{ELX,t}} K_{ELX,t} \right) - P_{Z,t} Z_{EL,t} - \\ - \sum_{ELX} PG_{ELX,t} ELX_t - P_{EL_{IMP,t}} EL_{IMP,t} \end{array} \right].$$

Optimal investment I_{ELX} is given by the positive root of the quadratic equation $I^2 + aI - b = 0$, where

$$\begin{aligned} a &= \left[\left(1 - \delta^{ELX}\right) - \left(\delta^{ELX} + g\right) + \frac{1}{\psi_{ELX}\left(1 - t^{prof}\right)} - \frac{sub_t^{I,ELX}}{\psi_{ELX}} \right] K_{ELX,t}, \\ b &= - \left[\begin{array}{c} \left(1 - \delta^{ELX}\right) \left(1 - sub_t^{I,ELX} \left(1 - t^{prof}\right)\right) - \\ -\psi_{ELX} \left(1 - \delta^{ELX}\right) \left(\delta^{ELX} + g\right) \left(1 - t^{prof}\right) - \frac{GV_{K,t+1}^{ELX}}{p_t^{inv} R_{t+1}^{EL} K_{ELX,t}} \end{array} \right] \frac{K_{ELX,t}^2}{\left(1 - t^{prof}\right) \psi_{ELX}}, \\ I_{ELX,t} &= \frac{1}{2} \left(-a + \sqrt{a^2 + 4b} \right). \end{aligned}$$

At the moment abatement decision and costs are switched off. So the electricity firm can reduce emissions by substitution of fuel.

3.3 Energy sector

The energy sector provides energy to final goods firms by transforming different energy sources and a corresponding capital stock into energy. It is very similar to the electricity sector but uses electricity from the electricity sector and does not import electricity. Energy sources are coal, oil, gas, renewable sources and electricity. It is assumed that the sector faces perfect competition. The representative firm in the electricity sector maximizes the following value function.

$$\begin{aligned} & V_t^E \left(K_{ECOAL,t}, K_{EOIL,t}, K_{EGAS,t}, K_{ERES,t} \right) = \\ & \max \left\{ \chi_{E,t} + \frac{GV_{t+1}^E \left(K_{ECOAL,t+1}, K_{EOIL,t+1}, K_{EGAS,t+1}, K_{ERES,t+1} \right)}{R_{t+1}^E} \right\}, \\ & \text{s.t. } GK_{EX,t+1} = \left(1 - \delta^{EX}\right) K_{EX,t} + I_{EX,t}, \end{aligned}$$

where, $EX \in \{ERES, ECOAL, EOIL, EGAS\}$ and δ^{EX} are depreciation rates. The representative firm produces energy from transformation of energy sources (in combination with the capital stock) and renewable sources by deciding about the level of investment in the capital stock for the transformation or production and the level of energy sources. Fossil sources are imported and not produced within the country. The structure of production nests for energy firms is provided in Figure 4.

Dividends $\chi_{E,t}$ are given by

$$\begin{aligned} & \chi_{E,t} = \\ & \left(1 - t^{prof}\right) \left\{ \begin{array}{c} P_{E,t} E_t^{net} - \sum_{EX} p_t^{inv} ADJ_{I_{EX,t}} - P_{Z,t} Z_{E,t} - \sum_{EX} t_{cap}^{EX} p_t^{inv} K_{EX,t} + \\ + \sum_{EX} sub_t^{I,EX} p_t^{inv} I_{EX,t} - \sum_{EX} PG_{EX,t} EX - P_{EL,t} EL_t^E \end{array} \right\} + \\ & + \sum_{EX} t^{prof} \delta^{EX} p_t^{inv} K_{EX,t} - \sum_{EX} p_t^{inv} I_{EX,t}, \\ & E_t^{net} = E_t - C_{E,t}. \end{aligned}$$

C_E represents abatement costs for the energy sector to avoid CO_2 emissions, $Z_{E,t}$ are emissions related costs (like the emissions trading system), $ADJ_{I_{EX}}$ reflect adjustment costs for capital stock changes, and

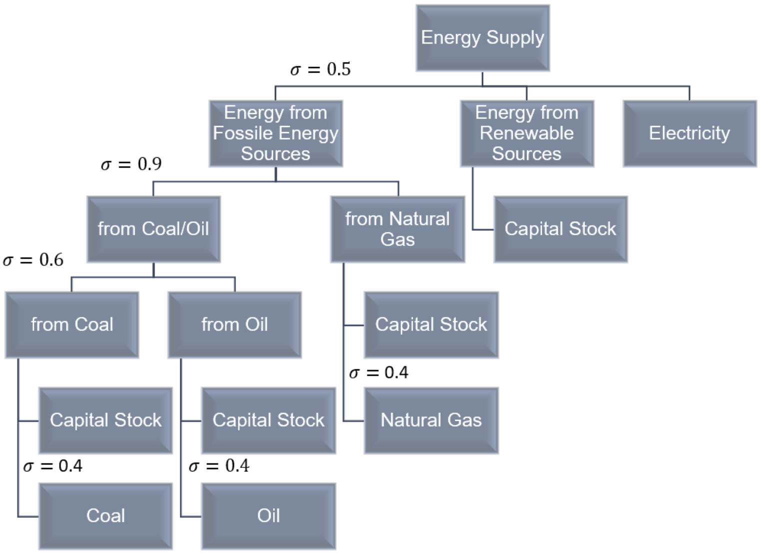

Figure 4: Nest-structure of energy firms

EL^E the demand of energy firms for electricity. The gross price for fossils PG includes ad valorem and excise taxes $PG_{EX,t} = \left(1 + t^{E,EX}\right) P_{EX,t} + t^{EX,EX}$. The same holds for the electricity price. Energy E is a nest of different energy sources as presented below.

$$\begin{aligned} E_t &= \left[c_1 E^{\theta_{E1}}_{FOS,t} + c_2 E^{\theta_{E1}}_{ERES,t} + (1 - c_1 - c_2)\, EL_t^{E^{\theta_{E1}}}\right]^{\frac{1}{\theta_{E1}}} \\ E_{FOS,t} &= \left[c_3 E^{\theta_{E3}}_{COIL,t} + (1 - c_3)\, E^{\theta_{E3}}_{EGAS,t}\right]^{\frac{1}{\theta_{E3}}} \\ E_{COIL,t} &= \left[c_4 E^{\theta_{E4}}_{ECOAL,t} + (1 - c_4)\, E^{\theta_{E4}}_{EOIL,t}\right]^{\frac{1}{\theta_{E4}}}. \end{aligned}$$

The adjustment costs for fossils and renewables investment is given by

$$ADJ_{I_{EX},t} = \frac{\psi_{EX}}{2} \left(j_{EX} - \delta^{EX} - g\right)^2 K_{EX,t}$$

where $j_{EX} = \frac{I_{EX}}{K_{EX}}$. The production function for renewable resources and the transformation function for other energy sources are given by

$$\begin{aligned} E_{ERES,t} &= tf_{ERES,t} \left(K_{ERES,t}\right)^{\alpha_{ERES}} \left(F_{ERES}\right)^{1-\alpha_{ERES}}, \\ E_{EX,t} &= tf_{EX} \left(a_{EX} K^{\theta_{EX}}_{EX,t} + (1 - a_{EX})\, EX^{\theta_{EX}}\right)^{\frac{1}{\theta_{EX}}}, \forall EX \neq RES \end{aligned}$$

where $K_{EX,t}$ is the capital employed in production, tf_{ERES} a transformation factor, and F_{ERES} denotes the endowment of natural resources. The production of electricity from fossil fuels contributes to carbon emissions according to:

$$Z_{E,t} = (1 - AB_{E,t}) \sum_{EX} \left[EMF_{EX} EX\right],$$

where $AB_{E,t}$ is the abatement effort and EMF_{EX} is the emission factor for the different CO_2-related energy resources. The abatement cost function C_E is defined as

$$C_{E,t} = \varphi_1^E AB_{E,t}^{\varphi_2^E} \sum_{EX \neq RES} EX + \frac{\gamma_{C_E}}{2} \left(\frac{AB_{E,t}}{AB_{E,t-1}} - 1\right)^2 \sum_{EX \neq RES} EX$$

The firm maximizes over

$$EL_t^E, I_{EX,t}, EX_t, AB_{E,t}.$$

The first order and envelope conditions are given by:

$$\begin{aligned}
\frac{\partial V_t^E}{\partial EL_t^E} &: \quad P_{E,t}\frac{\partial E_t}{\partial EL_t^E} = P_{EL,t} \\
\frac{\partial V_t^E}{\partial EX_t \neq ERES} &: \quad P_{E,t}\frac{\partial E_t}{\partial EX_t} = P_{E,t}\frac{\partial C_{E,t}}{\partial EX_t} + P_{Z,t}\frac{\partial Z_{E,t}}{\partial EX_t} + PG_{EX,t}, \\
\frac{\partial V_t^E}{\partial AB_{E,t}} &: \quad P_{Z,t}\frac{\partial Z_{E,t}}{\partial AB_{E,t}} = -P_{E,t}\frac{\partial C_{E,t}}{\partial AB_{E,t}}, \\
\frac{\partial V_t^E}{\partial I_{EX,t}} &: \quad \frac{q_{t+1}^{EX}}{R_{t+1}^E} = p_t^{inv}\left[\left(1 - t^{prof}\right)\left(\frac{\partial ADJ_{EX,t}}{\partial I_{EX,t}} - sub^{I,EX}\right) + 1\right], \\
\frac{\partial V_t^E}{\partial K_{EX,t}} &: \quad q_t^{EX} = \left(1 - t^{prof}\right)\left[P_{E,t}\frac{\partial E_t}{\partial K_{EX,t}} - p_t^{inv}\frac{\partial ADJ_{EX,t}}{\partial K_{EX,t}} - p_t^{inv}t_{cap}^{EX}\right] + t^{prof}p_t^{inv}\delta^{EX} + \\
&\quad + \frac{q_{t+1}^{EX}}{R_{t+1}^E}\left(1 - \delta^{EX}\right).
\end{aligned}$$

The partial derivatives of the energy nest are given by:

$$\begin{aligned}
\frac{\partial E_t}{\partial EL_t^E} &= \left(1 - c_1 - c_2\right) EL_t^{E^{\theta_{E1}-1}} E_t^{1-\theta_{E1}}, \\
\frac{\partial E_t}{\partial K_{ERES,t}} &= c_2 E_t^{1-\theta_{E1}} \alpha_{ERES} \frac{E_{RES,t}^{\theta_{E1}}}{K_{ERES,t}}, \\
\frac{\partial E_t}{\partial EGAS_t} &= c_1\left(1 - c_3\right)\left(1 - a_{EGAS}\right) tf_{EGAS}^{\theta_{EGAS}} EGAS_t^{\theta_{EGAS}-1} E_t^{1-\theta_{E1}} E_{FOS,t}^{\theta_{E1}-\theta_{E3}} E_{EGAS,t}^{\theta_{E3}-\theta_{EGAS}}, \\
\frac{\partial E_t}{\partial ECOAL_t} &= c_1 c_3 c_4 \left(1 - a_{ECOAL}\right) tf_{ECOAL}^{\theta_{ECOAL}} ECOAL_t^{\theta_{ECOAL}-1} E_t^{1-\theta_{E1}} E_{FOS,t}^{\theta_{E1}-\theta_{E3}} \cdot \\
&\quad \cdot E_{COIL,t}^{\theta_{E3}-\theta_{E4}} E_{ECOAL}^{\theta_{E4}-\theta_{ECOAL}}, \\
\frac{\partial E_t}{\partial EOIL_t} &= c_1 c_3 \left(1 - c_4\right)\left(1 - a_{EOIL}\right) tf_{EOIL}^{\theta_{EOIL}} EOIL_t^{\theta_{EOIL}-1} E_t^{1-\theta_{E1}} E_{FOS,t}^{\theta_{E1}-\theta_{E3}} \cdot \\
&\quad \cdot E_{COIL,t}^{\theta_{E3}-\theta_{E4}} E_{EOIL,t}^{\theta_{E4}-\theta_{EOIL}}, \\
\frac{\partial E_t}{\partial K_{EGAS,t}} &= c_1\left(1 - c_3\right) a_{EGAS} tf_{EGAS}^{\theta_{EGAS}} K_{EGAS,t}^{\theta_{EGAS}-1} E_t^{1-\theta_{E1}} E_{FOS,t}^{\theta_{E1}-\theta_{E3}} E_{EGAS,t}^{\theta_{E3}-\theta_{EGAS}}, \\
\frac{\partial E_t}{\partial K_{ECOAL,t}} &= c_1 c_3 c_4 a_{ECOAL} tf_{ECOAL}^{\theta_{ECOAL}} K_{ECOAL,t}^{\theta_{ECOAL}-1} EL_t^{1-\theta_{E1}} E_{FOS,t}^{\theta_{E1}-\theta_{E3}} E_{COIL,t}^{\theta_{E3}-\theta_{E4}} E_{ECOAL}^{\theta_{E4}-\theta_{ECOAL}}, \\
\frac{\partial E_t}{\partial K_{EOIL,t}} &= c_1 c_3 \left(1 - c_4\right) a_{EOIL} tf_{EOIL}^{\theta_{EOIL}} K_{EOIL,t}^{\theta_{EOIL}-1} E_t^{1-\theta_{E1}} E_{FOS,t}^{\theta_{E1}-\theta_{E3}} E_{COIL,t}^{\theta_{E3}-\theta_{E4}} E_{EOIL,t}^{\theta_{E4}-\theta_{EOIL}}.
\end{aligned}$$

The partial derivatives of cost functions are given by:

$$\begin{aligned}
\frac{\partial C_{E,t}}{\partial EX \neq ERES} &= \left[\varphi_1^E AB_{E,t}^{\varphi_2^E} + \frac{\gamma_{C_E}}{2}\left(\frac{AB_{E,t}}{AB_{E,t-1}} - 1\right)^2\right], \\
\frac{\partial C_{E,t}}{\partial AB_{E,t}} &= \sum_{EX \neq ERES} EX\left(\varphi_1^E \varphi_2^E AB_{E,t}^{\varphi_2^E-1} + \gamma_{C_E}\left(\frac{AB_{E,t}}{AB_{E,t-1}} - 1\right)\frac{1}{AB_{E,t-1}}\right), \\
\frac{\partial Z_{E,t}}{\partial AB_{E,t}} &= -\sum_{EX} EMF_{EX} EX_t, \\
\frac{\partial Z_{E,t}}{\partial EX_t} &= \left(1 - AB_{E,t}\right) EMF_{EX}, \\
\frac{\partial ADJ_{I_{EX},t}}{\partial I_{EX,t}} &= \psi_{EX}\left(\frac{I_{EX,t}}{K_{EX,t}} - \delta^{EX} - g\right), \\
\frac{\partial ADJ_{I_{EX},t}}{\partial K_{EX,t}} &= -\frac{\psi_{EX}}{2}\left(\frac{I_{EX,t}}{K_{EX,t}} - \delta^{EX} - g\right)\left(\frac{I_{EX,t}}{K_{EX,t}} + \delta^{EX} + g\right).
\end{aligned}$$

The value of the energy firm is given by:

$$V_t^E = \sum_{EX} \underbrace{q_t^{EX} K_{EX,t}}_{V_{K,t}^{EX}} + V_{E,t}^E = V_{K,t}^E + V_{E,t}^E,$$

where $V_{E,t}^E$ reflects rents.

$$\begin{aligned} V_{E,t}^E &= \text{rent}_t + \frac{GV_{E,t+1}^E}{R_{t+1}^E}, \\ V_{K,t}^E &= \chi_{E,t} - \text{rent}_t + \frac{GV_{K,t+1}^E}{R_{t+1}^E}, \end{aligned}$$

where rent_t is defined as:

$$\text{rent}_t = \left(1 - t^{prof}\right) \left[\begin{array}{c} P_E \left(E_t^{net} - \sum_{EX} \frac{\partial E_t}{\partial K_{EX,t}} K_{EX,t}\right) - P_{Z,t} Z_{E,t} - \\ - \sum_{EX} PG_{EX,t} EX_t - P_{EL,t} EL_t^E \end{array} \right]$$

Optimal investment I_{EX} is given by the positive root of the quadratic equation $I^2 + aI - b = 0$, where

$$\begin{aligned} a &= \left[\left(1 - \delta^{EX}\right) - \left(\delta^{EX} + g\right) + \frac{1}{\psi_{EX}\left(1 - t^{prof}\right)} - \frac{sub_t^{I,EX}}{\psi_{EX}}\right] K_{EX,t}, \\ b &= - \left[\begin{array}{c} \left(1 - \delta^{EX}\right)\left(1 - sub_t^{I,EX}\left(1 - t^{prof}\right)\right) - \\ -\psi_{EX}\left(1 - \delta^{EX}\right)\left(\delta^{EX} + g\right)\left(1 - t^{prof}\right) - \frac{GV_{K,t+1}^{EX}}{p_t^{inv} R_{t+1}^E K_{EX,t}} \end{array} \right] \frac{K_{EX,t}^2}{\left(1 - t^{prof}\right)\psi_{EX}}, \\ I_{EX,t} &= \frac{1}{2}\left(-a + \sqrt{a^2 + 4b}\right). \end{aligned}$$

At the moment abatement decision and costs are switched off. So the energy firm can reduce emissions by substitution of fuel.

3.4 Firms providing private transport and indoor climate equipment

Equipment for traffic and indoor climate in the private sector (cars, oven) is provided by firms. Households rent the capital stock from leasing companies at a price $p_t^{Y,X,capital}$. The leasing companies are modeled in a similar way as the investment goods firms. They maximize the net present value of dividend payments to the owners by choosing the optimal amount of investment goods bought at a price $pi_{Y,X,t}$. We assume perfect competition such that the firms earn the market rate of return in a steady state. In the following one can find the maximization problem of the leasing companies.

The maximization problem of the leasing companies in the traffic sector (tr) and indoor climate sector (heat) is:

$$\begin{aligned} V_{Y,t} &= \max_{I_{Y,X,t}} \left\{ \chi_{Y,t} + \frac{GV_{Y,t+1}}{R_{t+1}} \right\} \\ \text{s.t. } GK_{Y,X,t+1} &= (1 - \delta^{Y,X}) K_{Y,X,t} + I_{Y,X,t} \\ & Y \in \{\text{tr, heat}\} \\ & X \in \{\text{petrol, diesel, electricity}\} \text{ if Y = tr} \\ & X \in \{\text{natural gas, gasoil, timber, electricity}\} \text{ if Y = heat} \\ \chi_{Y,t} &= \sum_X p_t^{Y,X,capital} K_{Y,X,t} - \sum_X \left(1 - subi_{Y,X,t}\right) pi_{Y,X,t} I_{Y,X,t} - \sum_X pi_{Y,X,t} J_{Y,X,t} - \sum_X t_{Y,X,t}^{cap} K_{Y,X,t}, \end{aligned}$$

where $J_{Y,X,t}$ represent adjustment costs of investment and $subi_{Y,X,t}$ investment subsidies. The functional form of the adjustment costs is the same as for investment goods firms. The optimality and envelope conditions are given by:

$$\begin{aligned}
I_{Y,X,t} \quad &: \quad \frac{q_{Y,X,t+1}}{R_{t+1}} = pi_{Y,X,t}\left[(1 - subi_{Y,X,t}) + J^{I_{Y,X}}_{Y,X,t}\right] \\
K_{Y,X,t} \quad &: \quad q_{Y,X,t} = p_t^{Y,X,capital} - pi_{Y,X,t}J^{K_{Y,X}}_{Y,X,t} - t^{cap}_{Y,X,t} + \left(1 - \delta^{Y,X}\right)\frac{q_{Y,X,t+1}}{R_{t+1}}
\end{aligned}$$

Proposition 2 *The value of leasing companies is given by:*

$$V_{Y,t} = \sum_X q_{Y,X,t}K_{Y,X,t} = \sum_X V_{Y,X,t}$$

Proof. *Multiplying the envelope condition by $K_{Y,X,t}$ gives*

$$q_{Y,X,t}K_{Y,X,t} = p_t^{Y,X,capital}K_{Y,X,t} - pi_{Y,X,t}J^{K_{Y,X}}_{Y,X,t}K_{Y,X,t} - t^{cap}_{Y,X,t}K_{Y,X,t} + \underbrace{\left(1-\delta^{Y,X}\right)K_{Y,X,t}}_{GK_{Y,X,t+1}-I_{Y,X,t}}\frac{q_{Y,X,t+1}}{R_{t+1}}$$

Using the first order condition to replace $\frac{I_{Y,X,t}q_{Y,X,t+1}}{R_{t+1}}$ and the linear homogeneity of adjustment costs $J_{Y,X,t}$ leads to:

$$q_{Y,X,t}K_{Y,X,t} = V_{Y,X,t} = \chi_{Y,X,t} + \frac{GV_{Y,X,t+1}}{R_{t+1}}$$

Summing up over the different energy sources X proofs the proposition

$$\sum_X V_{Y,X,t} = V_{Y,t} = \underbrace{\sum_X \chi_{Y,X,t}}_{\chi_{Y,t}} + \underbrace{\sum_X V_{Y,X,t+1}}_{V_{Y,t+1}}\frac{G}{R_{t+1}}$$

■

Similar to the investment firm, optimal investment is given by:

$$I_{Y,X} = \frac{1}{2}\left(-a + \sqrt{a^2 + 4b}\right),$$

where

$$\begin{aligned}
a &= \left[\left(1-\delta^{Y,X}\right) - \left(\delta^{Y,X} + g\right) + \frac{1 - subi_{Y,X}}{\psi^{Y,X}}\right]K_{Y,X}, \\
b &= -\left\{\left(1-\delta^{Y,X}\right)\left(1 - subi_{Y,X}\right) - \left(1-\delta^{Y,X}\right)\left(\delta^{Y,X} + g\right)\psi^{Y,X} - \frac{GV_{Y,X,t+1}}{R_{t+1}pi_{Y,X}K_{Y,X}}\right\}\frac{K^2_{Y,X}}{\psi^{Y,X}}
\end{aligned}$$

The investment bundle for indoor climate and traffic consists of imported and home produced goods (e.g. new cars and repairs). In addition, demand for investment goods is divided across firms producing varieties. Leasing companies solve the following minimization problem (neglecting time index):

$$\begin{aligned}
pi_{Y,X} \quad &= \quad \min_{i^h_{Y,X}, i^f_{Y,X}} pi^h_{Y,X}i^h_{Y,X} + p^f_{Y,X}i^f_{Y,X}, \\
s.t. U^I_{Y,X} \quad &= \quad \left[{a^i_{Y,X}}^{\frac{1}{p^i_{Y,X}}}\left(i^h_{Y,X}\right)^{\frac{p^i_{Y,X}-1}{p^i_{Y,X}}} + \left(1 - a^i_{Y,X}\right)^{\frac{1}{p^i_{Y,X}}}\left(i^f_{Y,X}\right)^{\frac{p^i_{Y,X}-1}{p^i_{Y,X}}}\right]^{\frac{p^i_{Y,X}}{p^i_{Y,X}-1}} \geq 1,
\end{aligned}$$

where $i^h_{Y,X}$ is the investment demand for home produced goods and $i^f_{Y,X}$ for imported goods per utility unit. Optimization leads to:

$$\begin{aligned}
I^h_{Y,X} &= a^i_{Y,X} \left(\frac{pi_{Y,X}}{pi^h_{Y,X}} \right)^{p^i_{Y,X}} I_{Y,X} \\
I^f_{Y,X} &= (1 - a^i_{Y,X}) \left(\frac{pi_{Y,X}}{pi^f_{Y,X}} \right)^{p^i_{Y,X}} I_{Y,X} \\
pi_{Y,X} &= \left[a^i_{Y,X} \left(pi^h_{Y,X} \right)^{1-p^i_{Y,X}} + (1 - a^i_{Y,X}) \left(pi^f_{Y,X} \right)^{1-p^i_{Y,X}} \right]^{\frac{1}{1-p^i_{Y,X}}} \\
I^h_{Y,X,j} &= \left(\frac{pi^h_{Y,X}}{p_j} \right)^{\sigma} I^h_{Y,X} \\
pi^h_{Y,X} &= p\,(= p_j)\, N^{F\,\frac{1}{1-\sigma}},
\end{aligned}$$

where $I^h_{Y,X,j}$ is the investment demand for a variety in the home country.

4 Functional Forms

4.1 Functional Forms Concerning Firms

The **production function** used in the model is a nested CES-production function Y. The different inputs are the nests. Utilized Capital, energy and aggregate effective[2] labour input are the inputs for the production function.

$$Y = F^{Y}(uK, L_1^D, L_2^D, L_3^D, E) = A \cdot z_1,$$

where

$$\begin{aligned}
z_1 &= \left[a_1 \left(a_e E\right)^{\pi_1} + \left(1-a_1\right) z_2^{\pi_1}\right]^{1/\pi_1};\\
z_2 &= \left[a_2 \left(L_1^D\right)^{\pi_2} + \left(1-a_2\right) z_3^{\pi_2}\right]^{1/\pi_2};\\
z_3 &= \left[a_3 \left(L_2^D\right)^{\pi_3} + \left(1-a_3\right) z_4^{\pi_3}\right]^{1/\pi_3};\\
z_4 &= \left[a_4 \left(L_3^D\right)^{\pi_4} + \left(1-a_4\right) \left(uK\right)^{\pi_4}\right]^{1/\pi_4},
\end{aligned}$$

where a_e reflects energy efficiency. Given the functional form of the production function the marginal products of the different inputs are given by:

$$\begin{aligned}
F_E^Y &= A \cdot a_1 a_e^{\pi_1} \left(E\right)^{\pi_1-1} z_1^{1-\pi_1}; \qquad (15)\\
F_{L,1}^Y &= A\left(1-a_1\right) a_2 \left(L_1^D\right)^{\pi_2-1} z_1^{1-\pi_1} z_2^{\pi_1-\pi_2};\\
F_{L,2}^Y &= A\left(1-a_1\right)\left(1-a_2\right) a_3 \left(L_2^D\right)^{\pi_3-1} z_1^{1-\pi_1} z_2^{\pi_1-\pi_2} z_3^{\pi_2-\pi_3};\\
F_{L,3}^Y &= A\left(1-a_1\right)\left(1-a_2\right)\left(1-a_3\right) a_4 \left(L_3^D\right)^{\pi_4-1} z_1^{1-\pi_1} z_2^{\pi_1-\pi_2} z_3^{\pi_2-\pi_3} z_4^{\pi_3-\pi_4};\\
F_K^Y &= A\left(1-a_1\right)\left(1-a_2\right)\left(1-a_3\right)\left(1-a_4\right) u^{\pi_4} K^{\pi_4-1} z_1^{1-\pi_1} z_2^{\pi_1-\pi_2} z_3^{\pi_2-\pi_3} z_4^{\pi_3-\pi_4};\\
F_u^Y &= A\left(1-a_1\right)\left(1-a_2\right)\left(1-a_3\right)\left(1-a_4\right) u^{\pi_4-1} K^{\pi_4} z_1^{1-\pi_1} z_2^{\pi_1-\pi_2} z_3^{\pi_2-\pi_3} z_4^{\pi_3-\pi_4}.
\end{aligned}$$

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[2] Taking into account productivity units of the different age groups.

5 Calibration

5.1 Abatement Costs

In our baseline modeling, we assume that GHG emissions linked to the combustion of fuel (i.e. in the electricity and energy sector and for private households) can be abated by substituting away from fossil fuels towards cleaner energy, i.e. we assume that there is no explicit abatement technology in these sectors. For final goods firms, we follow the often cited results in Nordhaus (2008), which is also referred to by Cline (2011), for the parametrisation of abatement costs. The scale parameter of the abatement cost function (φ_1^{FG}) is set to 0.025, while the parameter governing the convexity of the functions (φ_2^{FG}) is set to 2.8. The parameter $\gamma_{C_{FG}}$, which determines the adjustment costs of abatement, is set in such way that half of the long-run increase of abatement takes place within five years (which is slightly faster than for capital stock adjustment).

5.2 Elasticities of Substitution for Energy and Electricity Firms

We consider well known dynamic general equilibrium models like the E-QUEST-model as in Varga et al. (2021), GEM-E3 (Capros et al., 2013), GTAP-E (Burniaux and Truong, 2002) and the WorldScan-model (Lejour et al., 2006) for the calibration of the elasticities of substitution in the CES-functions. The GTAP-E model incorporates Other (intermediate) Inputs, which are divided into domestic and foreign products and a Value-added-Energy bundle which includes skilled and un-skilled Labour, Land, Natural Resources and a capital-energy composite. The capital-energy composite is divided into non-electric and electric energy, which are then divided further into the particular sources of energy (coal, gas, oil and petroleum products) as well as into domestic and foreign energy (Burniaux and Truong, 2002). In the E-QUEST model, production is nested in five consecutive nests and includes the input factors intermediates, labour (low-, medium-, high-skilled), general capital as well as a ‘clean’ and a ‘dirty’ capital-energy composite (Varga et al., 2021). Capros et al. (2013) nest the GEM-E3 production side of the model by sectors and more explicitly differentiate various energy supply sectors but make use of a similar range of inputs as the two models described before. In the WorldScan-model (Lejour et al., 2006) the first nest consists of fixed factor inputs versus other inputs. The latter includes value-added/energy and intermediates, while value added contains R&D as well as capital, low-skilled and high-skilled labour. Further models with nested CES production functions are Bartocci and Pisani (2013), the REMIND-model by Hilaire and Bertram (2020), the GEEM-model by Annicchiarico et al. (2017), and the WEGDYN-AT model (Mayer et al. 2021). The elasticities of substitution used in production functions reflect the substitutability between input factors, where higher values imply better substitutability and elasticities near zero reflect complementary input factors. The survey shows, that elasticities vary across the models to some extent.

For the elasticity of energy towards other input factors, Annicchiarico et al. (2017) use 0.8, Capros et al. (2013) choose 0.25, Bartocci and Pisani (2013) choose 0.3. Mayer et al. (2021) apply values ranging from 0.25 and 0.8 in the vast majority of NACE sectors. Hilaire and Bertram (2020) as well as Lejour et al. (2006) determined 0.5 to be the fitting elasticity of substitution between Energy and other inputs. We choose a value of 0.3 in the baseline calibration, which is slightly higher than in Capros et al. (2013) but below, for instance, Lejour et al. (2006). Concerning elasticities of substitution of different energy sources towards each other, varying evidence can be found in the models as they also have different definitions and energy inputs. These elasticities cluster between 0.25 and 1.1. For θ_{E1}, the elasticity of substitution between fossil energy, renewable energy and electricity, we choose 0.5 in the baseline calibration which lies in the middle of common values and corresponds to what Capros et al. (2013) choose for their model. The elasticity of substitution between imported and domestically produced electricity, θ_{EL1}, takes the value 2, which reflects that tradable, similar energy sources are substitutable more easily. θ_{EL2}, the elasticity of substitution between electricity obtained by fossil energy sources and electricity derived from renewable energy sources is set to 0.6 which reflects the values of Annicchiarico et al. (2017). Fossil-obtained electricity is again divided in a coal-oil composite and gas while the elasticity of substitution, θ_{EL3}, takes the value of 0.9, also used in Capros et al. 2013 and Bartocci and Pisani (2013). This also holds for θ_{E3}, being the elasticity of substitution between energy generated from gas and energy generated in the coal-oil nest. Similarly θ_{EL4} and θ_{E4}, the substitution elasticity for coal and oil are assumed to be 0.6 in our model which is the average of values applied by Capros et al. (2013) and Annicchiarico et al. (2017). For substitution elasticities of capital used in energy generation/transformation and different energy inputs, the literature produces values between 0.3 (Bartocci and Pisani, 2013 and Annicchiarico et al., 2017) and 0.5 (Varga et al., 2021). For our baseline calibration, we find 0.4 to be the most fitting value, which also represents an average of the values that stand out in the literature.

5.3 Private households

Private households decide about the demand for equipment and energy sources for traffic and indoor climate as well as for electricity. It is necessary to set elasticities of substitution between equipment and energy sources and between different types of equipment. However, empirical literature focuses on demand elasticities for different energy sources. Elasticities of substitution are set in such a way that they result in the estimated demand elasticities.

Demand elasticities of energy sources for traffic

The economic literature provides a lot of empirical papers which estimate demand elasticities for fuel. Sterner (2006) provides an overview about the results of the earlier literature. He shows that the choice of the model has an important impact on the results. Nevertheless, the survey shows that short-run elasticities are considerably lower as long-run elasticities. Short-run elasticities range between -0.1 and -0.3, long-run elasticities between -0.6 and -0.9. For Austria the long-run elasticity lies between -0.6 and -1.2.

Hössinger et al. (2017) provide further and new evidence about elasticities of fuel demand with respect to prices (see Table 1). Estimations in these studies are based on aggregate consumption data. Again the studies show that short term elasticities are considerably lower than long term elasticities. Many of them focus on North America or worldwide demand. Elasticities are considerably lower than those cited in Sterner, especially in the long-term. In general they lie between -0.2 and -0.4.

Table 1: Price elasticities of fuel demand reported in the literature, by average year of observation

Source	Observation period	Average year	Geographic region	Elasticity of fuel demand		Data type
				Short term	Long term	
Archibald and Gillingham (1980)	1972-1973	1972	USA	-0.43	-	D
Goodwin et al. (2004)	1974-1981	1978	Worldwide	-0.35	-0.93	A,D
Hughes et al. (2008)	1975-1980	1978	USA	-0.275	-	A
Dahl (2012) - gasoline	1954-2005	1980	Worldwide	-0.15	-0.55	A,D
Dahl (2012) - diesel	1954-2005	1980	Worldwide	-0.10	-0.33	A,D
Kayser (2000)	1981	1981	USA	-0.23		D
Puller and Greening (1999)	1980-1990	1985	USA	-0.35	-	D
Hymel et al. (2010)	1966-2004	1985	USA	-0.075	-0.361	A
Brons et al. (2008)	1972-1999	1986	Worldwide	-0.36	-0.81	A,D
Goodwin et al. (2004)	1981-1991	1986	Worldwide	-0.16	-0.43	A,D
Brännlund and Nordström (2004)	1985-1992	1989	Sweden	-	-0.98	D
Sentenac-Chemin (2012)	1978-2005	1991	USA	-	-0.3	A
Havranek et al. (2012)	1974-2011	1993	Worldwide	-0.09	-0.31	A,D
Wadud et al. (2009)	1984-2003	1994	USA	-0.266	-	A
Odeck and Johansen (2016)	1980-2011	1995	Norway	-0.26	+0.09	A
Hirota et al. (2003)	1990-2002	1996	Worldwide	-0.195	-	A
West and Williams (2007)	1996-1998	1997	USA	-0.51	-	D
Romero-Jordán et al. (2010)	1998-2001	2000	Spain	-	-0.55	D
Wadud et al. (2010a)	1997-2002	2000	USA		-0.473	D
Austin and Dinan (2005)	2001	2001	USA	-	-0.39	A
Lin and Prince (2013)	1990-2012	2001	USA	-0.03	-0.239	A
Burguillo et al. (2017)	1998-2005	2001	Spain	-0.35 to -0.49		D
Burke and Nishitateno (2013)	1995-2008	2002	Worldwide	-	-0.2 to -0.5	A
Hughes et al. (2008)	2001-2006	2004	USA	-0.056	-	A
Hymel et al. (2010)	2004	2004	USA	-0.055	-0.285	A

Hössinger et al. (2017) use a stated preference survey to estimate the response to hypothetical fuel price changes. The sample is based on representative Austrian households. Immediate fuel price response elasticities rise from -0.12 for a fuel price of 1.5 euro per litre to -0.35 for a fuel price of 4 euro per litre. The response after one year corresponds to an elasticity of -0.19 for 1.5 euro and rises to -0.66 for 4 euro. The response after 5 years is similar to the results after 1 year. Kratena et al. (2008) also estimate the price elasticity for fuel demand in Austria. The estimated uncompensated elasticity is -0.59.

Results in Havranek et al. (2012) indicate that long-term elasticities may be significantly lower as often assumed. Based on a meta-analysis they test for a publication bias. Taking into account the publication bias, elasticities are half as high as previous meta-analysis have shown. Based on their estimations long-run elasticities are about -0.3.

Fridstrom and Ostli (2021) derive direct and cross demand market response functions for powertrains and energy sources in Norway from 2016 onwards. They derive direct and cross price elasticities of automobiles and demand price and cross price elasticities of automobiles with respect to energy prices. The own price elasticity of gasoline driven cars is estimated at -1.08, those of diesel driven and electric cars at -1.27 and -0.99, respectively. The cross price elasticities of demand for gasoline cars with respect to price of diesel cars are estimated at 0.64 and 0.51 vice versa. Cross price elasticities for electric cars with respect to gasoline and diesel cars are 0.36 and 0.48.

Holmgren (2007) provides a meta-analysis of public transport demand. The expected value of the own price elasticity for European countries in the short run is -0.75 and -0.91 in the long run, respectively.

Demand elasticities of indoor climate - heating

Literature about demand elasticities for heating is less comprehensive compared to the impact of prices on traffic demand. Rehdanz (2007) uses information of the German socioeconomic panel data for 1998 to 2003 to estimate demand elasticities for different energy sources and types of households. She finds that the elasticity for heat demand for oil based heating is between -2.03 and -1.68 and -0.63 and -0.44 for gas based heating systems. Hellmer (2013) finds that the elasticity for district heating is lower than of other types of heating systems. The estimate of the elasticity of households in small houses is -0.48, for households in residential buildings the elasticity is -0.25. Andersen et al. (2020) analyze barriers for switching between different heating systems in Denmark. They also derive demand elasticities, with -0.4 as medium estimate. Haas and Biermayr (2000) estimate an elasticity for heat demand of -0.2 in Austria, Kratena et al. (2008) estimate an uncompensated elasticity of -0.31.

In general, the results indicate that the demand elasticity for energy sources for heating is somewhat lower compared to traffic. This can be found also in Schulte and Heindl (2016). They use household consumption data to derive demand elasticities for different types of goods and households. They find an overall own price elasticity for transport demand of -0.57, for heating demand of -0.5 and for electricity demand of -0.4.

Demand elasticities of electricity demand

The literature finds rather inelastic demand of private households for electricity for the United States. Ito (2014) finds a price elasticity between -0.03 and -0.1, Burke and Abayasekara (2018) and Allcott (2011) also find a value of -0.1 in the short run. Ros (2017) on the other hand estimates an elasticity of between -0.1 and -0.5. In the long-run, elasticities are higher, -1 in Burke and Abayasekara and between -0.4 and -0.6 in Ros.

Several papers deal with the estimation of demand elasticities in Europe. Nesbakken (1999) uses data about Norway and reports an elasticity of -0.66, Filippini (2011) for the Switzerland of -0.8 and -0.95. Brännlund et al. (2007) use Swedish data and estimate a short-run elasticity of -0.24. Alberini (2019) focuses on the impact of a very large price increase in the Ukraine and comes up with an elasticity of -0.2 to -0.5. Kratena et al. (2008) find an uncompensated electricity demand elasticity for Austria of -0.20 and a compensated elasticity of -0.18. Schulte and Heindl (2016) find an elasticity for Germany of -0.43, being again considerably higher for higher expenditure quartiles.

In the model, elasticities of substitutions are set in such a way that demand elasticities are about -0.35 for fossil energy sources. The elasticities of substitution for different forms of traffic are set higher compared to heating. The lower elasticity of substitution for heating is motivated by less influence of private households living in flats on the decision about heating systems. The value replicates results in Fridstrom and Ostli (2021). Substitution between public and private traffic is based on Holmgren (2007). The elasticity of substitution on the top-level (between traffic, heating, electricity and other consumption goods) is set to 0.3 which leads to a demand elasticity of -0.3. An elasticity of substitution of 0.3 is also used in Bartocci and Pisani (2013), the EPPA[3]-calibration and in Bodenstein et al. (2011). Traffic demand elasticities of foreigners are based on Hirt (2015).

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[3] MIT Emission Prediction and Policy Analysis Model, see Paltsev (2005).

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Copyright und Kontakt:
Johannes Berger, johannes.berger@ecoaustria.ac.at, +4366488739624
Ludwig Strohner, ludwig.strohner@ecoaustria.ac.at, +4366488739626

www.ecoaustria.ac.at