CPB Netherlands Bureau for
Economic Analysis
PBL Netherlands Environmental
Assessment Agency

Documentation Green-R

CPB / PBL

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1 Introduction

The Dutch economy is currently in a transition to a climate-neutral economy. At the European level, it has been agreed to reduce greenhouse gas emissions by 55% by 2030 and to be climate neutral by 2050. Next to this climate target, the Dutch government also has set a goal for a fully circular economy (CE) by 2050.

In order to make well-informed policy decisions, it is important to have a clear understanding of the relationships between economic activities, energy markets, greenhouse gas emissions and use of materials. It is also useful to be able to make an ex ante assessment of the impact of policy measures. CPB and PBL have therefore jointly developed a multi-regional multi-sectoral global general equilibrium model (Computable General Equilibrium, CGE), which can be used to assess the impact of various policy options in the field of both climate and circular economy. The acronym used for the model is GREEN-R (Global Recursive Equilibrium model on ENergy and Resources). The model is a recursive dynamic model, which means that agents are not forward looking. Decisions by firms and households are based only on the previous and current period variables, independent of expectations on future developments. The first application of GREEN-R is a publication on the implications of CBAM for both emissions and output in the European and Dutch industry (Olijslagers et al., 2024).

We have set-up the model in a flexible way. After all, not the same amount of regional and sectoral detail is needed for each research question. The regional and sectoral breakdowns are flexible (with the maximum number of sectors and regions depending on the underlying data set). And additionally, the production structure is also flexible. For example, for a detailed analysis of steel recycling it is important to distinguish different materials and model the substitution possibilities between these in the various production functions, while that is too much detail for an analysis of European climate policy. In the latter case it is more relevant to distinguish multiple European regions and to have more detail in energy carriers and their substitutability.

For the current version of GREEN-R we have put most effort in modeling energy use and emissions. The most important way to reduce CO2 is to reduce the consumption of fossil fuels. This can be done by reducing total energy consumption or by substitution to fuels with lower or no emissions. The model makes a distinction between different fossil fuels (oil, gas and coal) and electricity. And within the electricity sector, we distinguish several electricity generation technologies. In our baseline scenarios we already take into account projected changes in energy use in different regions over time, because our model is dynamic.

There are different types of climate policies that can be implemented in the model. The model can for example simulate energy tax changes, carbon taxes, cap-and-trade-systems (with different design options, such as free allocation and banking) and carbon import tariffs. Firms and households will react to climate policy by lowering energy use and by substituting to cleaner energy sources. We model on the one hand effects of policy on the production (or extraction) of fossil fuels and on the other hand effects of policy on the use in various economic activities and by households.

At a later stage, we are planning to add the possibility to reduce carbon emissions by CCS (Carbon Capture and Storage). Furthermore, we are planning to improve the modeling of the electricity market. We for example would like to take into account network restrictions, deal with the issue of intermittency and storage and take into account the specific price behavior of the electricity market using the merit order. Additionally we are planning to model the production of hydrogen and the use of hydrogen as an abatement option.

For the analysis of circular economy policies, energy consumption is also very important, as the production of materials is in many cases an energy intensive process. To analyse the impact of policies to stimulate recycling or, more in general, a more efficient use of resources, the model should additionally take into account the flow of materials through the economy, related to all kind of economic activities. At this moment, we are working on a version of GREEN-R which includes material flows of steel. When the modeling of material flows is fully developed, we will add this model version to the documentation.

2 Model description

In this chapter we describe the model assumptions. Figure 1 gives a graphical overview of the most important interactions between agents in the model and the flows of goods and money trough the economy. The figure shows the interactions between households, firms and the government. Firms in different sectors also interact with each other because the good that one sector produces is an intermediate input in the production process of the other sector. And countries interact with each other through trade of goods and services.

We split the model into different blocks (for example firms, households, trade etc.). In this section we discuss the assumptions that we make for each model block. A longer version of this documentation with detailed description of the model equations is available on request.

2.1 Firms

Each sector in GREEN-R produces one good. We assume perfect competition, so firms do not make a profit. Total output is then equal to the sum of production costs including taxes and basic prices equal unit cost prices.

Firms maximize production given a production function. The production function is built up using multiple layers of Constant Elasticity of Substitution (CES). It is a so-called nested CES production function. The parameters of the CES-production function are calibrated for each sector based on global input-output data for 2017 from GTAP11. The substitution elasticities are based on literature, see appendix A.1 for an overview. For this version we assume that all sectors have the same production structure and substitution possibilities. It is technically easy to change this assumption, but because of data availability it is hard to estimate substitution elasticities for all sectors separately. The final production function does vary widely across sectors because the initial shares of factor inputs and intermediate inputs are very different. To give an example, the services sector initially has a much lower fossil fuel share compared to the steel-producing sector. This implies that the impact of climate policy will be very different, even if we assume the same elasticity of substitution between clean and fossil energy.

Figures 2, 3 and 4 show the structure of production. Figure 2 shows how capital and labor are combined with an elasticity of 0.8 and then energy is added with an elasticity of 0.5. The elasticity between capital-labor and energy determines how easy it is to save energy. If energy becomes more expensive because of climate policies, then companies will invest in energy-efficient machinery and smart systems for optimal energy use (capital), which might also be more labor-intensive (labor). Capital-labor-energy is then combined with intermediates. Only limited substitution is possible between intermediates because production processes often have limited possibilities to change raw materials (see figure 3). Finally,

Figure 1: Graphical overview of flows in the model

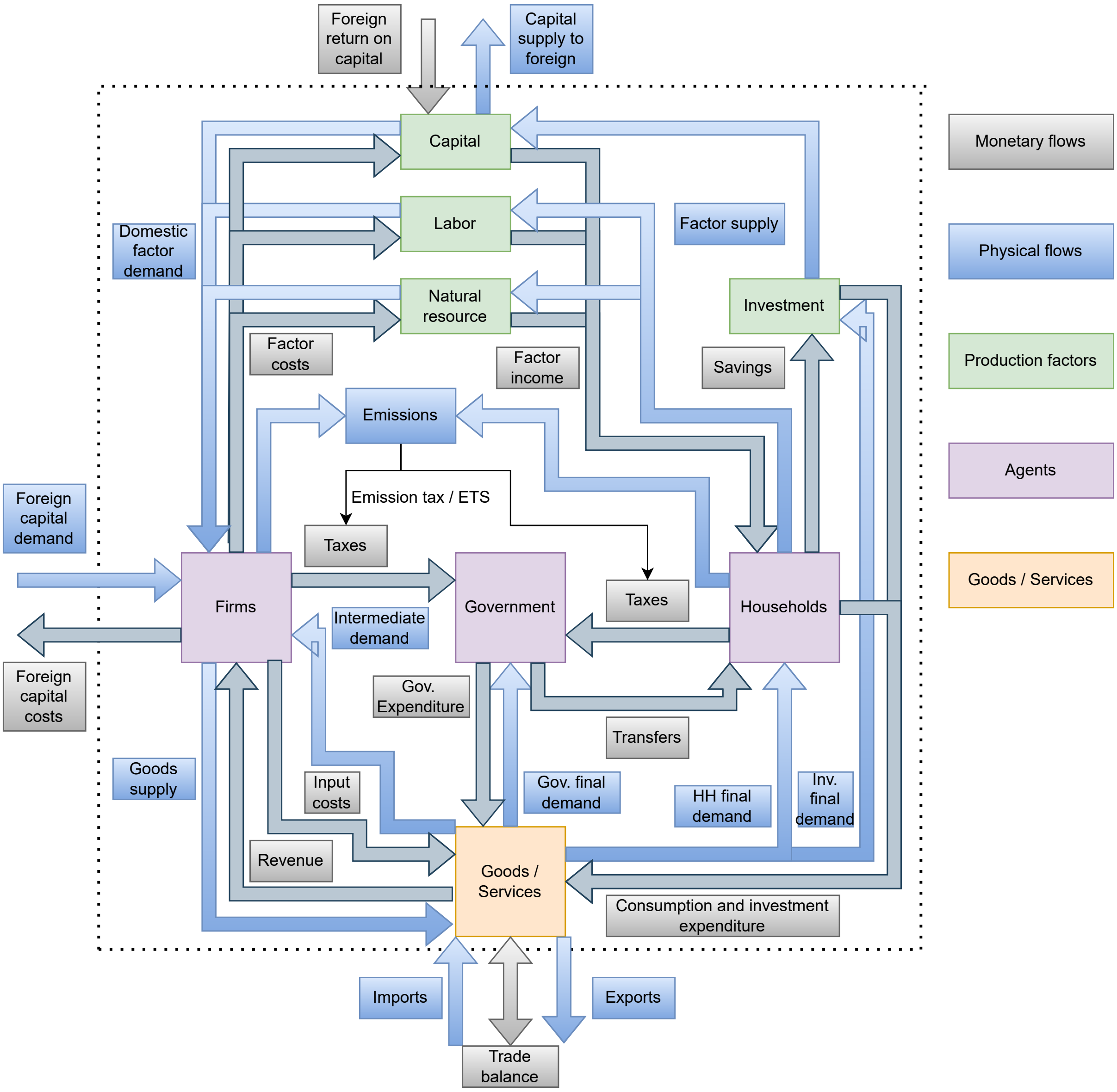
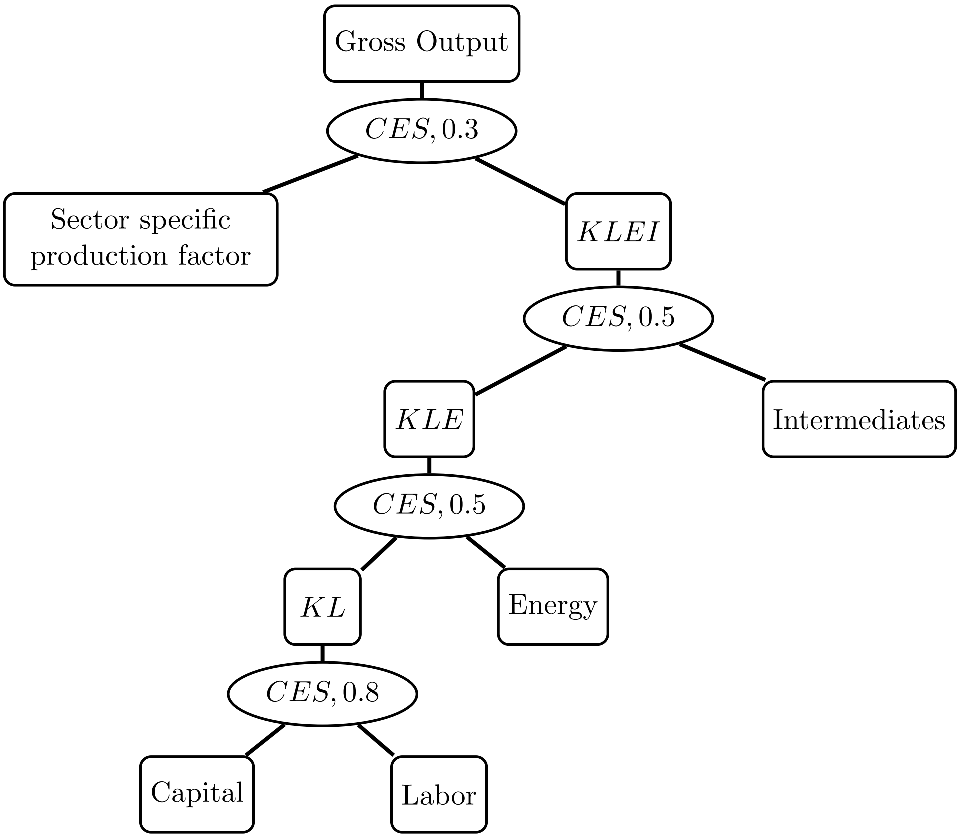


Figure 2: Production function



a sector-specific production factor is added. This production factor is only relevant for agriculture (land) and fossil fuel extraction (natural resources). Sectors with a sector-specific production factor can only scale up production to a limited extent when demand increases because the amount of land and natural resources is fixed.

Figure 4 shows how GREEN-R models the use of energy in production functions. As mentioned earlier, companies can reduce emissions by saving energy. But companies can also substitute between energy sources. We distinguish between oil, gas, coal and electricity. And within electricity production, we distinguish five generation technologies: Nuclear & Hydro, Coal, Gas, Wind & Solar and other. With a carbon tax, fossil fuels will become more expensive. The price increase will be highest for coal, because coal is the most carbon-intensive fuel. Companies will switch from fossil fuels to electricity in response to a price increase. Within fossil fuels, oil and gas will be more attractive than coal. And within generation technologies, renewable generation will take market share away from fossil generation. Substitution between generation technologies is not perfect to take into account the fact that different generation technologies have different supply variability. We do assume a relatively high elasticity of 2 because at a given point in time electricity is a homogeneous good.

2.2 Government

The government collects taxes that are paid. The model includes different types of taxes, such as a production tax, income tax, VAT, taxes on capital and labor, imports and exports. Part of the tax revenue is transferred to households (we assume the share of these transfers in total tax revenue to be constant over

Figure 3: Intermediates

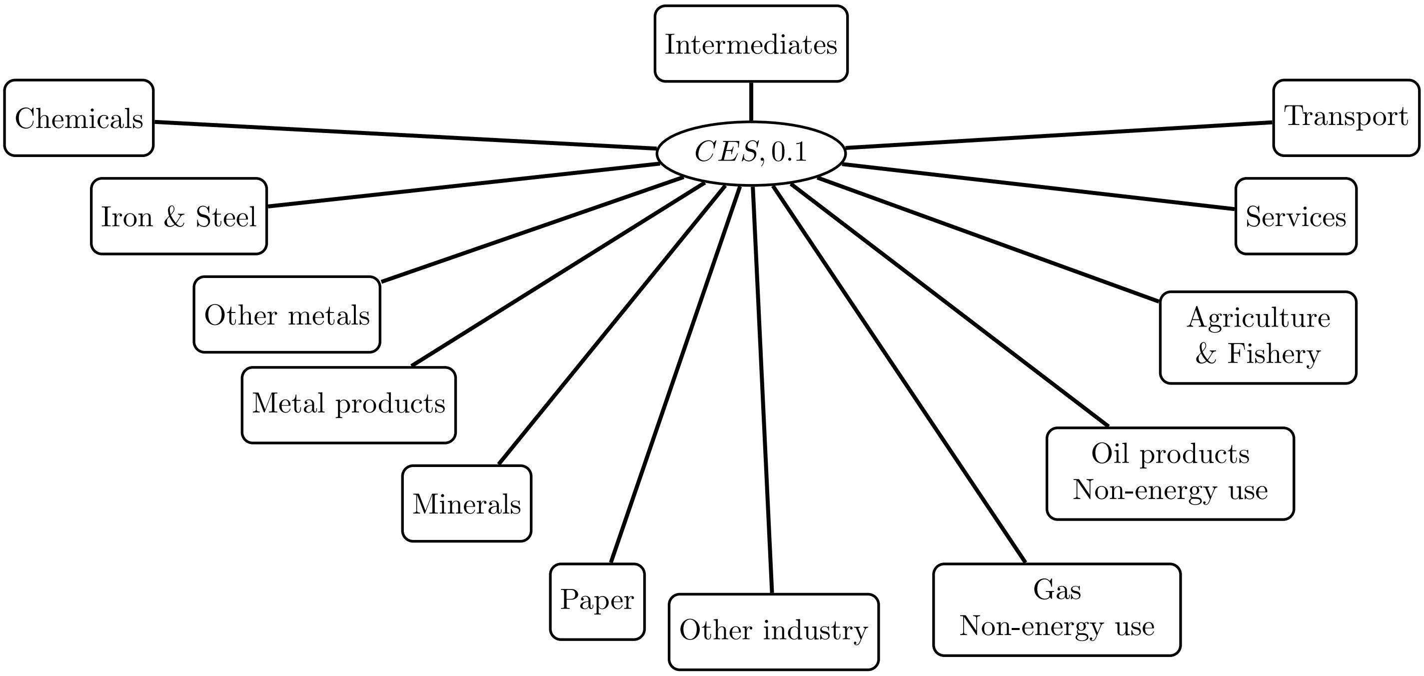


Figure 4: Energy composite

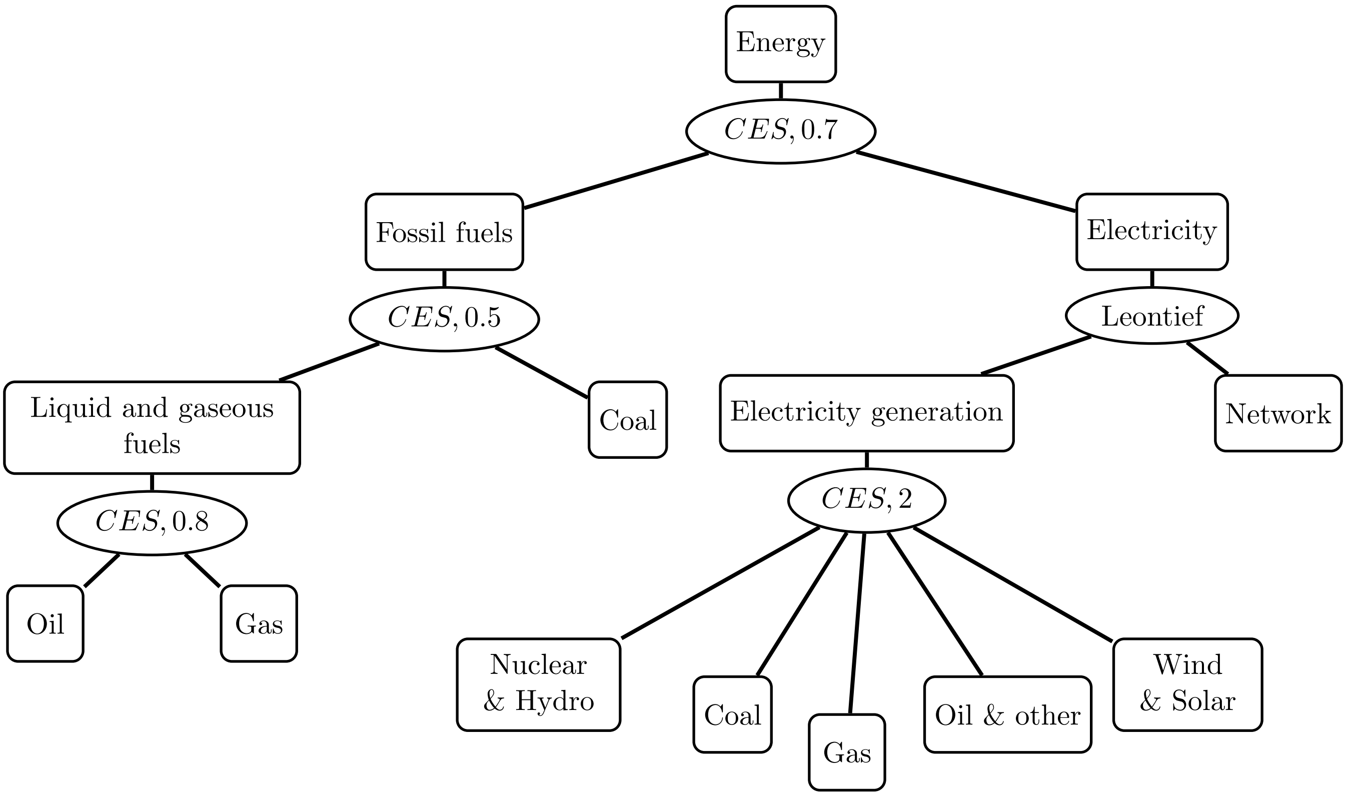
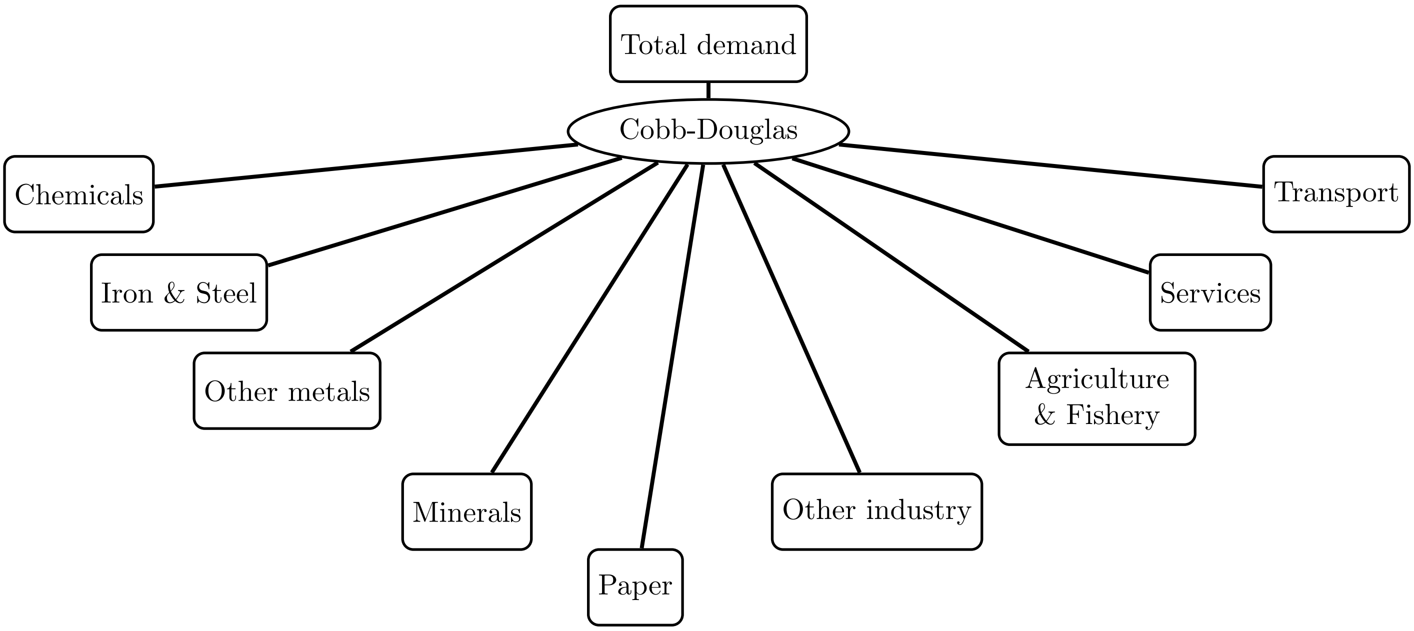


Figure 5: Government demand system



time). The remaining tax revenue is used by the government for the consumption of goods and services. We assume that the government has a Cobb-Douglas demand function, which keeps the share of expenditures on different product groups constant. This best matches the fixed budgets that governments often use. The government demand system is shown in figure 5.

2.3 Households

In GREEN-R, there is one representative household per region. Households own the factors of production (labor, capital, land and natural resources) and receive income from firms that use the factors. Over this factor income, households pay taxes to the government. On the other hand, households also receive a transfer from the government. In our default scenario the revenues of the EU ETS and of CBAM are rebated to households. This keeps the tax pressure constant when we introduce such a policy shock. In an alternative scenario the government can keep the revenues, which allows the government consumption to increase or other taxes to decrease. The modelling of these climate policies is discussed in more detail in section 2.8. Of the disposable income (after paying taxes), a fixed portion is saved and the remainder is consumed.

The household demand system is shown in figure 6. Compared to the government, households consume one additional good: energy. The government does not directly consume energy but only indirect through government consumption of services (for example through office services). The demand function of households is a CES function with substitution elasticity of 0.4. The elasticity is calibrated such that energy savings after an increase of energy prices are realistic. An own-price elasticity of energy of -0.4 is in line with estimates from the literature (see for example CE Delft and Ecorys (2021), Table 12).[1] This elasticity also captures substitution between other consumption goods. But given that our simulations of climate policy will mostly affect energy prices, we calibrate it to the own-price elasticity of energy.

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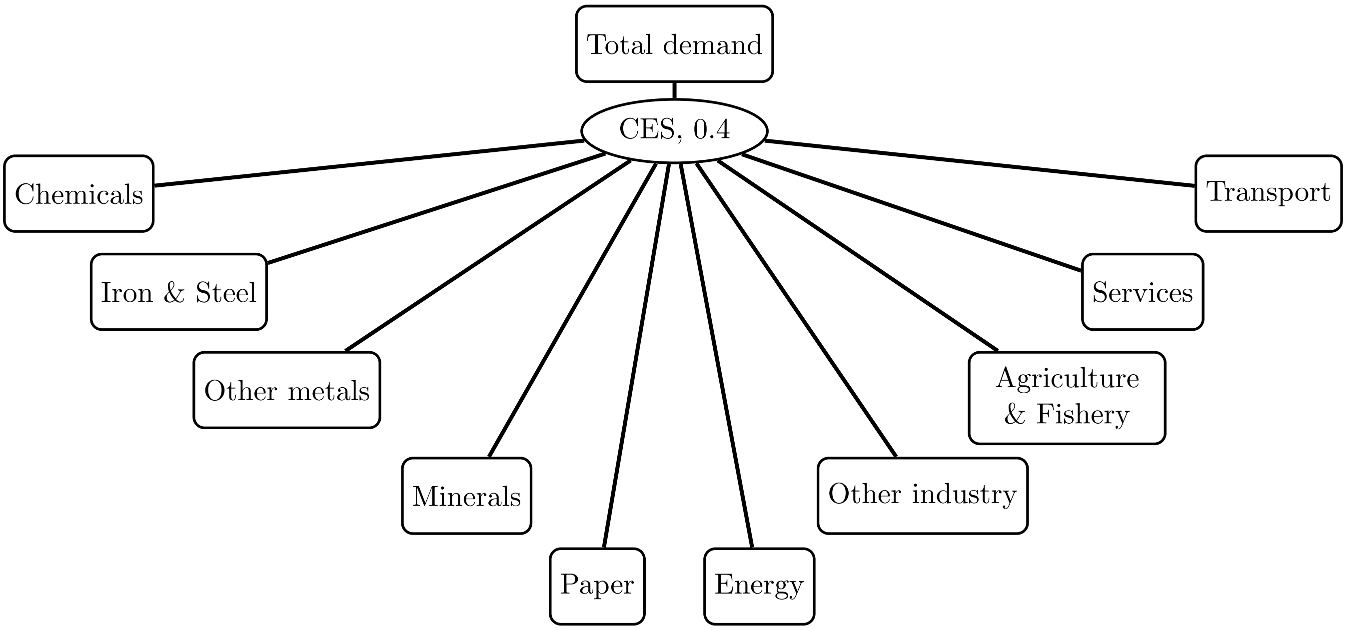
[1] The own-price elasticity of energy is equal to $-\sigma * (1 - sh_{ENE})$, where σ is the CES substitution elasticity and sh_{ENE} is the share of energy in total household expenditure. This gives a price elasticity which is approximately equal to the substitution elasticity because the share of energy is relatively small.

Figure 6: Household demand system



Energy use in the household demand system is a composite of different types of energy, similar to the production function of firms. We assume that households have the same substitution possibilities as firms within the energy products category. The energy tree for households is therefore also given by figure 4.

2.4 International capital mobility

We take the modelling approach for international capital mobility from Lejour et al. (2006). Households own the capital stock. The capital stock can either be fully used domestically or partly rented out to foreign regions. On the other hand, it is also possible to rent capital from other regions, which results in a larger domestically employed capital stock than the capital stock that the representative household owns.

Renting out capital is costly because of transport costs. These transport costs should be interpreted broadly because they also include capital movement barriers other than actual transportation costs. We assume that these transport costs are an increasing function of the rented out capital stock as percentage of GDP. The idea behind these increasing costs is that capital is first rented out to the regions with lowest transportation costs, but when a lot of capital is already rented out, capital has to be transported to regions with higher cost. These transport costs are of the 'Iceberg'-type, which means that part of the capital stock is lost during transportation. Renting capital from other regions is also costly. Regions renting capital will therefore also pay transport costs.

We assume that markets are efficient, but the rate of return on capital does differ between regions because of transport costs. Countries that have a low return on capital will become a net lender and countries with a high return on capital will be net borrowers.

To calibrate the degree of capital mobility, we obtain data on the return on capital from the Penn World Table (Feenstra et al., 2015) and data on the net international investment position (NIIP) from External Wealth of Nations Database (Lane and Milesi-Ferretti, 2018). Using a panel regression we estimate the negative relationship between the retun on capital and the net international investment position. We control for openness of the economy (export share), the debt-to-GDP ratio and inflation (all variables from the World Bank), financial developement indicator (from the IMF), capital market openness (Ito, 2005) and exchange rate volatility (Eklou, 2023).

We find the following relation:

$$\text{Return on capital}_r = \text{fixed effects} + \text{controls} - 0.009\frac{\text{NIIP}_r}{\text{GDP}_r}.$$

From our assumptions, the model predicts the following relation:

$$\text{Return on capital}_r = \Big(1 + tc\frac{\text{NIIP}_r}{\text{GDP}_r}\Big)\text{Return on capital}_{World}.$$

The average gross return on capital (so without depreciation) in our model equals around 9%, which implies that Return on capital$_{World}$ = 9%. Combined with the regression results, this yields a transport cost parameter of $tc = -0.009/0.09 = -0.1$.

To give an indication of the degree of capital mobility, an example is helpful. Consider Japan and the USA as examples. Japan had a net international investment position of around 75% in 2021 while the USA had a NIIP of around -80%. Using our assumption about the capital market, Japan would have a return on capital of $(1 - 0.1 * 0.75) * 9\% = 8.3\%$ while the USA would have a return of $(1 - 0.1 * -0.8) * 9\% = 9.7\%$.

2.5 Investment

Household savings are invested in investment goods. Investments consist of different goods (think buildings and machinery) and are distributed among these goods based on a Cobb-Douglas utility function. Thus, this means that the share of each investment category in the total budget for investments remains the same. The investment demand function is therefore identical to the government demand function shown in figure 5. Investments are added to the capital stock each year. Because a portion of the capital stock is also depreciated each year, the net increase depends on the difference between depreciation and investment.

2.6 Bilateral trade

The total demand for a good in a region is equal to the sum of demand from firms, households, government and investment demand in that region. Given this total demand, the choice between domestically produced goods and imported goods is determined using an origin demand function. This choice is made at the region level. You could interpret this as if one central intermediary in a region buys products from producers, both domestically produced and imported. And this middle party then delivers these products to domestic customers (firms, households, government).

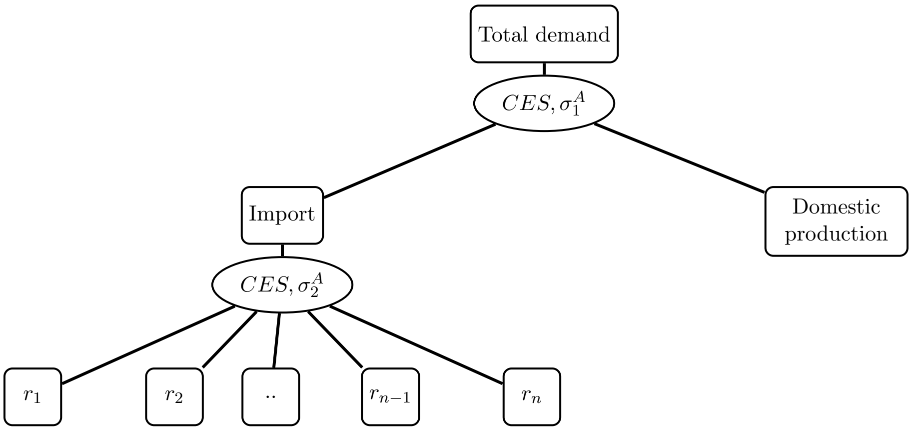
Products are assumed to be region-specific and not perfectly substitutable (Armington assumption). For example, Dutch companies and consumers may prefer the product variant produced in Germany over the one from France for a given product. We do not explicitly model why consumers have a preference for a certain variety, but we rather calibrate the preferences by assuming that the observed trade flows result from optimizing a demand function. So-called Armington elasticities then determine how easy it is to substitute between producers from different regions when relative prices change.

Armington elasticities differ between product groups. Some product groups are more homogeneous, which makes substitution between regions easier. We adopt the Armington elasticities from GTAP11. We use a CES function with two layers to model region choice. Here, as in the GTAP-model, we assume that it is easier to substitute between two foreign suppliers than between domestic production and imports (Hertel and van der Mensbrugghe, 2024). Figure 7 shows the CES structure and table 1 shows the Armington elasticities for industrial sectors. These elasticities play an important role in determining changes in international trade flows following the introduction of climate policies and the effectiveness of a carbon import tax such as CBAM.

Table 1: Armington elasticities industry

Industrial sectors	**Substitution between import and domestic production σ_1^A**	**Substitution between import from different regions σ_2^A**
Chemical products	3.3	6.6
Iron & steel	3.0	5.9
Other metals	4.2	8.4
Metal products	3.8	7.5
Minerals	2.9	5.8
Oil products	2.1	4.2
Paper and paper products	3.0	5.9
Other industry	3.4	6.7

Figure 7: Armington structure



2.7 Transport and trade services

When importing goods, the importer has to pay for transport and trade services. We model these transport and trade services explicitly. The amount of transport and trade services depends on the type of good that is imported and on the regions (both importer and exporter region). We assume that the quantity of transport and trade services is a fixed percentage of the quantity of the good that is imported. This percentage is called the transport and trade services rate. This fixed rate is calibrated based on the observed trade costs in the base year. Given this rate, we can calculate the demand for transport and trade services related to a specific import. Summing over all goods, importer regions and exporter regions we obtain the total global demand for transport and trade services.

The transport sectors in each region supply the transport and trade services. We assume that on the global scale, there is a demand preference for transport and trade services supplied by specific regions. We therefore assume that the global demand of transport and trade services is a Leontief-function of transport and trade services supplied by different regions. This keeps the country shares in the total supply of transport and trade services fixed.

2.8 Climate policy

Emissions from fossil fuel combustion by households and firms are calculated by multiplying the use of the fossil energy source (coal, gas or oil) by an emission factor.[2] Additionally we include process emissions of firms, which are assumed to be proportional to output. Emission reductions in our model can be achieved by introducing a price on carbon emissions. A higher price of for example fossil fuels will lead to substitution away from these fuels, which will lower emissions.

The most common climate policy instruments are a cap-and-trade-system and a carbon tax. Both instruments will increase the price of carbon emissions, but the tax directly controls the price while the cap controls the amount of emissions. Each instrument (cap-and-trade or carbon tax) can be targeted at specific emission sources (process emissions, coal, oil, gas, fertilizer), sectors and/or households, regions and greenhouse gases (CO2, methane and nitrous oxide). Next to a price on emissions, it is also possible to change energy taxes on specific energy carriers. This will affect emissions by changing the relative prices of different energy carriers. Scenarios with combinations of policy instruments can also be evaluated (for example a national system on top of the EU ETS).

We model cap-and-trade-systems using the approach of Brink et al. (2016). In principle our CGE-model is recursive dynamic, which means that households are myopic and not forward looking. This creates an issue with modelling a realistic cap-and-trade-system, because banking is an important element of such a system. We therefore want that households and firms in the model take into account the total amount of permits in the future when deciding on their current emissions. We implement this in the following way.

Theoretic models show that if firms behave optimal, the price in a cap-and-trade-system with banking should grow with the (risk-adjusted) interest rate. This is the so-called Hotelling rule for a cap-and-trade-system. We adopt this assumption and assume that the ETS-price grows exponentially with a constant risk-adjusted interest rate over time. We then start with an initial guess of the carbon price and solve the model forward with this growth rate. When there is no more supply of allowances, we check whether cumulative demand and supply of allowances is balanced. If cumulative demand for allowances is larger than total supply (i.e. if emissions exceed the cap), a higher carbon price is needed to provoke more emissions reduction. In this case we run the model again with an increased initial carbon price (and vice-versa if emissions are below the cap). After a few runs the model converges and we have solved for the

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[2] We only apply the emission factor to fossil fuels that are combusted. Fossil fuels that are used as a feedstock (such as oil used to produce plastics) do not produce emissions. In the production function of firms, feedstock use is part of the intermediate inputs while combustion use is part of the energy demand function.

carbon price path that balances demand and supply of allowances. By modelling a cap-and-trade system this way, current prices will increase if future allowance supply drops.

We have modelled some specific elements of the European cap-and-trade-systems (EU ETS1 & EU ETS2). Part of the allowances in the EU ETS1 is allocated for free, which is modelled as a production subsidy. In reality the free allocation in the EU ETS is based on historical emissions, so there is a lag in the relation between output and free allocation. In our model we abstract from this lag.[3] We determine the amount of free allocation that a sector receives as follows. First, we obtain data on the ratio between free allowances and verified emissions in a sector from the EU ETS Data Viewer (European Environment Agency). We then multiply this ratio with the emissions from GTAP to obtain an estimate of the amount of free allowances that a sector receives. We then divide this amount by the total output quantity from GTAP to determine the amount of free allowances per unit of output.

Over time, we keep the total amount of free allowances at 43% from the cap because the EU goal is to auction 57% of the allowances.[4] The amount of free allocation therefore decreases proportionally with the supply of allowances. We implement this by introducing a cross-sectoral correction factor which proportionally decreases the amount of free allowances in all sectors.

For ETS1 we have also introduced a Market Stability Reserve (MSR). Allowances will flow into the market stability reserve when there is an oversupply of allowances. These allowances will then not be auctioned in the next period. In the other situation with undersupply of allowances, allowances will be taken out of the MSR and these allowances will be auctioned in addition to the standard amount. If the market stability reserve contains more allowances then a certain threshold, the allowances above the threshold will be canceled. Introduction of the MSR in the model will increase the initial carbon price, because agents take into account that some allowances will be canceled in the future.

Last, we introduce a Carbon Border Adjustment Mechanism (CBAM) into the model. CBAM is modelled as an import tax where the tax base is the amount of carbon emissions that is released by production of the imported good. We include the option to include indirect emissions from electricity as well. Given that we do not have any heterogeneity of firms within a sector, we use the average emissions intensity of a sector to determine the tax base. In reality, the exported goods might be cleaner than the average due to selection effects. In our analysis we find that CBAM is more effective than free allocation in reducing carbon leakage (Olijslagers et al., 2024).

3 Base year calibration

We calibrate the model in the base year using the GTAP 11 dataset with 2017 as base year (Aguiar et al., 2022). The GTAP dataset contains data on input-output matrices, investment, government and household consumption, taxes, factor use (capital, labor, land and natural resources), bilateral trade and transport and trade services. We calibrate the parameters in the model in such a way that the GTAP data is the optimal outcome of the model in the base year.

The elasticity parameters cannot be calibrated using the GTAP data. We do not estimate the elasticities directly, but use estimates from other sources or from the literature to choose our elasticities. Appendix A gives an overview of our elasticity choices and choices of other parameters that we do not directly calibrate from GTAP. This appendix also compares our choices with elasticities from other CGE-models and/or empirical studies.

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[3] If output changes with more than 15%, free allocation in the EU ETS is adjusted annually. This implies that our assumption of yearly adjustment is not so far from the actual implementation.

[4] We adust the free allocation percentage of 43% when CBAM is introduced, because in that case free allocation is phased out for CBAM-sectors.

4 Baseline & model dynamics

GREEN-R is a recursive dynamic model. This implies that agents in the model are myopic and optimize their behaviour based on previous and current period variables, independent of expectations on future developments. So there will be no forward-looking behaviour or anticipation effects. We make this assumption this for two reasons. First, in reality agents are also not acting perfectly forward looking. Second, this allows us to solve the model period-by-period forward and makes the model computationally much easier to solve.

We make the model dynamic because several economic variables will be different from the current situation in the future. First, in a dynamic model we account for the fact that some regions have a higher savings rate than other, which will lead to faster capital stock growth in these regions. Second, we can account for demographic changes that will affect labor supply in different regions. Third, regions might have different productivity growth. We use GDP projections to calibrate productivity growth in the baseline. Fourth, energy prices are expected to change over time. We account for these energy price changes. Last, the energy mix will be very different in the future. In the baseline we already take into account that fossil fuel use will be reduced in several regions.

The savings rate will determine the investment in a region. Together with depreciation this investment will determine the capital stock growth in a region. In principle we keep the savings rate that we obtain in the base year from the GTAP dataset constant. But when the ratio between capital and GDP changes too much, we adjust the savings rate upward or downward. To determine future labor supply, we use projections from the United Nations World Population Prospects (United Nations, Department of Economic and Social Affairs, Population Division, 2022). We use the demographic projections of people aged between 15 and 64 as a proxy for changes in labor supply.

To account for changes in productivity between regions we include GDP projections in our baseline. We obtain these projections from the OECD (OECD, 2023). GDP is an endogenous variable in the model, so we cannot directly change GDP. In the baseline we therefore match GDP projections by adjusting labor productivity. In the counterfactual we then keep labor productivity the same as in the baseline, but GDP is again endogenous and will therefore differ from the baseline depending on the policy shock thas was analyzed.

Because our model is mostly focused on climate and energy related questions, we also want to account for expected changes in energy prices and energy demand in our baseline. We use the IEA World Energy Outlook (International Energy Agency, 2023) for energy price and energy demand projections.

We match average global energy prices for coal, crude oil and gas. We target these energy price changes by adjusting the availability of the natural resource factor for energy producing firms in a given year. When the natural resource factor becomes more scarce, production will decrease and prices will go up. We adjust the supply proportionally in all regions because we match a single price, which means we can only adjust a single variable. Last we match energy use projections from the WEO.

The population and GDP projections are available on the country level. The World Energy Outlook has less regional detail, so we are not able to match energy use at the country level. The regions outside the EU that we use in our model match quite well with the WEO-regions, but unfortunately Europe is one region. We therefore match energy use projections at the EU level and we thus have to assume that all regions in Europe have similar relative energy changes. We are currently working on an updated baseline that has energy use projections for different countries within Europe.

A Parameter choices

A.1 Production function elasticities

1. Elasticity of substitution between different types of electricity
    - Our pick - 2
    - Château et al. (2014) - OECD ENV-LINKAGES - 1 layer with elasticity 5
    - Chen et al. (2022) - MIT EPPA - Elasticity between solar and other and between wind and other equals either 1 or 4. Elasticity of 1.5 between conventional fossil generation.
    - Peters (2016) - GTAP-E POWER - Adjusted CES with elasticity 1.39 for base load and 0.47 for peak load. Elasticity between base and peak load is 1.
2. Elasticity of substitution between generation and transmission and distribution
    - Our pick - Leontief
    - Chen et al. (2022) - MIT EPPA - Leontief
    - Peters (2016) - GTAP-E POWER - Leontief
3. Elasticity between Oil and Gas and between liquids and coal
    - Our pick - 0.8 between oil and gas and 0.5 between coal and liquids
    - Lejour et al. (2006) - CPB Worldscan - Elasticity of 0.7 between coal and non-coal. Elasticity of 0.5 between gas, oil, biomass and other.
    - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity of 0.5 between coal and liquids for new capital. Elasticity of 1 between gas and oil for new capital.
    - Chen et al. (2022) - MIT EPPA - Elasticity of 1 between fossil energy inputs within the energy bundle.
    - McDougall and Golub (2007) - GTAP-E - Elasticity of 1 between gas and oil. Elasticity of 0.5 between coal and liquids.
    - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.5 between gas and oil. Elasticity of 0.5 between coal and liquids.
    - Stern (2012) - Meta study of estimates. Elasticity between oil and gas of 1. Between coal and gas/oil also close to 1.
4. Elasticity between non-electric and electric energy
    - Our pick - 0.7
    - Lejour et al. (2006) - CPB Worldscan - Elasticity of 0.25.
    - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity of 1 for new capital (except for energy producing sectors).
    - Chen et al. (2022) - MIT EPPA - Elasticity of 1.5 between electricity and fossil energy bundle.
    - McDougall and Golub (2007) - GTAP-E - Elasticity of 1 between electricity and non-electric.
    - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.5 between electric and non-electric.
    - Stern (2012) - Meta study of estimates. Elasticity of electricity with other fossil energy carriers - around 0.85.

5. Elasticity between energy and value added
    - Our pick - 0.5
    - Lejour et al. (2006) - CPB Worldscan - Elasticity of 0.5 (except for energy producing sectors).
    - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity between capital and energy of 0.1 to 0.95 depending on sector for new capital.
    - Chen et al. (2022) - MIT EPPA - Elasticity of 0.7 between capital-labor bundle and energy-intermediates bundle
    - McDougall and Golub (2007) - GTAP-E - Elasticity of 0.5 between capital and energy.
    - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.5 between energy and value added.
    - Bun et al. (2018) - DNB - Estimation of elasticity between value added and energy + overview of estimates in the literature. Quite some sectoral differences, but the average is around 0.5.
6. Elasticity between Capital and labor
    - Our pick - 0.8
    - Lejour et al. (2006) - CPB Worldscan - Elasticity of 0.85.
    - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity between labor and capital energy bundle of 0.3 to 2.0 depending on sector for new capital.
    - Chen et al. (2022) - MIT EPPA - Elasticity of 1 between capital and labor.
    - McDougall and Golub (2007) - GTAP-E - Elasticity between capital-energy bundle, labor and fixed factor. Between 0.2 and 1.45 depending on sector.
    - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.75 between capital and labor.
    - Antoszewski (2019) - Estimate of elasticity in the range 0.25-0.5.
    - Koesler and Schymura (2015) - Estimate: unweighted average over sectors of 0.5.
    - Dissou et al. (2015) - Estimate: unweighted average of 0.5-0.6.
    - Van der Werf (2008) - Estimates: unweighted average around 0.5.
    - Kemfert (1998) - Estimate of 0.8.
7. Elasticity between fixed factor and Capital-Labor-Energy-Intermediates bundles (determines the supply elasticity of fossil fuels)
    - Our pick - 0.3
    - Lejour et al. (2006) - CPB Worldscan - elasticity is endogenous to match supply elasticities for oil, gas and coal.
    - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity between 0.2 and 0.35.
    - Chen et al. (2022) - MIT EPPA - Elasticity between 0.3 and 0.5. Fixed factor is combined with energy-intermediates bundle.
    - McDougall and Golub (2007) - GTAP-E - Elasticity between capital-energy bundle, labor and fixed factor. Between 0.2 and 1.45 depending on sector.
    - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.25.
8. Elasticity within intermediates

  - Our pick - 0.1
  - Lejour et al. (2006) - CPB Worldscan - 0.6
  - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity of 0.1 for new capital in services and manufacturing.
  - Chen et al. (2022) - MIT EPPA - Leontief
  - Corong et al. (2017) - GTAP-model - Leontief
  - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.25.
  - Okagawa and Kanemi (2008) - Elasticity of on average 0.1 between services and materials.

9. Elasticity between Capital-Labor-Energy and Intermediates
   - Our pick - 0.5
   - Lejour et al. (2006) - CPB Worldscan - 0.01 (except for agriculture)
   - Château et al. (2014) - OECD ENV-LINKAGES - Elasticity of 0.1 for new capital in services and manufacturing.
   - Corong et al. (2017) - GTAP-model - Leontief
   - Chen et al. (2022) - MIT EPPA - Elasticity of 0.6 between energy and non-energy
   - Rosnes et al. (2019) - Statistics Norway SNOW - Elasticity of 0.5.
   - Antoszewski (2019) - Estimate of around 0.75.
   - Koesler and Schymura (2015) - Estimate of around 0.75.
   - Okagawa and Kanemi (2008) - Elasticity of 0.6.

A.2 Household/Government/Investment elasticities

1. Elasticity between Investment goods
   - Our pick - 1 (Cobb-Douglas, constant value shares)
   - Lejour et al. (2006) - CPB Worldscan - 1
   - Corong et al. (2017) - GTAP-model - Leontief
2. Elasticity between government goods
   - Our pick - 1 (Cobb-Douglas, constant value shares)
   - Corong et al. (2017) - GTAP-model - 1
3. Elasticity between non-energy and energy goods for households
   - Our pick - 0.4
   - Lejour et al. (2006) - CPB Worldscan - Average elasticity of 0.65 for OECD and 0.25 for non-OECD
   - Chen et al. (2022) - MIT EPPA - Between 0.1 and 0.5 (multiple layers)
   - Rosnes et al. (2019) - Elasticity of 0.5.
   - CE Delft and Ecorys (2021) - Table 12, average long-term price elasticity for electricity of -0.31 and for gas of -0.41 (households/small firms)
4. Elasticities within household energy tree
   - Our pick - same elasticities as firms

A.3 Other elasticities

1. Armington elasticities
    - Our pick - taken from GTAP. Elasticity for Gas is adjusted from 13 to 3 (coal and oil also have an elasticity of 3 in GTAP). Adjustment based on gas crisis (very different prices over the world). Also WEO predicts price differences for gas, while oil has single world price. This would imply Armington Oil is larger than Armington Gas.
2. Elasticity between suppliers of transport and trade services
    - Our pick - 0 (constant quantity share of supply for every region)
3. Supply elasticity of labor
    - Our pick - 100 (perfect labor mobility within countries)
4. Supply elasticity of capital
    - Our pick - 100 (perfect capital mobility within countries)

A.4 Other parameters

1. Depreciation rate
    - 3% for all countries, chosen such that GDP and capital on a global scale have a similar growth rate.
2. Capital mobility parameter
    - -0.1 based on own estimation
3. Emissions factor (tC per TJ) for coal, oil and gas combustion
    - 25.8 for coal, 19.5 for oil and 15.3 for gas, based on GTAP emissions database
4. Global warming potential (CO2-eq emissions per kton non-CO2 emissions)
    - 28 for CH4, 265 for N2O, from IPCC AR5

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