Centre for Climate and Energy Analyses

THE CGE MODEL D-PLACE

TECHNICAL DOCUMENTATION FOR THE MODEL

VERSION 2.0

Authors:

Jakub Boratyński, Maciej Pyrka, Izabela Tobiasz, Jan Witajewski-Baltvilks, Robert Jeszke, Jan Gąska, Wojciech Rabiega

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Jakub Boratyński, Maciej Pyrka, Izabela Tobiasz, Jan Witajewski-Baltvilks, Robert Jeszke, Jan Gąska, Wojciech Rabiega

All authors are experts of the Institute of Environmental Protection - National Research Institute (IOS-PIB)/the National Centre for Emissions Management (KOBiZE).

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If you have any comments or questions regarding this document, please contact: cake@kobize.pl

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The d-PLACE is based on the static CGE model called PLACE, which was created in 2013-2016 by the members of the Centre for Climate Policy Analysis (Polish acronym – CAK) working together with the Ministry of Economy, the Ministry of Environment and the Ministry of Finance of the Republic of Poland and the World Bank experts in cooperation with IOŚ - PIB.

CONTACT:

Address: Chmielna 132/134, 00-805 Warszawa
WWW: www.climatecake.pl
E-mail: cake@kobize.pl
Tel.: +48 22 56 96 570
Twitter: @climate_cake

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List of abbreviations

CAKE	Centre for Climate and Energy Analyses
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CGE model	Computable general equilibrium model
Carbon leakage list	The list of sectors and sub-sectors deemed to be exposed to a risk of carbon leakage in the EU
CLF	Carbon leakage factor (carbon leakage exposure factor)
CSCF	Cross-sectoral correction factor
EC	European Commission
EFTA	European Free Trade Association
EPICA	Evaluation of Policy Impacts - Climate and Agriculture Model
ESD	Effort Sharing Decision
ESR	Effort Sharing Regulation
ETP	Version of d-PLACE model with exogenous energy technical progress
EU	European Union
EUA	European Union Allowances
EU ETS	European Union Emissions Trading Scheme
EU28	European Union of 28 Member States
GAINS	Greenhouse gas-Air pollution Interactions and Synergies
GEM – E3	General Equilibrium Model for Economy-Energy-Environment
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GTAP	Global Trade Analysis Project
IO	Input – Output table
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
KOBiZE	The National Centre for Emissions Management
MEESA	Model for European Energy System Analysis
MPSGE	Mathematical Programming System for General Equilibrium analysis
MSR	Market Stability Reserve
NDC	Nationally Determined Contribution
NER	New Entrants Reserve

Non-ETS	Sectors not covered by the European Union Emissions Trading Scheme
OPEC	Organization of the Petroleum Exporting Countries
PLACE	Polish Laboratory for the Analysis of Climate and Energy
PLACE model	Computable General Equilibrium Model created in Polish Laboratory for the Analysis of Climate and Energy
d-PLACE model	Dynamic version of PLACE model created in the Centre for Climate and Energy Analyses
TNAC	Total number of allowances in circulation relevant for MSR
TR^{3}E	Transport European Emission Economic Model

Keywords: computable general equilibrium model, CGE, dynamic modelling, emissions, energy, GTAP, baseline scenario, climate policy, trade and the climate policy, EU ETS, non-ETS, low-emission transition.

1 Model overview

1.1 Main features

1. d-PLACE is a global, recursive-dynamic computable general equilibrium (CGE) model. As a typical CGE model, it:

   - distinguishes individual commodities (typically tens of) and industries that produce them,
   - distinguishes primary factors of production, such as labor, capital, natural resources etc.,
   - represents dependencies between industries, as each industry uses products of other industries as inputs to production,
   - assumes that commodity and primary factor prices adjust to equalize demand and supply in individual commodity and factor markets,
   - assumes that prices of commodities equal marginal costs of production, in line with competitive market assumptions,
   - represents industry-level production technologies in terms of proportions of various inputs (commodities and primary factors), as well as substitution possibilities between some of the inputs (characterized by elasticities of substitution),
   - identifies representative consumer(s) who own primary factors of production, receive income from employing them in the production processes and purchase goods,
   - accounts for taxes on income and products.

2. In addition, global CGE models show bilateral trade flows of commodities between countries. Recursive-dynamic models track capital accumulation and provide snapshots of the economy in subsequent periods, although decisions on investment and consumption are myopic – based on current economic outcomes (prices, income etc.) only, rather than expected future outcomes.

3. All of the above features also characterize the d-PLACE model. Beyond that, d-PLACE has a number of features suited to the analysis of climate and energy policies. These features include:

   - greenhouse gas emissions (gases and sources),
   - flexible setup of carbon pricing or cap and trade systems, for different groups of users and countries,
   - production functions allowing for inter-fuel substitution, fuel-electricity substitution and energy-capital substitution,

- calculation of energy volumes in physical units,
- prices of fossil fuels increasing with production volumes,
- special technologies for energy services (such as electric road transport or industrial hydrogen use) and emission abatement (such as CCS/CCU),
- link with sectoral models; also runs in standalone mode.

4. The following sections characterize the structure of the model (including regional and sectoral disaggregation), underlying data, theoretical specification and assumptions of the model (economic mechanisms covered), and technical implementation.

5. The d-PLACE is implemented in GAMS, using MPSGE – Mathematical Programming System for General Equilibrium (see Rutherford 1999). MPSGE is a high-level language, greatly facilitating coding and calibration of CGE models. In particular, it simplifies formulation of multi-level nested production functions. MPSGE generates the model in the MCP (mixed complementarity problem) form. MCP is, inter alia, well suited to modelling of carbon cap-and-trade systems – if the cap exceeds the demand for emission allowances, their price equals zero; otherwise a non-zero price is set in the market that balances demand with the number of available allowances.

1.2 Regional disaggregation

6. The d-PLACE model enables flexible aggregation of regions from GTAP database (see Aguiar, 2019), according to the needs of a specific analysis. In the case of regional aggregation, only computational tractability and availability of economic and energy data create some limitations.

d-PLACE focuses on the analysis of energy and climate policy of the European Union, and hence EU Member States groups are distinguished. The remaining regions represent the largest global economies with significant impact on GHG emissions. As shown in Table

7. Table 1, the current regional breakdown includes 19 regions (country groups or individual countries), including 9 EU regions, and 10 non-EU regions. The specific aggregation was based on expected regional distribution of policy impacts investigated in the reports.

Table 1. Example of regional aggregation in d-PLACE model and respective codes

Country	Code
Benelux countries (Belgium, the Netherlands, Luxembourg)	BEN
France	FRA
Central Europe (Austria, Czech Republic, Hungary, Slovakia, Slovenia)	CEU
Germany	DEU
Iberia (Spain, Portugal) and Italian Republic	IBI
Nordics and Baltics (Denmark, Sweden, Finland, Republic of Lithuania, Republic of Latvia, Republic of Estonia)	NTH
Republic of Poland	POL
South-eastern Europe (Croatia, Greece, Republic of Cyprus, Malta, Romania, Bulgaria)	STH
United Kingdom and Ireland	UKI
EFTA countries involved in EU ETS (Kingdom of Norway, Principality of Liechtenstein, Republic of Iceland)	EFT
Commonwealth of Australia and New Zealand	AUS
Federative Republic of Brazil	BRA
People's Republic of China	CHN
Republic of India	IND
Japan	JPN
Russian Federation	RUS
United States of America and Canada	USA
OPEC countries	OPE
Rest of the world	RWW

Source: CAKE/KOBiZE own study

1.3 Sectoral disaggregation

8. In the current setting, the model distinguishes 20 industries/commodities, including energy intensive and trade exposed industries, such as production of refined oil products and coke, chemicals, non-metallic mineral products, paper and pulp, iron and steel, and non-ferrous metals.

9. The energy sectors are linked to both primary energy (coal, crude oil, natural gas extraction) and secondary energy carriers (refined oil products, electricity, gas distribution and heating). Sectoral split is dependent on the classification used in the GTAP database. Therefore, some energy industries are aggregated, e.g. “oil” sector include refined oil products, coke and nuclear fuels. Even though the latest GTAP database distinguishes between major electricity generation technologies (based on fuel combustion, renewables or nuclear power), this division was not included in the model. Such an approach is justified by the fact that d-PLACE now includes an optional link with a detailed, comprehensive energy model, covering electricity generation and district heating in the EU. All energy sectors are covered by the EU ETS. There are 7 non-energy sectors also covered by the EU ETS: food industry, chemical, non-metallic minerals, iron and steel, nonferrous metals, pulp-paper, air transport. Table Table 2 shows the sectoral disaggregation in the d-PLACE model.

Table 2. Sectors in d-PLACE model and respective codes

List of sectors in d-PLACE model		Corresponding sectors in GTAP Data Base	EU ETS	non-ETS
		Energy sectors		
Col	Coal (mining and agglomeration)	col	+	
Cru	Crude oil (extraction and service activities)	cru	+	
Gas	Natural gas (extraction and service activities)	gas	+	
Oil	Refined oil products, coke, nuclear fuels	oil	+	
Ele	Electricity	ele	+	
Gdt	Gas distribution and heating	gdt	+	
		Non-energy sectors		
Agr	Rest of agriculture and fishing	pdr, wht, gro, osd, c_b, vol, pfb, ocr, ctl, oap, rmk, wol, fsh, v_f		+
Foo	Food industry	omt, mil, pcr, sgr, ofd, b_t, cmt	+	
Frs	Forestry	frs		+

Chm	Chemical industry	crp	+	
Nmm	Non-metallic minerals	nmm	+	
Isi	Iron and steel industry	i_s	+	
Nem	Non-ferrous metals	nfm	+	
Ppp	Paper–pulp–print	ppp	+	
Con	Construction	cns		+
Oth	Other manufactures	ome, omn, lum, tex, wa, lea, eeq, fmp, omf		+
Atr	Air transport	atp	+	
Trn	Other transport	otp, wtp		+
Trv	Motor vehicles and parts and transport equipment	mvh, otn		+
Srv	Services	trd, ofi, isr, obs, wtr, cmn, ros, osg, dwe		+

Source: CAKE/KOBiZE own study

1.4 Greenhouse gas coverage

10. The model distinguishes between CO_2 emissions and emissions of other greenhouse gases such as N_2O (nitrous oxide), CH_4 (methane), HFC (hydrofluorocarbons). Emissions from different gases are converted into CO_2-equivalent volumes. Emissions are classified into two broad categories:

- related to fuel combustion – emission is proportional to the energy/fuel used,
- process emissions (e.g. CO_2 emission from cement production) – related to the activity level and, by default, proportional to output (with abatement possibilities based on carbon capture – see section 2.10 and 2.11).

11. Inclusion of non-CO_2 emissions in d-PLACE implies that reduction targets for developed countries also cover these gases. The model uses emissions data from the GTAP 10 database, covering all GHGs emissions from fuel combustion, as well as non-CO_2 emissions from other sources. However, that database does not include industrial CO_2 process emissions. For the latter, the following data sources have been used:

- For EU regions – the database of the European Environment Agency.
- For non-EU regions –the EDGAR database, maintained by the Joint Research Center (JRC).

1.5 Energy forms

The model features six energy forms, associated with fossil fuels, oil and coal products, as well as electricity and district heating. Data on energy volumes in physical energy units (for the base year, 2014) come from the GTAP 10 database. The volumes data accompany regular GTAP input-output data expressed in monetary units. The energy volumes data file include three arrays reporting the volume of energy purchases by firms and by households, as well as the volumes of bilateral trade in energy products, in millions of tons of oil equivalents. The classification of energy goods used in d-PLACE is shown in Table 3.

Table 3. Energy goods

GTAP code	Description
oil	Refined oil products and coke
gas	Natural gas
ele	Electricity and district heating
gdt	Gas distribution and heating
col	Coal
cru	Crude oil

Source: CAKE/KOBiZE own study

12. In addition, on the demand side the "ele" good is split on the demand-side into electricity and district heating, based on auxiliary data from energy balances. Accordingly, electricity and district heating user prices are modelled separately.

13. d-PLACE does not explicitly represent renewable or nuclear energy – these energy sources are implicit in the production structure of the "ele" sector. As a result, an increase in capital intensity of electricity and heat generation is interpreted as increase renewables or nuclear share. The scope and detail of energy representation is effectively enhanced when d-PLACE is linked with MEESA – bottom up energy system model.

14. In addition to energy sources distinguished in GTAP, d-PLACE also includes hydrogen. Unlike the other fuels, hydrogen is available only in later years of model solutions, as it becomes competitive with natural gas, including emission cost (see section 2.11 for more details).

1.6 Data sources

15. The basic data source for the d-PLACE model is the global input-output (I-O) table from the GTAP 10 database. It provides data on industry-level production processes, inter-industry links through intermediate inputs, final demand (including consumption and investment) and international trade (including transport and customs data), distinguishing between 141 regions and 65 goods (industries), for the years 2004, 2007, 2011 and 2014. Data for the year 2014 was used for model calibration. GTAP also contains information on different types of taxes and subsidies, as well as a number of complementary extensions. For the d-PLACE model, the most important extension is the GTAP-E, which complements economic data with energy consumption and CO_2 emissions. The global IO table in the d-PLACE model is supplemented by additional data sources concerning economy and energy.

16. Apart from the base-year GTAP data, GDP projections are used to generate the baseline solution. The following sources of GDP growth forecast were used:

- For EU regions, historical GDP developments were taken from Eurostat by 2019. These figures are complemented by projections from the Primes 2020 Reference scenario, taking into account the COVID-19 pandemic.
- For non-EU regions, GDP growth rates have been calculated on the basis of:
  - ✓ World Economic Outlook (IMF), October 2020: A Long and Difficult Ascent,
  - ✓ OECD: Dataset: Economic Outlook No 103 - July 2018 - Long-term baseline projections.

1.7 Implementation of baseline and policy scenarios

17. Evaluation of the policies or effects of exogenous shocks involves comparison of a policy (shock) scenario versus a baseline scenario.

18. Baseline scenario incorporates projections of future economic growth, technological change and mitigation of GHG gases. The baseline scenario is built through implementation of shocks for subsequent periods in the model to adjust the state of the economy, starting from the state defined by the GTAP I-O tables for the base period (2014). In this way, we obtain scenario of economic development until 2050. The scope of exogenous shocks that can be imposed in the model for the baseline scenario includes:

- GDP growth,
- fuel prices dynamics (including gas, coal and crude oil),
- autonomous energy efficiency improvement,
- coal phase out,

- GHG emission limits.

19. The shock values that define the baseline scenario can be changed depending on the needs of a given analysis and available projections.

20. In the baseline scenario the value of foreign trade surplus or deficit is assumed (roughly) fixed as per cent of the GDP. It is also assumed that real government consumption grows at the same rate as the GDP.

21. Economic growth is implemented by increasing the endowment of effective labour, in line with the exogenous economic growth rate. However, the final GDP growth in the baseline scenario will not be a perfect reflection of the rate of growth of effective labour. This is due to other shocks applied into the model after GDP change, in particular it is related to implementation of emission reduction targets. The GHG emission constraint typically causes labour and capital resources to be allocated in a less effective way, comparing to a scenario without emission limits (at least in models without endogenous technical change or other long-run benefits of climate change mitigation).

22. Fuel prices are adjusted in baseline by changing the capital costs in the fuel extraction sectors (gas, oil and coal). In the model it is determined how much capital expenditure per unit of production needs to be increased in order to achieve assumed fuel price change. In addition, the model takes into account the autonomous energy efficiency improvement, which is a cost-free reduction of energy use per unit of production or consumption. This improvement can be interpreted as a result of technological progress taking place in the economy: new technologies become mature and economically competitive, and replace more energy-consuming solutions.

23. The implementation of coal phase-out is crucial in the entire decarbonisation process and has become a part of the internal policies of the EU Member States, and therefore included in the baseline scenario. Technically, this functionality has been implemented by adding an artificial "tax" that raises the price of coal in a sector that purchases coal, but simultaneously the value of this tax is returned to this sector as output subsidy. This way the cost of production does not change as a result of the "tax", but as a result of the substitution of coal with other fuels or an increase in the use of capital and labour resources. This modelling strategy results in exactly the same outcome as imposing a constraint on the use of coal at the sectoral level.

24. GHG emission limits are modelled by endowing the government with emission permits which are defined exogenously. Each GHG emission appearing in the model requires a certain number of permits, which creates a demand for them. The price of permits, equivalent to marginal emission abatement cost in the model, is defined as the equilibrium price between supply and demand. For more information about the emission limits implementation in d-PLACE see section 2.12.

2 Technical specification

2.1 Introduction

25. d-PLACE shares many of the features with other recursive dynamic global CGE models. In particular, it draws on the ROCA model (see Böhringer & Rutherford, 2013). The current d-PLACE version 2.0 is an update of the previous version 1.0 documented in (see Gąska et al., 2020).

26. TableTable 4 summarizes the sets and variables used in the core MPSGE formulation of the model. It is worth to emphasize that the scope of results available from d-PLACE simulations is actually wider than the list of variables shown in the table, as some of them are only implicit in the model code (for example, demands for goods and primary factors by industries or greenhouse gas emissions), due to various substitutions used in equations generated by MPSGE. Therefore, some other results are calculated in post-processing of model solutions.

27. In this chapter, rather than discussing actual model implementation, we present it mostly in a more transparent, stylized form. For the same reason, notation used in the exposition of equations, may depart from the one shown in TableTable 4. The presentation focuses on main and specific features of d-PLACE.

Table 4. Definition of selected d-PLACE model sets and variables

Symbol	Description	Type
b	Blocks of regions	Set
ca	Capital	Set
e	Primary and secondary energy inputs	Set
ep	Energy services and related processes	Set
et	Technologies facilitating energy services and related processes	Set
es	Emission (market) segments	Set
f	Primary factors of production	Set
g	Industries plus final demand aggregates	Set
i	Industries/Commodities	Set
j	Alias with i	Set
la	Labour	Set
r	Regions	Set
tx	Instruments for equal-yield constraint	Set
A(i, r)	Armington composite supply	Variable
AES(es, b)	Supply of additional emission allowances when their price exceeds an assumed ceiling price	Variable
DI(r)	Index of aggregate final demand (household consumption and investment)	Variable

EMR(es, r)	Supply of emission allowances at region level (transformation from block level allowances)	Variable
GAMMA(g,r)	Subsidy related with free allocation of emission allowances	Variable
GV(r)	Government income	Variable
L(la,r)	Labor supply	Variable
KN(ca,i,r)	Capital market intermediary - sector specific supply of new capital	Variable
KN(ca,i,r)	Capital market intermediary - sector specific supply of extant capital	Variable
M(i,r)	Imports	Variable
MLE(ep,et,g,r)	Index of capacity of energy technology	Variable
P(g,r)	Domestic output price	Variable
PA(i,r)	Armington composite price	Variable
PCRU	World market crude oil price	Variable
PEI(i,g,r)	Phantom tax on energy, enforcing compliance with energy standards	Variable
PEMB(es,b)	Price of emission allowances for blocks of regions (USD per t)	Variable
PEMR(es,r)	Price of emission allowances for individual regions (USD per t)	Variable
PEP(ep,g,r)	Price of energy service or related process	Variable
PEPT(ep,et,g,r)	Price of energy service or related process (type II)	Variable
PF(f,r)	Regional price of mobile factors (user cost of factors - net of the tax)	Variable
PL(la,r)	Consumer wage	Variable
PM(j,r)	Import price	Variable
PR(f,g,r)	Natural resource rent	Variable
PRE(ep,et,g,r)	Rent on technology supplying energy service or related process	Variable
QTOB(r)	Multiplier linking investment demand with rate on return on capital	Variable
PT(j)	Transportation services price	Variable
RA(r)	Representative household income	Variable
RK(ca,i,r)	Return on capital - sector and region specific	Variable
RKN(ca,r)	Return on new capital – region specific	Variable
RKX(ca,i,r)	Return on extant capita – sector and region specific	Variable
TAU(tx,r)	Multiplier of government transfers or labour tax rate (for revenue recycling)	Variable
TXEL(r)	Artificial tax/subsidy on electricity – adjustment of relative prices of electricity and district heating	Variable
TXHE(r)	Artificial tax/subsidy on district heating – adjustment of relative prices of electricity and district heating	Variable
Y(g,r)	Commodity supply	Variable
YET(ep,et,g,r)	Supply of energy service or related process	Variable
YETI(ep,g,r)	Supply of energy service or related process	Variable
YT(j)	International transportation services	Variable

Source: CAKE/KOBiZE own study

2.2 Production activities

28. The specification of production technologies is also similar to the one used in PLACE model and its predecessor – ROCA (see Böhringer & Rutherford, 2013). It is based on nested CES functions, commonly used in CGE models. However, the nesting structures are specifically designed to appropriately reflect the use of energy, and emissions.

29. Each producer (representative producer in a given sector) maximizes profits from production (minimizes the costs), where the production function is the constraint. We use the following general approach, related to Shephard's lemma, for calculating the demand for production factors and intermediate inputs:

$$C_{i,r}(P_{1,r},\dots,P_{s,r}) = Y_{i,r}\cdot c_{i,r}(P_{1,r},\dots,P_{s,r})$$

$$A_{i,j,r} = \frac{\partial C_{i,r}}{\partial P^A_{j,r}} = Y_{i,r}\frac{\partial c_{i,r}}{\partial P^A_{j,r}}$$

Where: $C_{i,r}(\dots)$ is the cost function in sector i and region r, $c_{i,r}(\dots)$ – unit cost function, $A_{i,j,r}$ represents the demand for intermediate input of good j , $P^A_{j,r}$ is the price of this good and $Y_{i,r}$ represents production.

Similarly, the demand for primary production factors ($F_{f,i,r}$) is calculated as:

$$C_{i,r}(w_{K,r},w_{LL,r},w_{LH,r},w_{R,r}) = Y_{i,r}\cdot c_{i,r}(w_{K,r},w_{LL,r},w_{LH,r},w_{R,r})$$

$$F_{f,i,r} = \frac{\partial C_{i,r}}{\partial w_{f,r}} = Y_{i,r}\frac{\partial c_{i,r}}{\partial w_{f,r}}, f \in \{K, LH, LL, R\}$$

30. There are four primary production factors in the model: capital and land (K), natural resources (R), skilled labor (LH) and unskilled labour (LL). These demands enter then the market clearing conditions.

31. Production functions are sector-specific. They differ in the input-mix (cost shares of individual inputs), substitution elasticities and nesting structures. The nesting structures for subsequent sectors are shown in Figures 2-11 below. In these figures (graphs), the nodes at the bottom represent individual inputs to production, whereas higher-level nodes represent input bundles. The lines linking the nodes indicate which inputs (or input bundles) enter a given input bundle. The nested structure of the production technology

tree is necessary as it allows different degrees of substitutability between different inputs. Special cases, such as strict complementarity or perfect substitution are marked with $\sigma = 0$ or $\sigma = \infty$, respectively, where σ is the elasticity of substitution. In all other cases it is assumed that the elasticity of substitution is non-zero and non-infinite, thus indicating imperfect substitution of varying degrees (see the elasticities in Table 7**Table 7**). Substitution possibilities are represented by CES production functions.

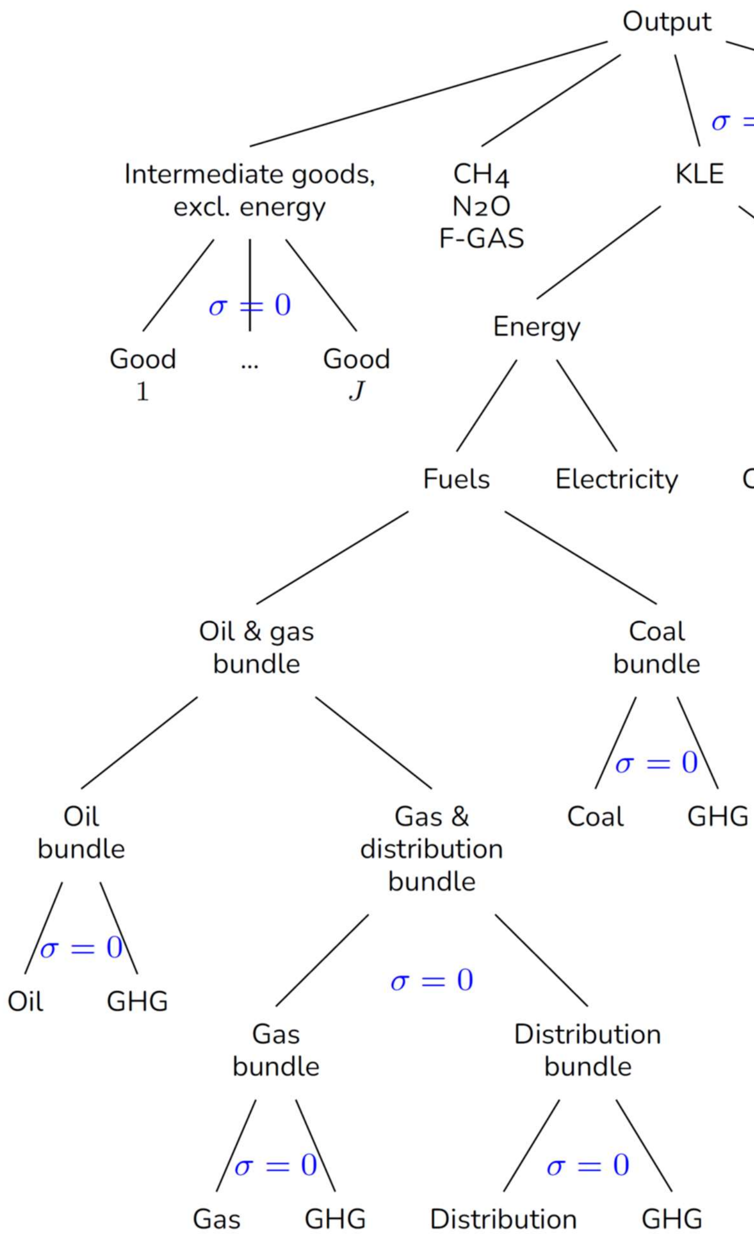
32. A few general assumptions regarding production function structure apply to a broad group of sectors:

- Intermediate inputs, excluding energy goods, are used in fixed proportions, and fixed amounts (in constant-price terms) per unit of output, in line with the Leontief production function.
- The capital-labour-energy bundle is fixed per unit of output.
- Inter-fuel substitution is allowed, except special cases. Typically, at the top level of the production function tree, electricity is bundled with fuels; next, coal is bundled with oil & gas bundle; next, oil is bundled with gas, the latter being itself a (Leontief) bundle of the fuel and the distribution services.
- Greenhouse gas emissions are linked (complementary) to fuel use (combustion), by a fixed ratio. This implies fixed emissions per unit of fuel in a given sector.
- Capital is a (imperfect) substitute of labour bundle.
- Skilled and non-skilled labour are (imperfect) substitutes.
- Non-CO_2 (CH_4, N_2O and F-GAS) "process" emissions (that is, in our case, emissions not related to fuel combustion or chemicals uses) are proportional to sector's output, – with the exception of agriculture, as discussed below.
- District heating substitutes with insulation services. The district-heating-insulation bundle is used in a fixed amount per unit of sector's output.

The above assumptions are summarized in Figure

33. Figure 1 below, denoted "base nesting structure". That generic structure is not directly implemented in any sector, but the production functions in other sectors build on that structure. In specific, nested CES-Leontief production functions are augmented with energy or emission abatement technologies that are not initially existent in the benchmark data, and are only deployed in later years, as they become cost-competitive. These include, inter alia, the use of CCS/CCU and hydrogen.

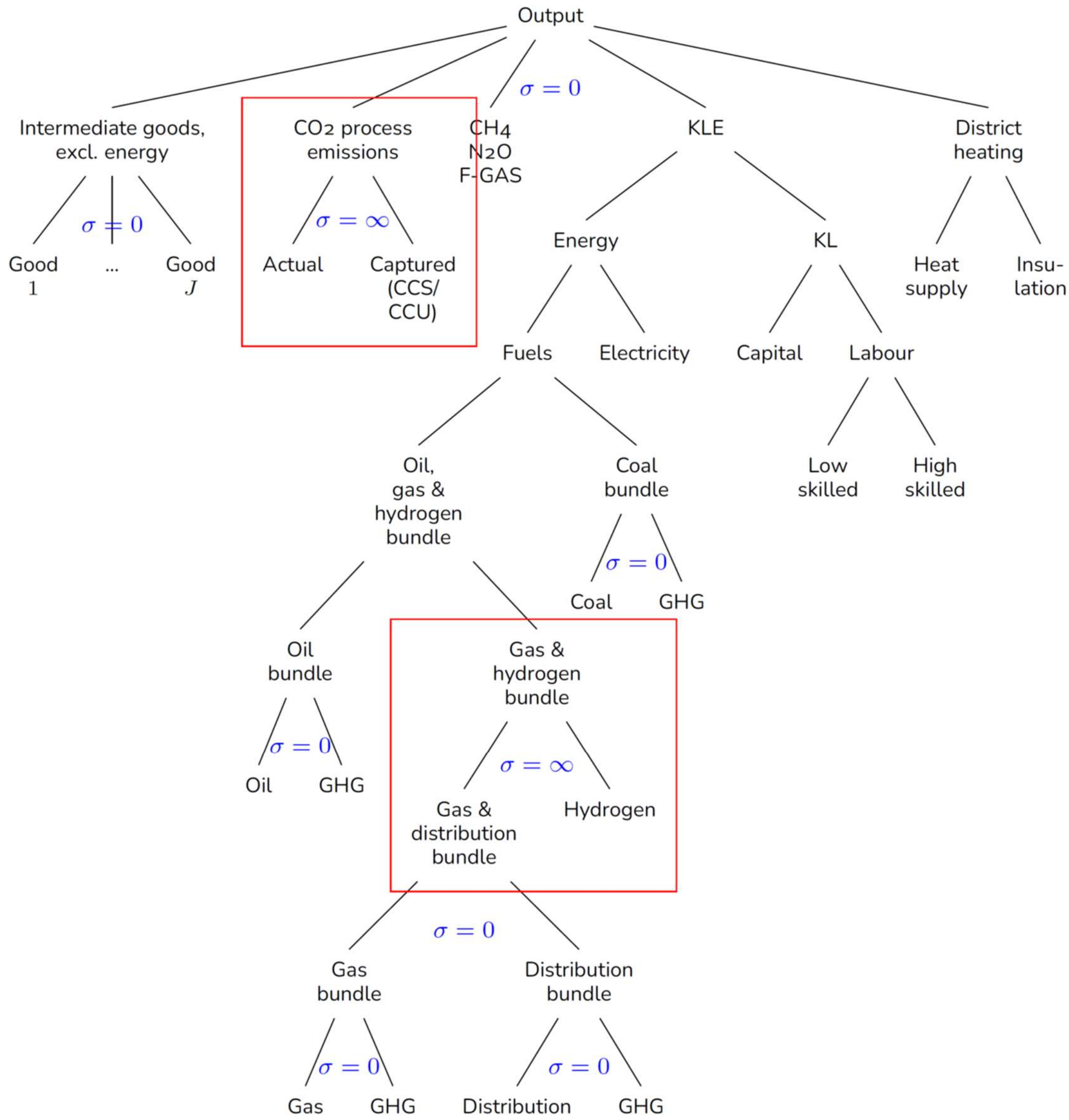
Figure 1. Base nesting structure



Source: CAKE/KOBiZE own study

34. Figure 2 shows the production function structure for energy intensive sectors, including Iron and steel, Non-ferrous metals, Non-metallic minerals and Chemicals. It introduces two nests to the base structure – CO_2 process emissions bundle, and gas & hydrogen bundle. CO_2 process emissions can be substituted with the deployment of CCS/CCU technologies. Similarly, natural gas can be substituted with hydrogen. In both cases, the alternatives are treated as perfect substitutes which implies that expansion of CCS/CCU or hydrogen takes place at a fixed marginal cost. A technology that is cheaper at a given time point is deployed up to an available limit. For more details see section 2.10.1.

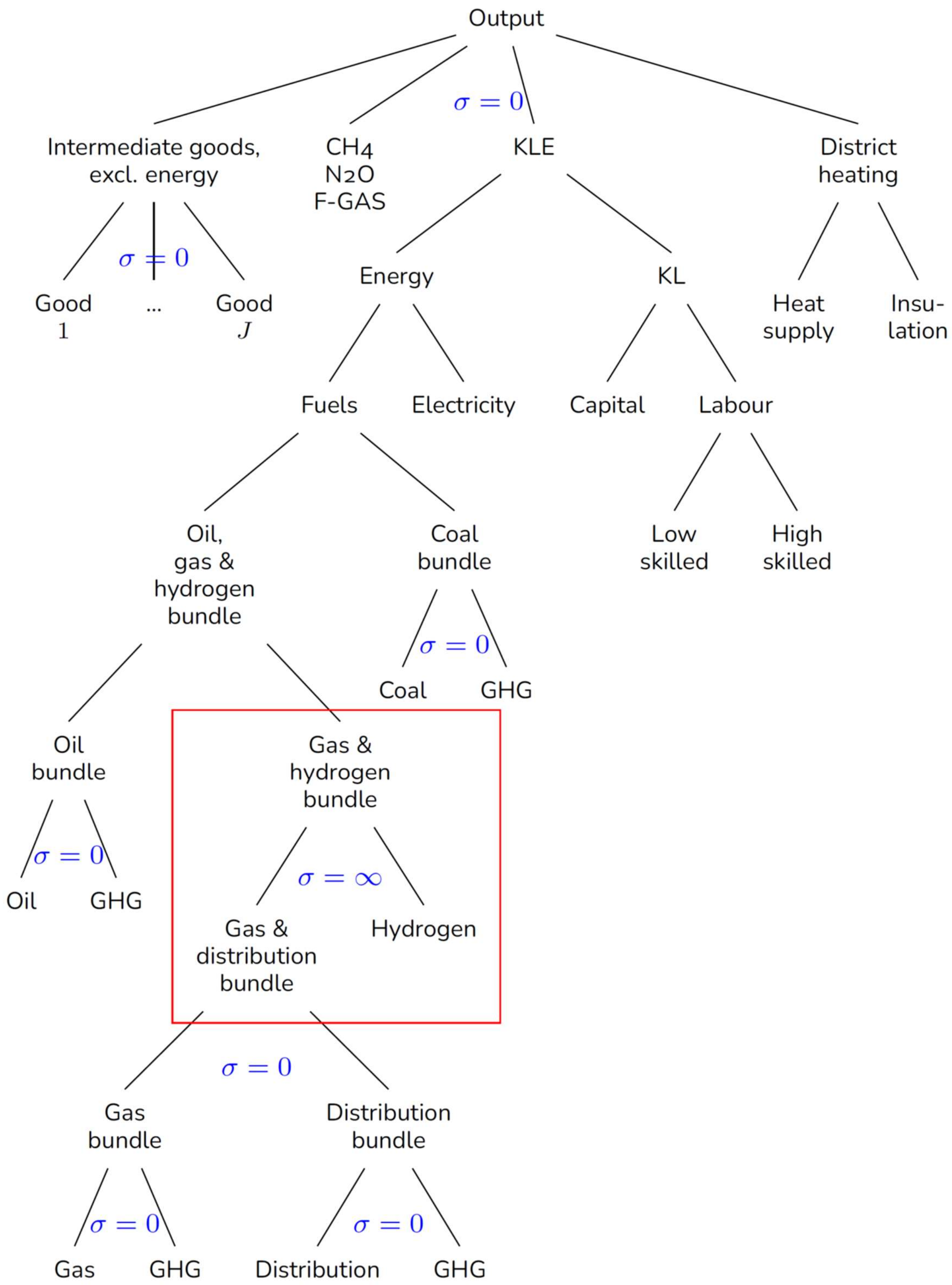
Figure 2. Energy intensive industries with process emissions



Source: CAKE/KOBiZE own study

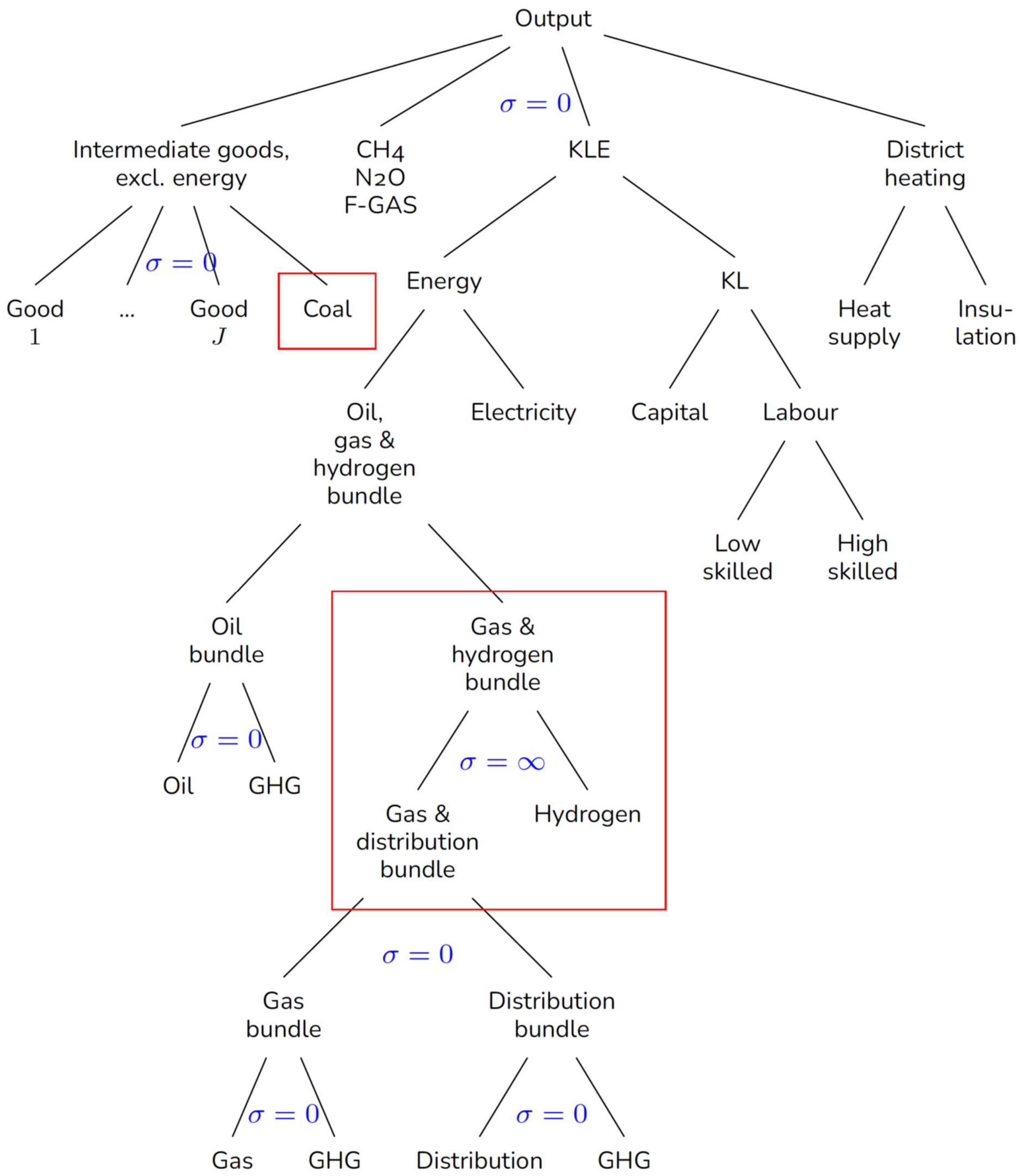
35. Other manufacturing industries and construction also have the option of gas-hydrogen substitution, but they do not generate CO_2 process emissions, and so the CCS/CCU option does not apply (see Figure 3). A similar production function structure is used in the Refineries and coke sector, except that coal is bundled with intermediate inputs and it does not substitute with other energy sources (see Figure 4). This is because in that sector coal is primarily used for transformation to coke, rather than as final energy.

Figure 3. Other manufacturing industries and construction



Source: CAKE/KOBiZE own study

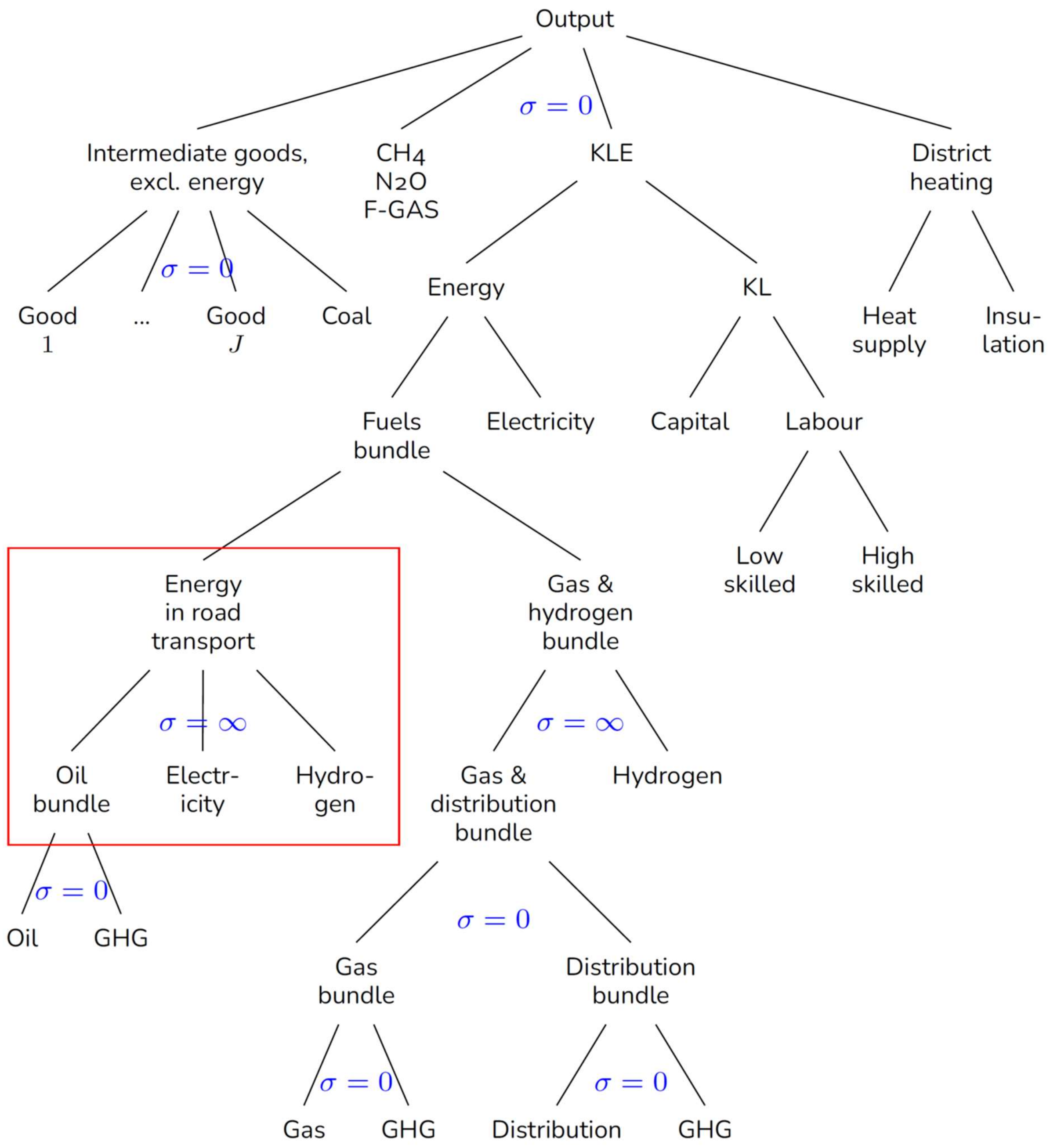
Figure 4. Oil refining and coke production



Source: CAKE/KOBiZE own study

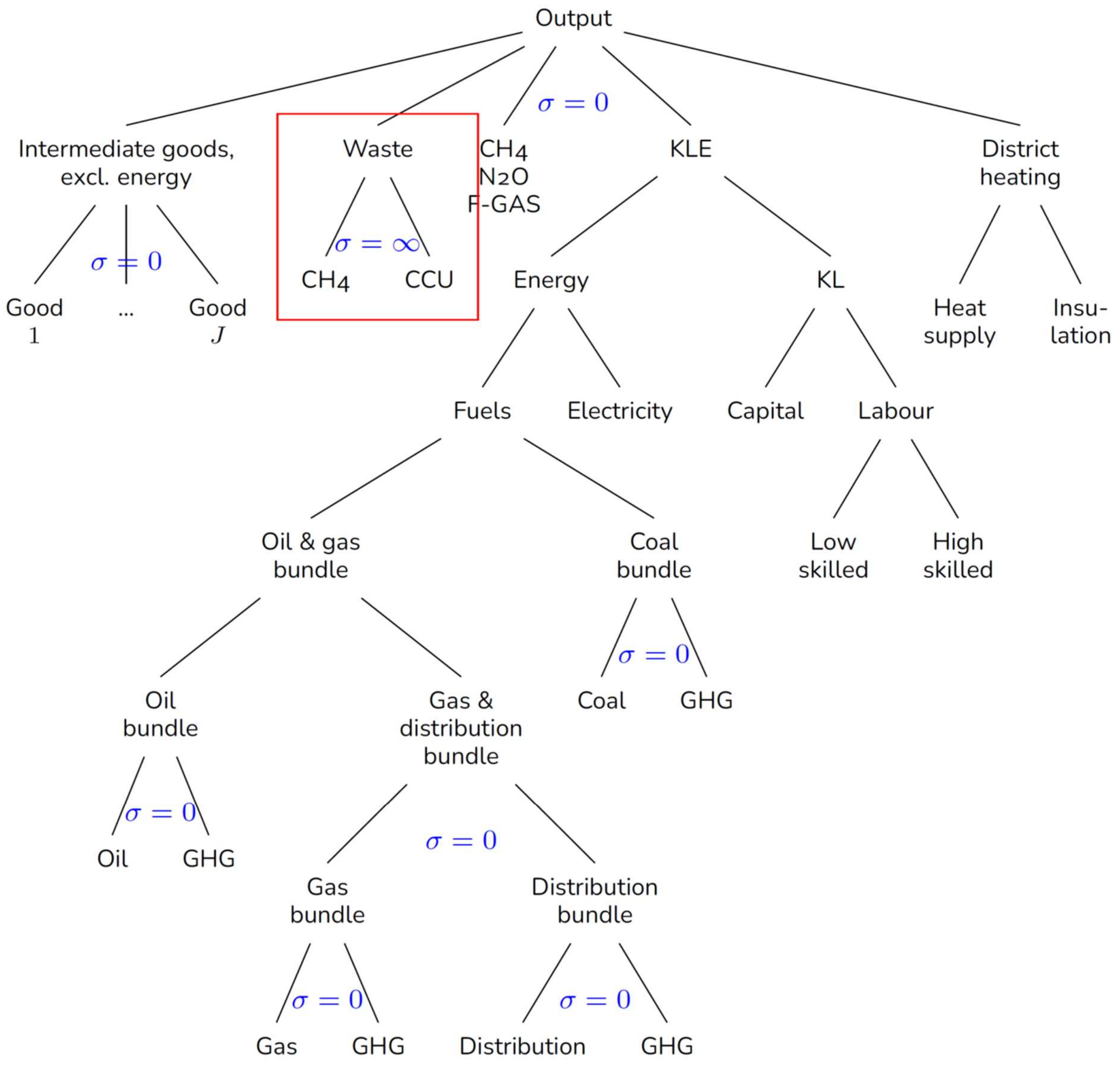
36. The distinguishing feature of the transport services production function (see Figure 5) is the oil-electricity-hydrogen bundle, representing the possibility of switching to electric or hydrogen-fuelled vehicles in road transport. In turn, the Services sector, covering market and public services other than transport and construction, features a special nest showing the option of capturing CH_4 emissions from waste (thus, CH4-CCU nest – see Figure 6).

Figure 5. Land transport services



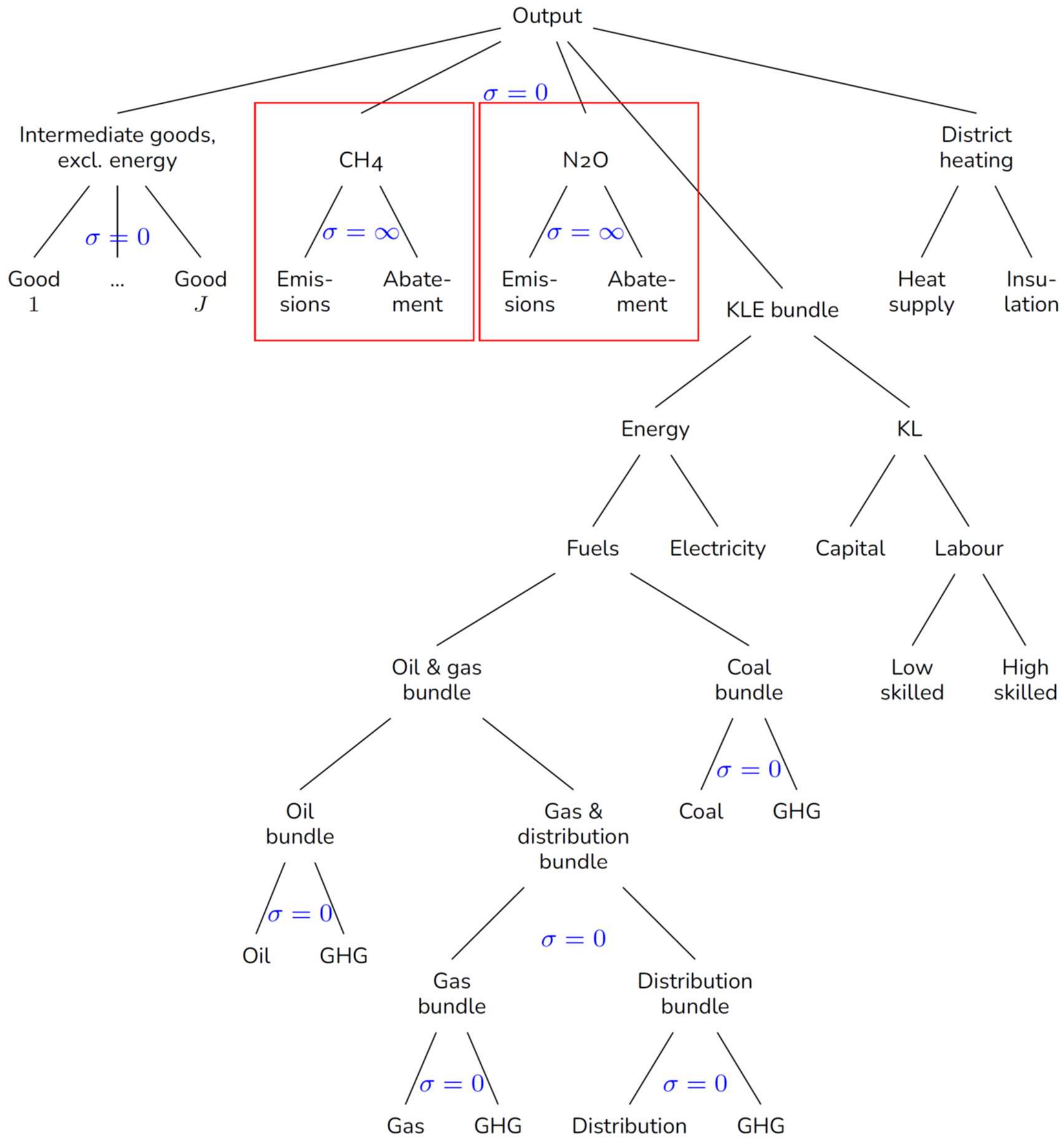
Source: CAKE/KOBiZE own study

Figure 6. Other market and public services



Source: CAKE/KOBiZE own study

Figure 7. Agriculture

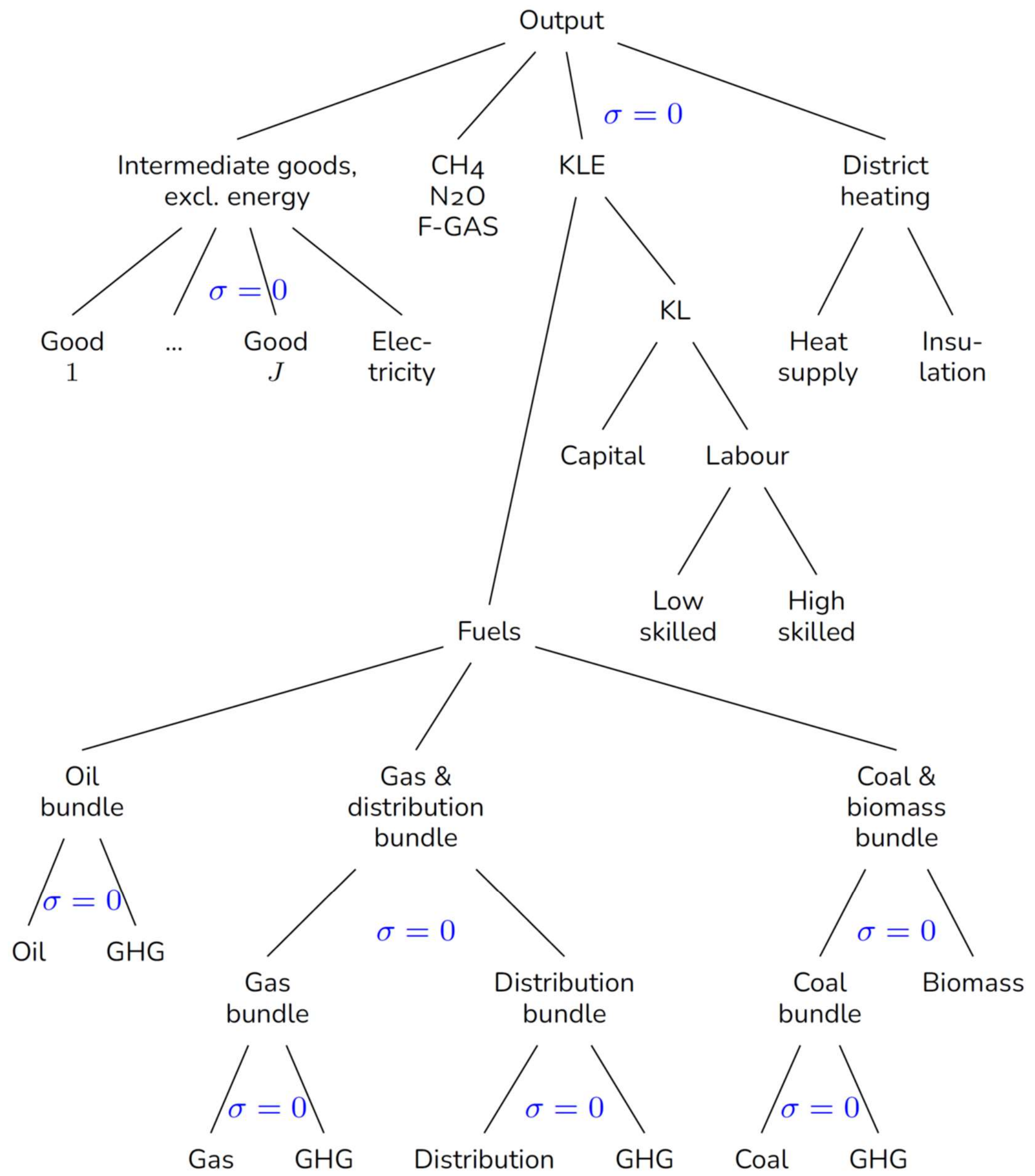


Source: CAKE/KOBiZE own study

37. In the case of Agriculture, two additional nests represent the possibility of taking actions to reduce CH_4 and N_2O emissions (see Figure 7). Those actions are not defined explicitly – they are specified in terms of marginal abatement cost and can be interpreted broadly (as a change in agricultural production structure, deployment of specific technological options etc.).

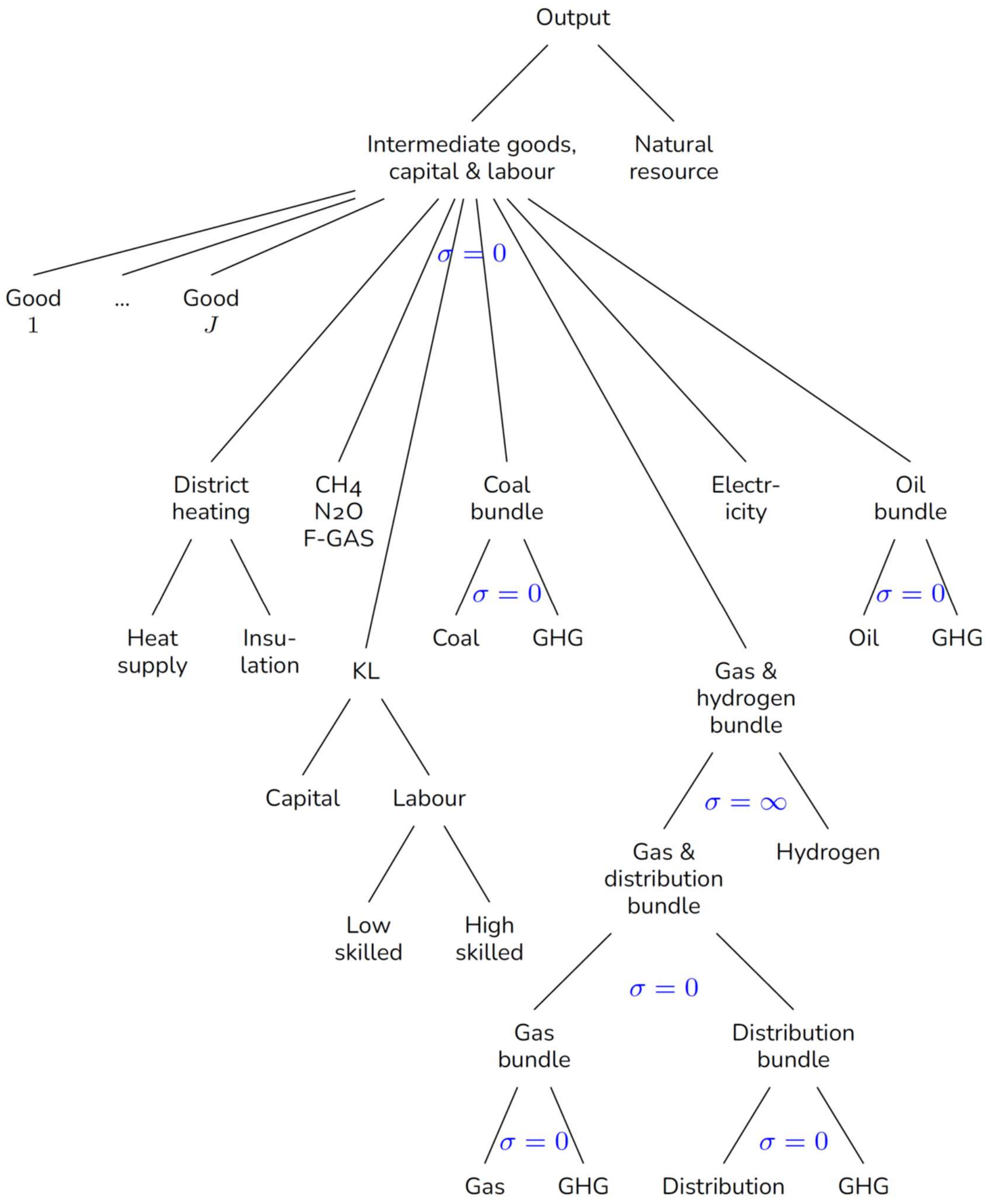
38. Electricity and heat generation sector differs from the other sectors in the scheme of energy bundling (see Figure 8). First, own use of electricity is proportional to sectors output, and it thus cannot be substituted with other energy sources. Second, coal, gas and oil form a single bundle, so substitution possibilities between each of the fuels are the same. Third, coal is used with a fixed proportion of biomass, here equated with the forestry products.

Figure 8. Electricity and heat generation



Source: CAKE/KOBiZE own study

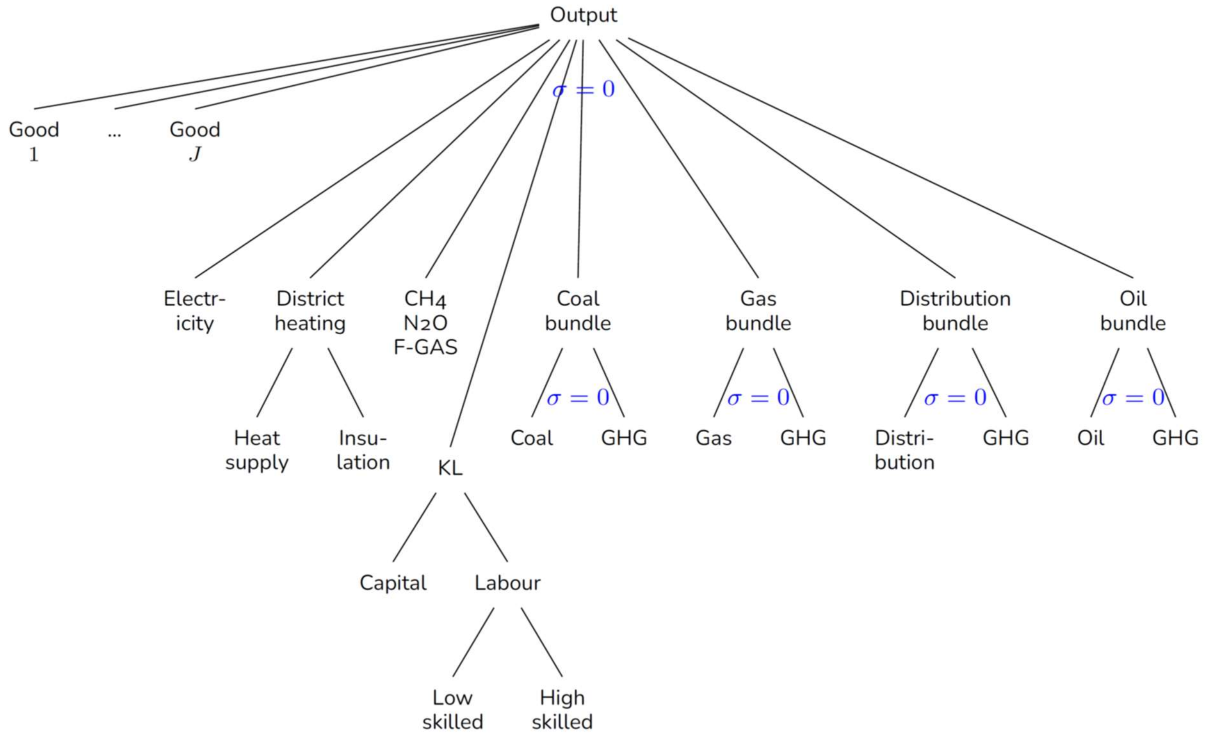
Figure 9. Fossil fuel extraction



Source: CAKE/KOBiZE own study

39. Production functions of the fossil fuel extraction sectors – crude oil, coal and gas – include an additional production factor, representing natural resources, such as fossils deposits (see Figure 9). The natural resource is specific of a given sector and its amount is fixed. It is linked with a bundle of other production factors (primary and intermediate). Due to diminishing returns, additions of primary and intermediate factors to the fixed resource generate lower and lower production increments, thus leading to an increase in the unit cost of the extracted fossil fuel. Consequently, an increase in demand for fuels drives up their prices, and a decrease in demand lowers the prices.

Figure 10. Gas distribution



Source: CAKE/KOBiZE own study

40. The gas distribution sector (see Figure 10) is treated as an energy transformation sector. The "transformation" input – gas – cannot be substituted with other energy sources. Similarly, it cannot be substituted with more capital – otherwise the model could show an "energy efficiency improvement", implying that the distribution sector supplies the same amount of energy with less gas. To prevent such effects, the production function is mostly of Leontief type, with substitution allowed only within the capital-labour nest and the district heating nest.

2.3 Households

41. The model features one representative consumer (household) per region. The representative household receives income from labour, capital and natural resources (of which it is a sole owner). In addition, it receives (or pays) net transfers from the government, being an aggregate balance of social benefits and other payments between households and the government (including, inter alia, government borrowing, and lump-sum transfers allowed by additional government revenues, but excluding taxes and contributions accounted for elsewhere in the model – for example as taxes on products or taxes on labour or capital income). Also, foreign trade deficit is treated as income component, since – from macroeconomic perspective – it increases current households'

purchasing power. Household income formation can be summarized in a following stylized form:

$$\begin{aligned}&Household\ income =\\&= Labour\ income\\&+ Capital\ income\\&+ Resource\ rent\\&+ Net\ transfers\ with\ government\\&+ Foreign\ trade\ deficit\end{aligned}$$

42. It is worth emphasizing that household income used in the model does not align with the categories defined in national accounts, such as gross disposable income of households. Here income covers consumption, as well as economy-wide investment expenditure. Thus:

$$Household\ consumption = Household\ income - Investment$$

43. Dependent on the setting, investment is either determined exogenously or endogenously, based on the rate of return (in addition, when linked to the energy system model, part of investment expenditure related to electricity and heat generation equipment is provided by that model).

44. Aggregate consumption is allocated across goods in the following way. First, demand for food and heat are determined exogenously (in real terms). Exogenous specification of those consumption components allows for setting the demand paths more aligned with historical trends. It yields:

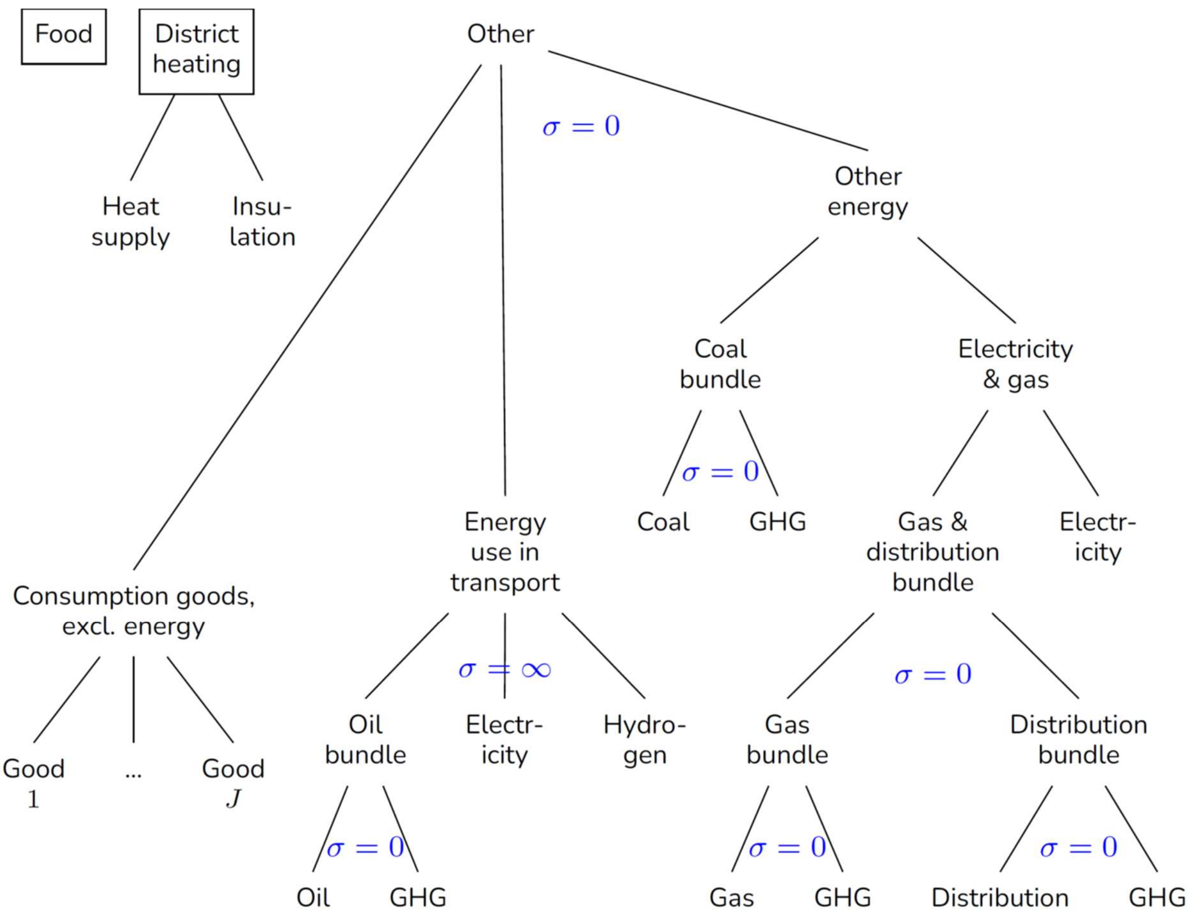
$$Other\ goods = Household\ consumption - Food - Heat$$

45. Food demand maps to the goods supplied by agriculture and the food industry. Whereas "heat" is a bundle of district heating and insulation. The cost of insulation is modelled in a simplified way, as a portion of demand for services (in this case, general services, rather than specifically construction services have been used, because in the base year data for some countries household demand for construction services is very low). As district heating prices increase, households substitute it for more "insulation services". Note that this mechanism currently does not apply in the model to individual heating from other energy sources, such as coal or gas stoves, heat pumps etc.

46. Allocation of "Other goods" consumption to individual commodities is driven by a nested CES-Leontief demand system, as shown in FigureFigure 11. At the top level, the aggregate of "Other goods" is split into three bundles, consumed in fixed proportions. The transport bundle includes initially (that is, in the base year) only oil (gasoline, diesel etc.), which in time can be substituted with electricity and hydrogen. "Other energy" bundle covers all remaining energy uses (individual heating, cooking, use of electric appliances

etc.), with substitution opportunities driven by nested CES structure. Note that unlike in production sectors, no capital-energy substitution is modelled on the household side, as the consumption data do not track the cost of durable equipment goods and the related investment expenditure. The third bundle is a CES composite of all goods and services not specified elsewhere (including both durables and non-durables).

Figure 11. Nested Leontief and CES consumption function structure for households



Source: CAKE/KOBiZE own study

2.4 Labour market

47. The model distinguishes two labour types – skilled and unskilled – treated as imperfect substitutes, as discussed in section 2.2. Given the long-run focus of d-PLACE, unemployment is not modelled explicitly. Supply of labour of both types in efficiency units is determined exogenously, based on the assumed rate of economic growth.

48. In the default model setup it is assumed that adjustments of wages ensures that demand for labour is equated with the pre-determined supply (note that such a setting still allows

for an implicit, “natural” unemployment rate). Labour moves freely between sectors, but not between regions or between skilled-unskilled labour groups.

49. d-PLACE also features an extension, allowing for wage differentiation between sectors, and introducing a cost associated with movements of labour between sectors. In such a setup labour is supplied by two representative workers, one for each skill group. Each worker receives an endowment of labour L from households. The worker can transform this labour into productive units of labour dedicated for each sector i, l_i, according to the following transformation-possibility frontier:

$$\sum_j \left(\frac{N_j}{s_j}\right)^\rho = L$$

Where: s_j is the share parameter and parameter determines how easy it is to transform units of labour across sectors (the higher the value of ρ, the more difficult the transformation is).

50. Note that N_j denotes amount of labour in efficiency units and hence does not have to sum up to . Note also that in this setup labour is sector specific in the sense that one unit of labour cannot be freely moved between sectors without change in productivity. When the representative worker transforms a unit of efficient labour from one sector to fit another sector, the amount of efficient units that is now available for the new sector is given by:

$$\frac{dN_k}{dN_j} = -\left(\frac{N_j}{N_k}\right)^{\rho-1}\left(\frac{s_j}{s_k}\right)^{-\rho}$$

The objective of the representative worker is to choose the allocation of efficient labour, N_j that maximize total return to labour. Formally, the optimization problem reads

$$\max_{\{N_j\}_{j=1}^k} \sum_j N_j w_j$$

subject to constraint $\sum_j \left(\frac{N_j}{s_j}\right)^\rho = L$.

The optimal allocation satisfies the first order conditions to the problem above given by

$$w_j - \lambda(s_j)^{-\rho}(N_j)^{\rho-1} = 0$$

Where: λ is the shadow value of a marginal unit of endowment. Using the constraint, $\sum_j \left(\frac{N_j}{s_j}\right)^\rho = L$, one can show that

$$\lambda = \left(\sum_j (s_j w_j)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}$$

and

$$N_j = s_j w_j \left(\frac{(s_j)^{\frac{\rho}{\rho-1}} (w_j)^{\frac{1}{\rho-1}}}{\left(\sum_k (s_k w_k)^{\frac{\rho}{\rho-1}}\right)^{\frac{1}{\rho}}} \right)^{\frac{1}{\rho-1}}$$

which means that labour supply in efficiency units in sector j is an increasing function of wage in that sector relative to wages in other sectors.

51. This setup allows to take into account that policies that force labour to move across sectors could generate costs on the side of workers. An economic distortion introduced by a policy will typically change the allocation of labour away from the allocation in the laissez faire economy. In this situation, the policy will result in lower compensation for workers. The intuition is that in the laissez faire economy each worker works in the sector that gives him or her the highest possible payoff. When some workers are forced to move due to a policy, they will obtain lower payoff in the new sectors than in their original sector.

52. The user can also switch-off this feature of the model and assume a free flow of labour between sectors.

2.5 Foreign trade

53. The formulation of international trade in the model is based on the standard CGE assumption of product differentiation by origin. Intermediate goods and consumer goods are bundles of domestic and imported goods. An imported good that is linked to a domestic product is modelled in two stages. Firstly, the goods that are imported to sector j from different countries are linked in fixed proportion to the international transport services attributed to these goods. In the other words, the cost of transporting good j from country s to country r is strictly proportional to the amount of good that is transported (and is route-specific). Consequently, the production function at this stage is as follows:

$$X_{j,s} = g(X_{j,s}, T_{r,j,s}) = min(X_{j,s}, T_{r,j,s})$$

54. At the next stage, goods from sector j originating from different countries are linked together to build the imported goods bundle using the CES function. The elasticity of substitution between goods imported from different countries varies across sectors (products) but not across regions. Formally, the production function of an imported good for sector j in country r is as follows:

$$M_{j,r} = f(X_{j,1,r} \dots X_{j,S,r}) = (\sum_{s\epsilon\{1..S\}} \beta_{j,s,r} X_{j,s,r}^{\rho})^{1/\rho}$$

55. At the highest stage, aggregate imported goods are linked to domestic production using the Armington aggregate. Armington aggregate is the name for an aggregate that uses a CES function. As with the other equations, a good that is consumed on the domestic market is thus created using CES function. Similarly to other goods that are produced using CES functions, we can describe the 'production' (or aggregation) process of a good used for the domestic production or consumption as follows:

$$A_{j,r} = f\left(M_{j,r}, D_{j,r},\right) = (\beta_{j,r} D_{j,r}^{\rho_{IM}} + (1-\beta_{j,r}) M_{j,r}^{\rho_{IM}})^{1/\rho_{IM}}$$

56. In the current model version, each sector supplies a homogenous commodity, and the split of supply between domestic and foreign markets is only driven by relative domestic to foreign demand.

2.6 Investment

57. Investment in the model depends on the price of investment good and the return to capital in given period, according to the following equation:

$$I_r = inv_r \cdot \left(\frac{RK_r}{PINV_r}\right)^{\varepsilon_{inv,r}}$$

58. In this equation I_r denotes the investment level RK_r is return to capital (capital rental rate) in region r and $PINV_r$ is the price of investment bundle, inv_r is a multiplicative constant, and $\varepsilon_{inv,r}$ is elasticity of investment with respect to rate of return.

59. Investment bundle is composed of goods linked in fixed proportions. Therefore, we have the following equation:

$$Y_{INV,r} = g(A_i, \dots, A_I) = \min\left(\frac{A_1}{a_1}, \dots, \frac{A_I}{a_I}\right)$$

60. Market clearing equation for investment takes the form: $I_r = Y_{INV,r}$. In the current setting investment is driven by changes in rate of return, while the supply of investment goods (and the funds) adjusts to investment demand.

61. The savings rate in the model adjusts to match investment. Concerning clarity and the proper welfare effects' calculation of the policies introduced, the international capital flows are not allowed in the model, so the country investment rate adjusts to match the investment rate.

2.7 Government

62. The d-PLACE model distinguishes the government sector which collects taxes, makes and receives transfer payments (in particular, for emission allowances) and purchases goods and services. In the model, government expenditure is equal to government revenue, with implicit budget deficit included in the net transfers between government and households. Government consumption combines goods and services – in particular non-market services, such as public administration, health and education – in fixed proportions (in real terms).

Using the model formalism, this assumption can be stated as that aggregate government consumption good (Y_{GOV}) is `produced' from goods and services (A_i) using Leontief technology:

$$Y_{GOV} = g(A_1, \dots, A_I) = \min\left(\frac{A_1}{a_1}, \dots, \frac{A_I}{a_I}\right)$$

63. The government receives revenues from the following sources:

- taxes on labour: $TL_i = \sum_L t_{L,i} P_L L_{L,i}$, where P_L denotes after-tax (net) wage, $t_{L,i}$–tax rate on labour,
- taxes on capital: $TK_i = t_{K,i} P_K K_i$, where P_K denotes after-tax (net) price of capital, $t_{K,i}$– tax rate on capital,
- taxes on natural resources and land: $TR_i = t_R P_R R_{R,i}$, where P_R denotes net price of natural resources, t_R- tax rate on natural resources,
- taxes on products: $TA_i = t_{IM,i} P_{IM,i} M_i + t_{D,i} P_{D,i} D_i$, where $P_{D,i}$ denotes the supplier price of the Armington composite's domestic component, $P_{IM,i}$ – the price of the Armington composite's imported component, $t_{IM,i}$ and $t_{D,i}$ – the tax rates on imported and domestic components, respectively,
- taxes on domestic production: $TY_i = t_{Y,i} P_{Y,i} Y_i$, where $P_{Y,i}$ denotes the producer price of domestic output Y_i, and $t_{Y,i}$ – the tax rate on production Y_i,
- import tariffs: $TM_i = t_{M,i}(1 - t_{X,i}) P_{M,i} M_i$, where $P_{M,i}$denotes the producer price of imported products, and M_i, $t_{M,i}$ – the tax rate on imported products M_i,
- taxes on exported products: $TX_i = t_{X,i} P_{X,i} X_i$, where P_X denotes the producer price of exported products X_i, and $t_{X,i}$ – the tax rate on exported products X_i,
- taxes on pollution emissions: $TEM_i = \sum_{EM}(t_{EM} + P_{EM}) EM_i$, where P_{EM} denotes the price of emission permits for greenhouse gases, and t_{EM} – the tax rate on pollution emissions. EM_i denotes the volume of emissions.

64. These taxes are reported net of subsidies. Consequently, government revenues are sum of the following taxes.

$$I_{GOV} = \sum_i (TL_i + TK_i + TR_i + TY_i + TA_i + TM_i + TX_i + TEM_i)$$

65. These taxes are indexed over sectors (index i). Moreover, government balance rule implies that the government expenditures are equal to revenues, so:

$$I_{GOV} = Y_{GOV} + S_{GOV}$$

66. In this equation, S_{GOV} is the actual transfers from the government *plus* government investments *plus* other government expenditures (e.g., interest on debt) *minus* other government revenues (e.g., property income) *minus* the government deficit (which is eliminated in the model by transfers between government and households). Public investments are covered by S_{GOV}. Government consumption is fixed in real terms. The commodity-structure of government consumption is also fixed in real terms. The same formulation is applied to each region (although government consumption structures differ across regions).

67. Therefore, each increase in government revenues is transferred to households and used for consumption purposes. Nevertheless, this assumption may be modified, if needed. Government expenditures are by default equal to government incomes and therefore the government deficit is not modelled explicitly. Transfers are adjusted, such that the government accounts are balanced.

2.8 Dynamics – capital accumulation

68. Calibration to the balanced growth path was made on the basis of input output table data –return on capital (i.e. gross operating surplus) and investment expenditure – as well as universal assumption on interest rate (on the basis of historical data / behavioural assumptions) and depreciation of capital (calculated, economy average):

$$gop_{i,r,t} = (r_r + \delta_r) \cdot K_{i,r,t}$$

$$I_{i,r,t} = \delta_r \cdot K_{i,r,t}$$

$$K_{r,t} = \frac{\sum gop_{i,r,t} - inv_{r,t}}{r}$$

$$\delta_r = \frac{inv_{r,t}}{K_{r,t}}$$

$$K_{i,t} = \frac{gop_{i,t}}{r_r + \delta_r}$$

Where: $gop_{i,r,t}$ is gross operating surplus, δ_r is regional average depreciation rate, $I_{i,r,t}$ is investment, $K_{r,t}$ is capital in period t and region r.

69. The dynamics in the model allow for different temporal model resolutions – the basic setting was assumed to be 5-year time period, but for some applications annual time period seems to be better and, if needed, can be applied.

70. In general, there are two variables in the model, related to the capital level – sector specific extant capital, which is depreciated, and the new capital, which is allowed to flow freely between sectors. In the multiannual setting, the extant capital must be depreciated multiannually and the new capital must be also depreciated.

71. The extant capital is simply depreciated multiannually – therefore we have ("i" is the number of years):

$$KXD_{i,r,t} = (1 - \delta_r)^i K_{i,r,t-1}$$

72. The new capital is previous period investment – but they must be also depreciated. The equation for the *n-th* partial sum of geometric sequence: $S_n = a_1 \frac{1-q^i}{1-q}$, in our case $a_1 = I_{r,t}$ and $q = (1 - \delta_r)$. Therefore we have:

$$KN_{r,t} = \frac{(1 - (1 - \delta_r)^i)}{\delta_r} I_{r,t-1}$$

73. To reflect the economic growth, these values need to be updated, therefore, they are also multiplied by $(1 + g_r)$ where g_r is target GDP growth between subsequent periods. Consequently, technical progress is *implicitly* reflected in the „value" of capital, there is no separate variable reflecting the changes in efficiency. This may change in future versions of the model, according to the specific simulation need.

2.9 Macro closure

74. Closure rules reflect main macroeconomic assumptions of policy simulations. Although these assumptions may be adjusted in specific scenarios, below we summarize the default options in d-PLACE simulations:

- Government expenditure is exogenous – fixed in real terms in a given year. That is, if a policy shock improves net government revenues (for example, due to introduction of the carbon tax), excess revenue is transferred to household as a lump-sum. Conversely, if the shocks would lead to a deterioration of the government balance, net transfers with households are diminished to preserve the balance.
- The current account (trade balance) is exogenous – fixed in real terms in a given year. Real exchange rate adjusts to preserve the trade balance. Real exchange rate adjustments are facilitated by changes in factor (capital and labour) prices relative to world prices, which leads, inter alia, to changes in export prices relative to import prices.
- Investment is determined endogenously – it increases (decreases) with an increase (decrease) of the current rate of return to capital. Effectively, investment financing is provided by adjustments in household savings.
- Labour and capital are immobile between regions in the model, so wages and capital rentals do not converge between regions. In the default setting, labour is mobile between industries – movements of labour ensure that wage rate (per effective labour unit) is equalized across sectors. However, it is also possible to choose an option of immobile labour mobility across regions and differentiate the response of wages in different sectors. Total effective labour stock available in a given region, in a given period, is exogenous. Capital stocks built in previous periods are industry-specific – they cannot move between sectors, and they are diminished in each period subject to a fixed depreciation rate. New capital is allocated freely across sectors, such that the rate of return on it is equalized.

2.10 Energy and emissions

75. Emissions are linked to fuel consumption or production from a specific sector, so emission reduction can take place by decreasing the output or by decreasing the consumption of fuels (although note that formulation discussed in section 2.11 extends these possibilities with the CCS/CCU technologies). In d-PLACE, sectoral transformation to less-emission technologies is modelled by substitution between more and less emission intensive fuels (e.g. switching coal to gas) or by substitution of fuels for capital and labour.

76. There are several types of emissions in d-PLACE:

- Energy-related emissions bound to the use of fossil fuels in fixed proportion,
- Process-related emissions bound to sectoral output in fixed proportion,
- Process-related emissions linked to sectoral capital in fixed proportion.

77. Therefore, abatement techniques aiming at, e.g., the introduction of better technologies (keeping the use of fuels at the same level with decrease in emissions) are not explicitly modelled. However, they are modelled implicitly as the substitution between capital and fossil fuels use.

78. Within the EU the emissions must be covered in EU ETS by European Emissions Allowances (EUA), purchased by industries. In the case of the EU ETS system, emissions from different industries and regions are indistinguishable – therefore there is one cap on EU ETS emissions. In the case of non-ETS, an emission cap is granted to each region (country) individually (as described above), so countries cannot trade their non-ETS targets or NDCs. Consequently, the price of the non-ETS emissions is region (country) specific. In the case of NDCs for regions outside the EU, all sectors in a given region use the same emission cap, which is calculated using NDCs – so there is only one price of greenhouse gas emissions for a given region (country).

2.11 Combined top-down and bottom-up representation of technologies

79. d-PLACE primarily uses the nested CES-Leontief framework – typical to CGE models – to represent energy demand. Industries and consumers adjust their energy mix in response to changes in relative prices of different fuels (including the cost of emissions) and electricity. Additionally, producers may substitute energy for fixed capital (equipment), thus leading to energy efficiency improvement. Finally district heating can be substituted for services, as a proxy for building insulation. The nested CES-Leontief model is often referred to as the top-down approach to technology representation.

80. d-PLACE augments the above specification with several technologies modeled in a bottom-up fashion, following the approach proposed by Böhringer and Rutherford (2008) in the paper titled “Combining bottom-up and top-down”. In most cases these technologies are initially inactive, activated when they become profitable. While in the cited paper the authors use the specification to model electricity supply, we use it to model energy demand and specific emission abatement options.

81. Technically, bottom-up technologies add a new layer to the model specification. In particular, two new dimensions are introduced, represented by sets ep and et. The ep set denotes energy services or other processes that can be facilitated by alternative competing

technologies, indexed by set et. Even though the specification is quite general, allowing to model various processes related to production or consumption, we shall hereafter refer to them broadly as "energy technologies". The ep set extends inputs to production or consumption beyond regular commodities (set i) and primary factors (set f). Each element of the ep set is associated with a specific subset of technologies within the et set. The mapping between energy- or emission-related services (ep) and particular technologies (et), currently included in the model, is shown in TableTable 5.

Table 5. Mapping between energy – or emission – related services and technologies

pr: Industrial process emissions	$proc$: Actual CO_2 emissions $ccpr$: Emissions capture (CCS/CCU)
gh: Gas/hydrogen energy services	$gagd$: Gas and distribution bundle $hgen$: Hydrogen
tr: Transport energy services	$oilt$: Oil $elet$: Electricity $hgen$: Hydrogen
wm: Waste emissions management	$wast$: Actual CH_4 emissions $cwtg$: Emissions capture
ac: Agricultural CH_4	$agem$: Actual emissions $agab$: Emission abatement activities
an: Agricultural N_2O	$agem$: Actual emissions $agab$: Emission abatement activities

Source: CAKE/KOBiZE own study

82. As in the case of technologies describing production of goods and services distinguished, the new "energy technologies" are represented by unit cost functions, denoted as UC. In general, one can write (skipping the regional dimension, r):

$$UC_{ep,et,g} = \sum_i PA_i \cdot UA_{ep,et,i,g}$$
$$+ \sum_{es} PEMR_{es} \cdot UE_{ep,et,es}$$
$$+ RK_g \cdot UK_{ep,et,g}$$
$$+ \sum_l PF_g \cdot UL_{ep,et,l,g}$$
$$+ PRE_{ep,et,g}$$

Where: UA, UE, UK, and UL denote unit intermediate inputs, unit emissions, unit capital and unit labour inputs, respectively. Accordingly, the prices of those inputs are PA for intermediates, $PEMR$ for emissions, RK for capital and PF for labour. PRE denotes a rent accruable to owner (operator) of the technology.

83. The model includes the following complementarity conditions:

$$UC_{ep,et,g} - PEP_{ep,g} \geq 0$$
$$YET_{ep,et,g} \geq 0$$
$$YET_{ep,et,g} \cdot (UC_{ep,et,g} - PEP_{ep,g}) = 0$$

Where: YET is the output (index) of technology et facilitating energy service (or other process) ep, whereas PEP is the price of that energy service. The complementarity states that when the unit cost of a given technology is higher than the market price of its services ($UC - PEP > 0$) then that technology is inactive (output equals zero, $YET = 0$). In turn, non-zero output ($YET > 0$) requires that the profit equal (unit cost equals the market price, $UC - PEP = 0$).

84. In principle, such a setting implies that a given energy service should be provided by the cheapest of the competing technologies, that would also set the market price of the service. However, this is not the case when a cheap technology faces a constraint (upper bound) on its output, such that it is not able to satisfy all demand for an energy service. Then the technology yields a rent just sufficient to equalize the unit cost (including the rent) with the next, more expensive technology, providing the residual supplies. In the current model setting, one of technologies competing in supply of an energy service is always unconstrained. This typically relates to "traditional technologies", such as oil use in transport or industrial process resulting in GHG emissions, while new technologies, such as electric vehicles or CCS/CCU face capacity limits. Consequently, rents PRE may only arise in "new technologies", with constrained output. The rent is also equivalent to the shadow price related to the capacity constraint of a given technology (see Böhringer and Rutherford, 2008).

85. Capacity constraints for energy technologies are imposed by defining an artificial production factor that is used only by that technology (MLE variable in the model is used to index the amount of that factor). Production capacity of a given technology is defined by the following assumptions:

- $limei_{ep,et,g}$: maximum annual increments of technology et facilitating energy service ep in sector g,
- $limet_{ep,et,g,t}$: time path of ceiling levels of capacity of technology et facilitating energy service ep in sector g.

86. Capacity limit in a given simulation period is represented by parameter $lime_{ep,et,g}$. Capacity limits (as well as their increments and ceilings) are expressed in terms of market shares of a given technology in total supplies of a given energy service. For example, $lime_{"tr","elet","trn"}$ is a maximum share of electric transport in total road transport in the transport services sector, $lime_{"pr","ccpr","isi"}$ is the share of captured CO_2 process emissions in the iron and steel sector. The actual shares in a given period are determined endogenously, based on demand and supply conditions. These share of technology et in energy service ep utilized by sector g can be expressed using the activity levels YET, introduced above:

$$\frac{YET_{ep,et,g}}{\sum_e YET_{ep,e,g}}$$

<u>Where:</u> e is an alias for set et.

87. In each period of the recursive-dynamic solutions, the maximum capacities, $lime$, are updated before the model is solved, based on the previous period shares, maximum annual increments and technology ceiling shares, in the following two consecutive steps:

Step 1: $$lime_{ep,et,g} = max\left\{\begin{matrix} 0 \\ limei_{ep,et,g} \cdot yd \\ \frac{YET_{ep,et,g}}{\sum_e YET_{ep,e,g}} + limei_{ep,et,g} \cdot yd \end{matrix}\right\}$$

Step 2: $$lime_{ep,et,g} = min\left\{\begin{matrix} lime_{ep,et,g} \\ limet_{ep,et,g,t} \end{matrix}\right\}$$

<u>Where:</u> yd is the time-step – the number of periods from the previous solution. Note that in the above calculations, the YET variable contains the solutions from the previous period.

88. In the model, MLE is then determined endogenously as:

$$MLE_{ep,et,g} = limei_{ep,et,g} \cdot \sum_e YET_{ep,e,g}$$

89. Recall that $MLE_{ep,et,g}$ is and index of the special production factor, used solely by technology et facilitating energy service ep in sector g. The price of that factor, the rent $PRE_{ep,et,g}$ is determined using complementary condition, related to the market clearance assumption. Demand for factor MLE is derived from Shepard's lemma as:

$$\frac{\partial UC_{ep,et,g}}{\partial PRE_{ep,et,g}} \cdot YET_{ep,et,g}$$

90. Since, in our case, the partial derivative in the above expression equals 1, the demand for the specific factor reduces to $YET_{ep,et,g}$. This allows to write the market clearance complementarity condition as:

$$MLE_{ep,et,g} - YET_{ep,et,g} \geq 0$$

$$PRE_{ep,et,g} \geq 0$$
$$PRE_{ep,et,g} \cdot \left(MLE_{ep,et,g} - YET_{ep,et,g}\right) = 0$$

91. Consequently, if $MLE - YET = 0$, so the available capacity of the technology is fully used, that technology can yield a positive rent, $PRE > 0$. Alternatively, if the current capacity is not fully used, that is $MLE - YET > 0$, the rent equals zero, $PRE = 0$.

92. The final part of the implementation of "energy technologies" are the market clearance conditions for particular energy services:

$$\sum_{et} YET_{ep,et,g} \cdot \overline{YET}_{ep,et,g} - \frac{\partial Y_g}{\partial PEP_{ep,g}} \cdot Y_g \cdot \bar{Y}_g \geq 0$$
$$PEP_{ep,g} \geq 0$$
$$PEP_{ep,g} \cdot \left(\sum_{et} YET_{ep,et,g} \cdot \overline{YET}_{ep,et,g} - \frac{\partial Y_g}{\partial PEP_{ep,g}} \cdot Y_g \cdot \bar{Y}_g\right) = 0$$

Where: Y_g is output in sector g, whereas $\bar{Y}$ and $\overline{YET}$ denote base year levels of the respective categories (recall that Y and YET are indices). In case the available capacity ($\sum YET \cdot \overline{YET}$) exceeds the demand...

93. Energy technologies are represented in a simplistic form, merely reflecting an assumed, constant marginal cost, as well as assumed maximum potentials and their evolution over time. For example, CCS/CCU, marginal cost reflect the cost of emission abatement per tonne of CO_2 equivalent, expressed in constant prices, based on estimates found in the literature (see Table Table 6). Whereas the costs of hydrogen or electric transport are calibrated based on results from sectoral models (energy system model and transport model). In most cases the costs consist solely of capital cost (not counting the rent) or electricity (in the case of electric transport). One possible future development of d-PLACE is modelling the costs of technologies more comprehensively, using external assessments of the cost structures, rates of expected technical change etc. The d-PLACE model used for simulation of CCS/CCU technology in industrial sectors to provide cost and maximum absorption data.

Table 6. Technical and economic parameters of the CCS / CCU technology

Sector	Potential for absorbing	Cost $/tCO₂	Data sources
Iron and steel industry	50%	68.7	Tsupari et al. (2013)
Oil refineries, chemical industry	50%	121.8	van Straelen et al. (2010)
Pulp and paper	75%	56.4	IEA (2013)
Cement industry	90%	61.5	

Source: CAKE/KOBiZE own study

94. When hydrogen is used, it is assumed that this fuel can be a substitute for gas. The cost of hydrogen production is determined in the MESSA energy model (based on electricity production costs). However, the maximum potential for switching gas to hydrogen was set at 95% by 2050.

95. As mentioned above, energy services and their underlying technologies form a separate layer in the model. That is, energy services form a group of inputs (priced PEP) separate from other intermediate inputs (the so called "Armington bundles", priced PA).

96. Consider the example of electric transport in the transport services sector. Under the top-down approach, the use of oil in that sector is treated as intermediate input in (Armington bundle) within the nested CES production function. Under the bottom up approach the oil bundle is taken out of the nested CES production tree, and instead placed as an input to oil transport technology ("oilt") producing the transport energy service ("tr"). Whereas transport energy service "tr", rather than oil directly, is now treated as an input to production of the transport energy sector.

2.12 Emission limits and pricing

97. To depict the GHGs mitigation police the cap and trade system has been implemented which directly determines the total carbon permits supply in the market. The government is responsible for the permits supply and collects ETS revenue. The GHG emissions must not exceed the assumed number of permits that are released by the government. Each sector that emits greenhouse gases requires permits, creating demand for emissions. The price of carbon emissions is calculated endogenously and it is result of market clearing (balance of the total demand and the total supply for each market).

98. Generally, four main features of emission markets are implemented in d-PLACE model:

- the ETS can cover any number of defined regions and sectors;
- within one sector and region, some emissions may belong to one ETS and the rest to the another ETS, or part of the emission from sector may not be covered by any ETS;
- a separate permits price is set for each ETS;
- free allocation of permits may be implemented through subsidies to the sectors; the value of the subsidy depends on the exogenous number of free allocation and the endogenous price of permits.

99. Part of the emissions from sectors that are not covered by the ETS in the EU is also modelled as emissions trading markets. In this case, however, the scope of regions is limited to one and to the assumed group of sectors according to climate policies rules. As

a result of calculation, we get the lowest possible emission reduction prices in non-ETS sectors for each EU region.

100. At the technical level, the prices of emission permits are modelled using variables $PEMB(es, b)$ and $PEMR(es, r)$. For variable $PEMB(es, b)$ two dimensions are introduced, represented by set es and set b. The es set represents emission market segment. For example, in the European Union it includes the EU ETS, non-ETS, and, possibly, other prospective systems such as an ETS covering transport and housing. The b set defines a block of regions included into the specific market segment. To reflect the regional price of emission in the model code, the mapping between emission price related to the block of regions $PEMB(es, b)$ and price in the particular region $PEMR(es, r)$ is implemented. Each element of the b set is associated with specific regions within the r set. The model uses parameter $emshr(es, ghg, emsrc, g, r)$, which defines the share of emissions (of a given greenhouse gas ghg, in a given sector g and region r, from a given source $emsrc$) that is assigned to a specific market segment (es).

101. The volume of emissions in individual regions r and in given market segments es (associated with the price $PEMR(es, r)$) is calculated as $emit_{ghg,emsrc,g,r} \cdot emshr_{es,ghg,emsrc,g,r}$.

2.13 Elasticities

102. The benchmark CGE model solution reflects the state of an economy in a base year under the assumption that the general equilibrium conditions are met. The CGE model parameters are calibrated, meaning that they result from a mathematical procedure to solve non-linear equations given the base year data. However, some parameters (like elasticities) need to be taken from exogenous sources (i.e., they must be determined outside the model). Exogenous parameters typically take the form of elasticities: price elasticities, income elasticities, and elasticities of substitution, broadly rooted in empirical research. The simulation results of CGE models are sensitive to the assumed elasticity values. The elasticity assumptions for the d-PLACE model are based mostly on GEM-E3 model (see Capros, 2013). Elasticities differ across sectors, but values for each sector are identical for all countries/regions.

103.

104.

105. **Table 7** shows default values of substitution elasticities used in d-PLACE in sectoral production functions and the household consumption function. Note that these defaults can be overridden in sensitivity analyses or changed in specific simulations, upon analysis of results or new external information.

Table 7. Elasticities assumptions in d-PLACE model

	crol	cofr	oibi	nsol	fuel	biof	ener	labs	klab	klle	kkee	klma	gele	klem	armi	impr
col		0.2					1	2	0.5	1		1.7	0.9		1.1	6.1
cru		0.2					1	2	0.5	1		0.5	0.9			10.4
gas		0.2					1	2	0.5	1		0.5	0.9		1.1	20
gdt								2	0.5						0.9	20
oil		0.2	0.5	0.2	0.1		1	2	0.5	1			0.9		2.1	4.2
ele	1	0.2			1	0.1		2	0.5	1	2		0.9		2.8	5.6
frs				0.8	0.7		1	2	0.5	1			0.9	0.3	2.91	5.81
agr				0.8	0.7		1	2	0	1			0.9	0.3	0.15	5.81
foo				1	0.9		1	2	0.5	1			0.9		0.15	6.43
chm				1	0.9		1	2	0.5	1			0.9		3.3	6.6
nmm				1	0.9		1	2	0.5	1			0.9		1.9	3.8
isi				1	0.9		1	2	0.5	1			0.9		2.95	5.9
nem				1	0.9		1	2	0.5	1			0.9		3.97	7.95
ppp				1	0.9		1	2	0.5	1			0.9		2.95	5.9
con				1	0.9		1	2	0.5	1			0.9		1.9	3.8
oth				1	0.9		1	2	0.5	1			0.9		3.9	7.8
trv				1	0.9		1	2	0.5	1			0.9		3.9	7.8
srv				0.5	0.9		1	2	0.5	0.75			0.9		2.03	4.06
atr		0.2	0.5	0.2	0.1			2	0.5	0.2			0.9		1.9	3.8
trn	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2	0.5	1			0.5		1.9	3.8
c					0.4		1			1			0.9			

Source: CAKE/KOBiZE own study

<u>Where:</u>

- klle - substitution elasticity - Value-added versus energy,
- klma - substitution elasticity - Value-added versus materials,
- klem - substitution elasticity - Materials versus energy_K_L,
- klab - substitution elasticity - K versus L,
- labs - substitution elasticity - LL versus LH,
- ener - substitution elasticity - ELE versus fuels,
- fuel - substitution elasticity - Between fuels,
- nsol - substitution elasticity - OIL versus CRU versus GAS,
- gele - substitution elasticity - ELE versus CRU versus GAS,
- oibi - substitution elasticity - OIL versus BIO,
- crol - substitution elasticity - OIL versus CRU,
- cofr - substitution elasticity - BIO versus other fuels,
- kkee - substitution elasticity - K versus fuels,

- biof - substitution elasticity - BIO versus fuels,
- armi - substitution elasticity - Domestic and imported goods (Armington),
- impr - substitution elasticity - Imported goods from different regions (Armington),

2.14 Models linking

106. This chapter describes the linking between four models developed and maintained by the Center for Climate and Energy Analysis (CAKE): the macroeconomic Computable General Equilibrium (CGE) model (d-PLACE), energy model (MEESA), transport model (TR^3E) and agriculture model (EPICA). It explains the procedure for solving the models in the iterative mode and provides documentation of additional components of the models' code that facilitate the linking.

107. The primary purpose of linking is to ensure that changes due to mitigation effort in one sector are reflected in the costs and potential of mitigation effort in the other sectors. Standard sectoral models are a valuable source of projections of detailed changes in the structure of production inputs and output in individual sectors. However, when these models run in isolation, the projections rest on the assumptions that a number of critical variables, such as demand for sectoral output, carbon price and prices of inputs are exogenous, that is they do not react to changes in climate policy considered in the simulation, or this reaction is crudely simplified.

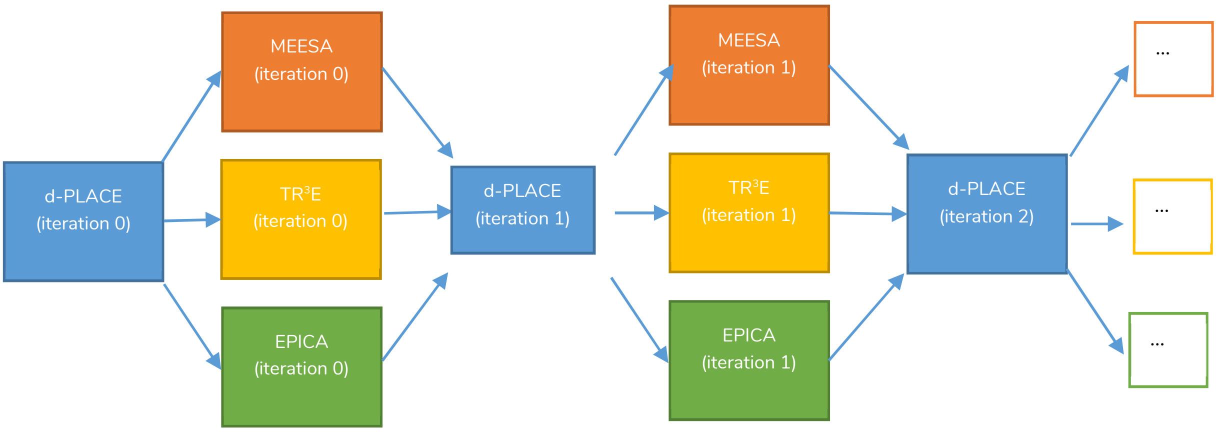
108. In reality, individual sectors are not isolated from the rest of the economy: they have an impact on and are affected by changes in prices and macro conditions.

The individual sectoral models are separate tools that can be used independently. Their linking is based on sequential solving, which is accompanied by the mutual transfer of selected information (simulation results). The diagram of this procedure is presented in Figure

109. Figure 12. The scope of information transferred between particular models is presented in Table Table **8**. The information transferred between the models covers the entire time horizon of the simulation (until 2050), and all EU regions and countries belonging to the EU ETS (except for the agricultural sector covering only Poland).

110. Apart from providing its own results, the d-PLACE model also serves as a hub for information exchange to sectoral models. For example, it transfers electricity and hydrogen prices from MEESA model to TR^{3}E model, as well as the use of electricity by electric vehicles from TR^{3}E model to MEESA model.

Figure 12. Iterations between models d-PLACE, MEESA, TR^{3}E and EPICA



Source: CAKE/KOBiZE own study

Table 8. Information exchange between d-PLACE and sectoral models: MEESA, TR^{3}E and EPICA

d-PLACE → MEESA	**MEESA → d-PLACE**

- Marginal abatement cost in the EU-ETS (assumed to be equal to the price of emission allowances)
- Demand for electricity,
  • Including separate information on demand for electricity by electric vehicles (based on the results from TR^{3}E)
- Demand for district heating
- Demand for hydrogen in transport (based on the results from TR^{3}E) and in the industry
	- Use of fuels (coal, natural gas, oil products) in the production of electricity and district heating
	- CO_2 emissions associated with the generation of electricity and district heating,
	  • including the „negative emissions” associated with the use of BECCS technology
	- Average price of electricity
	- Average price of district heating
	- Average price of hydrogen
	- Investment costs in the sector of electricity and district heating production

d-PLACE → TR^{3}E	**TR^{3}E → d-PLACE**
- Gross domestic product (GDP) - Marginal abatement cost (emission price) in the non-ETS sector - Electricity price (based on information from the MEESA model) - Price of hydrogen (based on information from the MEESA model)	- Use of fuels (oil products), electricity and hydrogen in road transport - Emissions in road transport
d-PLACE → EPICA	**EPICA → d-PLACE**
- Marginal abatement cost (emission price) in the non-ETS sector - Wage dynamics - Changes in prices of material inputs in agricultural production	- CH_4 and N_2O emissions in agriculture

Source: CAKE/KOBiZE own study

111. Iterative exchange of results between the d-PLACE model and the sectoral models allows to determine marginal abatement costs for EU ETS sectors for the EU as a whole (using exchange with the MEESA model) and for non-ETS sectors for each region (using exchange with TR^3E and EPICA models). The initial estimate of this cost, obtained in the d-PLACE model, invokes changes in the emission intensity of energy, transport and agricultural production in the MEESA, TR^3E and EPICA models, which in the next iteration leads to a change in the "demand for emissions" in the d-PLACE model and the related correction of the marginal abatement costs (see Boratyński et al., 2021).

3. Prospective model developments

112. Prospective developments of the model will primarily depend on the topics of forthcoming analyses using the modelling toolbox. However, a few potential directions can already be envisaged:

- Enhancing technological detail of d-PLACE, particularly in the area of energy use by industries and households and specific emission abatement opportunities. Including more detailed cost structures, sourcing of inputs (e.g., equipment), projections of technology costs evolution, possible fixed costs and the facilitating investment (infrastructure).
- Explicit modeling of new “green industries”, supplying goods and services necessary to operate low-carbon technologies.
- Strengthening empirical support for model parametrization (substitution elasticities in production and consumption, investment elasticity), closure rules and baseline development.
- Extending the household consumption system, to account for durable goods (energy-related investment) and more comprehensive complementarity and substitution effects in consumption.
- Extending the link between d-PLACE and sectoral models (reconciling transport and agriculture activity levels between models, reconciling the profitability of capital/discount rate between d-PLACE and MEESA).
- Distinguishing between short- and long-term adjustments in the model - e.g. the possibility of substitution of energy with capital should be smaller in the short term and larger in the long term. Possibilities include recognition of capital vintages or the use of "phantom tax" to spread price signals over time.
- Ensuring strict additivity of energy volumes by switching to additive CES formulation in nested production functions.

- Introducing explicit sources of funding for low-carbon transformation and the constraints/costs of this funding into the model.
- Development of the household module (income distribution, energy poverty, transformation expenditure, etc.) based on the household budget surveys.

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Annex

Main changes in the d-PLACE model between versions

Main changes in the d-PLACE model between current 2.0 version and previously published 1.0 version:

- Modification of production functions of individual industries.
- Addition of special technologies, initially inactive, facilitating energy services or emission abatement options (e.g., CCS/CCU, hydrogen, electric transport).
- Splitting the use and prices of electricity from district heating.
- Adding the option to model the costs of transition due to imperfect labour market mobility across sectors.
- Flexible specification of carbon pricing and emission reduction targets, for user defined groups of sectors, regions and emission sources.
- Linking with sectoral models (energy, transport and agriculture) to ensure that changes due to mitigation effort in one sector are reflected in the costs and potential of mitigation effort in the other sectors.
- Extended reporting of simulation results.