Centre for Climate
and Energy Analyses

PROCEDURE FOR LINKING SECTORAL MODELS WITH THE CGE MODEL

TECHNICAL DOCUMENTATION

VERSION 1.0

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List of abbreviations

BAU	Baseline scenario in the report “Polska net-zero 2050”, CAKE, 2021, assuming 60% emission reduction by 2050 (relative to 1990), excluding the LULUCF sector
BECCS	BioEnergy with Carbon Capture and Storage
CAKE	Center for Climate and Energy Analysis
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CES	Constant Elasticity of Substitution
CGE	General Equilibrium Model
d-PLACE	Recursive dynamic, computable general equilibrium model used and developed by CAKE.
DSGE	Dynamic Stochastic General Equilibrium
EPICA	Evaluation of Policy Impacts - Climate and Agriculture Model (EPICA). The agriculture model used and developed by CAKE.
EU ETS	EU Emissions Trading System
GAMS	General Algebraic Modelling System
GHG	Greenhouse gases
KOBiZE	The National Centre for Emissions Management
LULUCF	Land Use, Land Use Change and Forestry
MEESA	Model for European Energy System Analysis (MEESA). The energy sector model used and develop by CAKE
MPSGE	Mathematical Programming System for General Equilibrium analysis
NDCs	Nationally Determined Contributions submitted by countries under the Paris Agreement
NEU	Neutrality scenario in the report “Polska net-zero 2050”, CAKE, 2021, assuming 90% reduction by 2050 (relative to 1990) and achievement of net-zero emission levels by inclusion of the LULUCF sector and using technologies to remove GHG emissions from the atmosphere (e.g. BECCS)
Non-ETS	Sectors not included in the EU Emissions Trading System (EU ETS)
OSeMOSYS	Open Source energy MOdelling SYStem
REF	Reference scenario in the report “Polska net-zero 2050”, CAKE, 2021, assuming 80% reduction by 2050 (relative to 1990), excluding the LULUCF sector
TR^{3}E	Transport European Emission Economic Model (TR^{3}E). The transport sector model used and develop by CAKE

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1. Introduction: The purpose of linking the models

This paper 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^{3}E) 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.

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 are based 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. 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.

These feedback effects and inter-sectoral dependencies are likely to have critical importance for the evaluation of climate policies. For instance, faster deployment of renewable energy sources (RES) in the energy sector (e.g. induced by climate policy) will reduce demand for emission allowances and reduce their price. A drop in the price will have a negative effect on the adoption of low-carbon technologies in industry as well as a feedback effect on deployment of renewables in the energy sector. Similarly, reduction in the availability of BioEnergy with Carbon Capture and Storage (BECCS) technologies in the energy sector would have an effect spilling over all EU ETS sectors. Acceleration of electric vehicles in the transport sector generates demand for electricity that increases its price – again, with consequences for transport, energy and all other industrial sectors. Reduction in beef consumption in agriculture reduces demand for emissions in non-ETS sectors, which will decrease pressure for the decarbonisation in the transport sector.

Interaction between macroeconomic conditions and individual sectors are taken into account in models with General Equilibrium (GE) setting, but this is at the expense of less detailed modelling at the sectoral level. GE macroeconomic models, such as CGE and Dynamic Stochastic General Equilibrium (DSGE) models, analyse simultaneously changes in all key sectors of the economy (transport, energy, agriculture), however this necessitates limiting the number of commodities in each sector, comparing to sectoral models. In addition, GE models often do not include physical constraints, such as availability of particular technologies or constraints on the availability of resources, which can be easily incorporated in the sectoral models. Moreover, the detailed structure of sectoral models allows to explicitly take into account the time necessary for new technologies to diffuse (e.g. the diffusion paths of electric vehicles), complex complementarities between technologies (e.g. the potential of dispatchable energy technologies to stabilize renewable energy sources), variability of demand (e.g. changes in demand for electricity across seasons, days of the week and hours) and complex cross-price effects across commodities (e.g. impact of price of emission-intensive agricultural products on the demand for other agricultural products).

The solution to this problem, which we adopted in LIFE Climate CAKE PL project, is the linking between a CGE model and partial equilibrium sectoral models. The linking of the models ensures that the projections of the models provide the complete and detailed picture of actions aimed at reducing greenhouse gas emissions. In particular, the use of sectoral models made it possible to capture in greater detail the specificity of reduction potentials and technologies in key areas – energy, transport and agriculture. On the other hand, the linking ensures that the estimated changes in emissions in various sectors of the economy add up to the assumed total reduction targets, and moreover, the marginal costs of reducing emissions in individual sectors are equal.

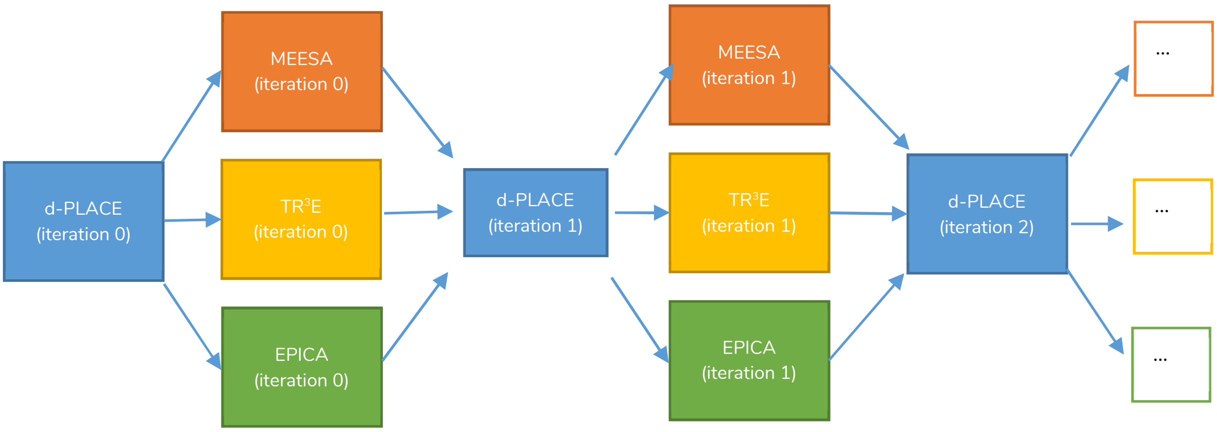
2. General architecture of the linking

The individual models mentioned in section 1 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 1. The procedure is reiterated until the path of prices of emissions in all models converge. The number of iterations required for convergence vary between scenarios. The climate neutrality scenario – the scenario with the most ambitious emission reduction we considered – required 38 iterations. Scenarios with the less ambitious emission reduction required larger number of iterations. Note however, that these numbers are probably exaggerated, due to the fact that the models and the link were undergoing slight corrections and tweaking during the iterative process. In fact, our most recent experiments indicate that convergence can be achieved within roughly 20 iterations. We did not set any formal threshold for the distance between prices after which we terminate iterations. Instead, after each iteration, we inspected the results, compared them with the results of the previous iteration and assessed whether another iteration is needed. This approach allowed us to spot immediately any potential problems with convergence. In the future, we plan to automatize the iteration procedure and select a formal threshold for convergence.

The scope of information transferred between particular models in each iteration is presented in Table 1. 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).

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

Figure 1. Iterations between models d-PLACE, MEESA, TR^{3}E and EPICA



Source: CAKE/KOBiZE own study

Table 1. 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 TR³E) ▸ Demand for district heating ▸ Demand for hydrogen in transport (based on the results from TR³E) 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 → TR³E	**TR³E → d-PLACE**
▸ Gross domestic product (GDP) – TR³E use this information as an input in econometrically estimated module to project grows of transport activity ▸ 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

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^{3}E and EPICA models). In the case of EU ETS price, initially the price is determined endogenously within the d-PLACE model by equalizing the emission limit for a given scenario with the demand from all EU ETS sectors (including power sector and carbon-intensive industries in all EU countries). Subsequently, this price is transferred to the MEESA model, which, using its much more detailed structure of the power sector, provides a new estimate of power sector emissions for this price level. At the beginning of next iteration, this new estimate is used in d-PLACE model to recalibrate emission intensity of the power sector. Similarly, in the case of non-ETS emission abatement cost, the initial estimate of the cost, obtained in the d-PLACE model, invokes changes in the emission intensity of transport and agricultural production in the TR^{3}E 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. Note that mitigation options in sectors that are not covered by sectoral models (e.g. buildings, steel, paper, cement) are modelled in d-PLACE model. Firms in these sectors have a possibility to substitute fossil fuels with other energy carriers (electricity or hydrogen) and substitute their energy inputs with capital. In addition, we allow some sectors to use CCS technology.

Note that all parameters of technologies, such as technology installation costs are exogenous in all models, i.e. we do not consider any learning effects. Our approach does allow us to recover information on deployment of individual technologies (from MEESA and TR^{3}E model), however these projections are available only at the EU level, while substantial learning effects are taking place at the global level.

3. Overview of individual models

3.1. d-PLACE

D-PLACE is a recursive dynamic, global, multi-sector Computable General Equilibrium (CGE) model, based on GTAP 10 (Global Trade Analysis Project) data. In a 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), and 19 regions (country groups or individual countries), including 9 EU regions, and 10 non-EU regions. The model is solved for the years 2014-2050, in 5 years steps (with the exception of the first step that spans 1 year). The baseline scenario conforms with external projections of GDP growth rates by country, fossil fuel prices level and the emission limits for the EU and rest of the world regions.

In its core, d-PLACE follows standard formulations, with nested Leontief-CES (Constant Elasticity of Substitution) production functions, marginal cost pricing and bilateral trade based on the Armington assumption. In most industries, in the bottom nests, gas and oil are combined into non-solid fuel composite, which is then combined with coal. The resulting fossil fuel composite is combined with electricity to form the energy composite. On the other side of the nesting tree, skilled and unskilled labour are combined into labour composite, which is then combined with capital. The resulting composite is combined with energy to form the value added composite. This is combined with Leontief aggregator of materials to form the final output. The details of this nesting structure and the nesting tree for other sectors and households are provided in the d-PLACE documentation.

Beyond that, several specific features of d-PLACE have been designed to meet the needs of climate and energy policy analysis.

First, greenhouse gas emissions are modelled at a detailed level. Emissions originating from fuel combustion and process emissions are treated separately. The model distinguishes between CO_2 emissions and emissions of other greenhouse gases, such as N_2O (nitrous oxide), CH_4 (methane), HFCs (hydrofluorocarbons). The model recognizes 6 energy goods, including coal, natural gas, crude oil, refined oil products and coke, electricity and district heating (electricity and district heating are a product of a single energy sector).

Second, the model implements emission reduction targets in the EU ETS (European Union Emissions Trading System), as well as country-level targets for the non-ETS sectors in the EU. For the rest of the world, emission reductions follow the Nationally Determined Contributions (NDCs) – in this case single economy-wide targets apply, without sectoral split.

Third, emission pricing is used as an instrument to facilitate emission reductions, modelled as a cap-and-trade system in both the EU ETS and non-ETS sectors. In the latter case, while no emission trading actually exists, such a modelling approach ensures that marginal abatement cost is equalized across non-ETS industries. By default, revenues from emission prices (taxes), are transferred to the representative household as a lump sum. We assume that there is one representative household for each region, hence we do not consider distributional effects of the policy.

Fourth, the model includes a few explicit (although simplistic) technologies of emission abatement that are not active or negligible in the benchmark year. They are modelled in a way alluding more to the optimization model framework. For example, natural gas competes with hydrogen as an alternative fuel, and each of these options is represented in the model in terms of its marginal cost. For hydrogen use, which is initially more expensive, a maximum potential (more specifically, maximum share in total energy services provided by gas and hydrogen in a given sector) is also assumed, along with the maximum increments in this potential in time. As gas combustion becomes more costly due to an increase in emission price, hydrogen starts being utilized, to the extent allowed by the current potential. When hydrogen use is cheaper than gas use, the difference between these costs is a rent accruing to the supplier/owner of the facility providing the energy service. In the same way we model other sets of alternative technologies, such as: (i) fuel versus electricity versus hydrogen in transportation, (ii) industry process emissions versus emissions with Carbon Capture and Storage (CCS)/ Carbon Capture and Utilisation (CCU), (iii) agricultural CH_4 emissions versus abatement action, (iv) agricultural N_2O emissions versus abatement action, (v) waste emissions versus waste emission management. However, the model does not include technology learning which could result in endogenous decrease of their cost over time.

Apart from the approach discussed above, d-PLACE uses the nested CES 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), and thus reduce energy intensity of their production. In addition to this change, which is endogenous in the model and depends on relative prices of energy and capital, we assume autonomous energy efficiency improvement. Finally district heating can be substituted for services, as a proxy for building insulation.

The mechanisms described above allow for standalone CGE modelling of the effects climate and energy policies. However, when in link mode, a part of those mechanisms is overridden by the results from sectoral models.

Total investment in a given region is a constant-elasticity function of real rate of return. Foreign savings are fixed in all regions, so increases changes in investment are financed domestically, and household consumption adjusts accordingly. Currently the model does not differentiate patterns of investment expenditure depending on sector undertaking investment or technology for which investment is intended. This assumption reflects the limitation of the GTAP data underlying d-PLACE, in which only a single investment vector is available for each economy. The structure of each such vector represents an “average” composition of investment expenditure in a given economy, that is, average share of expenditure on construction services, machinery, and other investment goods. Fixed capital in each sector follows an accumulation equation – capital stock from previous period is diminished by depreciation and increased by new investment. The old capital remains sector-specific, whereas new investment is allocated freely between sectors. Capital stocks cannot flow between regions.

The current model uses a single labor category that can flow freely between sectors, but not between regions. Wage adjustments ensure full employment, leaning to a long-run view on the labor market. Note that the full employment assumption is also consistent with an implicit “natural” unemployment (although, in such a case, the policies are assumed not to affect the unemployment rate).

The model does not explicitly model competition for land and therefore it does not take into account endogenous changes in the emission from land use, land use change and forestry (LULUCF). Changes in the emissions of this sector are treated as exogenous and they are reflected in emission limits for the other sectors.

For more details regarding the d-PLACE model see Gąska et al. (2020) and Antoszewski et al. (2015).

3.2. MEESA

The energy model MEESA covers primarily the supply side of the energy sector, enabling detailed analyses of the effects of the climate and energy policies pursued. The model has a European range[1], with a greater focus on Poland’s energy system. The model addresses the issues of power security and sufficiency, its transmission and storage, the operation of unstable renewable sources, conventional and nuclear generators, cross-border electricity exchange, district heating generation (including cogeneration), the capabilities and directions of fuel imports.

The model includes approximately 50 energy technologies – existing and new conventional thermal units, RES, energy storage, electrolysers, and demand side response (DSR) services. The hydrogen produced by electrolysers can be used in the model to produce electricity in gas turbines or directed to sectors where there is a demand for this energy carrier. Each technology defined in the model was assigned an appropriate CO_2 emission factor related to its generating unit, which allows to predict the total emissions from the energy sector and to include in the optimisation the costs related to the necessity of purchasing allowances on the market.

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[1] EU-27 plus UK, Norway and Switzerland.

The model disaggregates demand in optimised year for electricity and heat in 18 time slices based on historical data of demand profile for each country, according to seasons (winter, summer), types of days (low, medium and high demand or different RES productivity) and time of day (day, night, peak demand period). It provides basis for determining the mode of operation of individual units in the system. This solution also enables the analysis of the level and direction of intersystem electricity exchange, each region being one node. Apart from meeting demand in every time slice, model ensures that available capacity in the system exceeds maximum demand by 15% (every technology has a parameter describing its ability to provide power on demand).

MEESA is implemented in the GAMS (General Algebraic Modelling System) linear programming language and based on OSeMOSYS (Open Source energy MOdelling SYStem) modelling platform which was chosen due to open access to the source code enabling its modification in order to better reflect the specifics of the analysed scenarios for energy sector development, as well as to facilitate its connection with other CAKE models – especially the d-PLACE CGE model.

For a detailed description of the MEESA model see Tatarewicz et al. (2020).

3.3. TR^{3}E

The transport sector model TR^{3}E is based on the concept of partial equilibrium (it means that covers only a part of the market to attain equilibrium). TR^{3}E model is based on the bottom-up approach. The immanent characteristic of bottom-up models is the fragmented view of representative model agent. In other words, each agent understands only a small part of the whole economy. Transport model covers 4 main transport modes (road, rail, aviation and water transport) for passenger and freight transport, up to 37 means of transport, as well as the characteristics on engine types and technology options per mean. TR^{3}E covers all 28 EU countries[2], it is solved with a time horizon up to 2050 with an annual resolution. Model outputs include activity levels, energy consumptions (oil, electricity and hydrogen) and emissions levels. The model has an extended fleet module for passenger car, light and heavy duty vehicles. The fleet module varies according to fuel and age of vehicles (Annex 1 presents all activities included in the model).

In the TR^{3}E model the choice between the transport modes is derived on the basis of demand functions that take into the account the specific prices for users and the differences between those prices. In the transport demand module, the concept of cost per mile was used. We distinguish three components of the cost per mile:

- cost of fuel
- cost of maintenance per each vehicle
- cost of new vehicle

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[2] From 2021 EU27 plus UK.

Formula shows this disaggregation of cost per mile:

$$\begin{bmatrix}\boldsymbol{cost}\\ \boldsymbol{per}\\ \boldsymbol{mile}\end{bmatrix}=\begin{bmatrix}fuel\\ price\end{bmatrix}+\begin{bmatrix}maint\\ cost\end{bmatrix}\cdot\frac{\begin{bmatrix}number\\ of\\ vehicles\end{bmatrix}}{\begin{bmatrix}total\\ demand\end{bmatrix}}+\begin{bmatrix}price\\ new\\ vehicle\end{bmatrix}\cdot\frac{\begin{bmatrix}number\\ of\\ new\ vehicles\end{bmatrix}}{\begin{bmatrix}total\\ demand\end{bmatrix}}$$

The model allows to disaggregate the cost per mile according to the policy scenario (i.e. reduced cost of purchasing a new vehicle thanks to government subsidies). The cost per mile may depend on the respective transportation policy, for instance, we may extend the cost per mile with the additional cost of emissions added to the fuel cost.

For a detailed description of the TR^{3}E model see Rabiega et al. (2020).

3.4. EPICA

The original agriculture model EPICA contained the farm module, which allowed to project changes in quantity supplied induced by climate policy. The farm module is an Positive Mathematical Programming optimisation model. It is constructed for 19 different farm types. In order to comprehensively assess responses of agricultural sector to policy measures the farm module, at its basic level, is divided into interlinked crop and animal production, each represented by both extensive and intensive production intensities. The outcome of the farm module is the projected supply based on the new farm activities' structure. The results include the volume and value of agricultural commodities, area of crop activities, size of animal population, level of yields, amounts of required inputs, level of costs, and farm income. The model include also the component for projecting changes in the structure of farms regarding its economic size and type of production. Thus the final results covers both changes within the farms and also changes within the framing sector.

In order to link it with CGE model in the same fashion as other sectoral models, the agriculture model was converted into a partial equilibrium model by adding a market module. The purpose of this addition was to enable the model to project (and take into account) changes in prices of agricultural commodities. The current version of the model covers emission sources included in National Inventory Report (KOBiZE 2021), thus it does not include KP-LULUCF activities, which are not directly linked with agricultural production. The model will be developed towards including LULUCF emissions. Also a wider range of energy crops will be introduced to develop a link with the MEESA model.

For a detailed description of the EPICA model see Wąs et al. (2020).

4. Links of individual models with the CGE model

4.1. Linking energy model with the CGE model

The MEESA model uses the information on the marginal cost of reducing emissions in the EU ETS and the demand for electricity, district heating and hydrogen, obtained from the d-PLACE model (d-PLACE provides information on annual energy demand, while detailed seasonal and daily distribution of demand is based on historical data for specific country and on the development of new technologies within MEESA model). Based on this information the model determines, inter alia, the cost of energy production, production structure (shares of individual technologies in energy production) and the level of CO_2 emissions.

If, for example, the emission intensity of energy production decreases (compared to the previous iteration), then in the next iteration in the d-PLACE model, the demand for emission allowances from the energy sector decreases. As a result, other sectors of the economy can emit more and the marginal cost of abatement across the EU ETS decreases. Subsequently, in the next iteration in the MEESA model, the emission intensity increases, etc. The process of solving the models is carried out until the mentioned fluctuations in the marginal abatement costs in the EU ETS and emissions in the energy sector stop or decrease to an acceptable level. In the same iterative process, the balance between other variables of the models is established - e.g. an increase in the cost of energy generation in a given iteration (MEESA) leads to a decrease in demand for it (d-PLACE), which may then reduce the cost of production (MEESA), which, in turn, increase the demand (d-PLACE) etc. until the solution stability is obtained.

The MEESA model takes into account the possibility that some emissions can be absorbed as a result of using the BECCS technology. Since the combustion of biomass is treated as non-emission, capture of emissions from biomass results in "negative emissions". The "negative emissions" obtained from MEESA are included in d-PLACE by increasing the number of EU ETS emission allowances in a given region. Hence, effectively, the BECCS removals allow to increase actual emissions in other sectors of the economy.

The representation of the energy sector in the d-PLACE model is much less detailed than in the MEESA model. d-PLACE distinguishes between consumption (and associated emissions) of different fuels (coal, natural gas and crude oil products), but, for example, energy production from renewable sources, biomass or nuclear energy is not explicit. The costs of these technologies are reflected in the total annual capital cost (and also to some extent in the costs of labour, materials and external services). To ensure consistency of results from d-PLACE and MEESA, one must ensure the consistency of fuel consumption and emissions as well as capital costs between the two models. Capital costs in the d-PLACE model are modified to reflect the dynamics of the average cost of electricity and district heat from the MEESA model. For example, an increase in the share of renewable sources in electricity production is expressed in the d-PLACE model by an increase in the share of the capital costs in the price of energy. Note that alignment of capital cost between MEESA and d-PLACE is not explicit, nor is it done for individual technologies, as the latter are not distinguished in the CGE model. Instead, the total capital intensity of energy generation in d-PLACE is adjusted to reflect the changes in technology mix resulting from MEESA. Technically, we do not use capital costs reported from MEESA directly. Rather than that, in d-PLACE we target the average cost of electricity and heat from MEESA, which effectively adjusts capital intensity (taking into account that fuel- and emission-intensities are targeted separately).

4.2. Linking transport model with the CGE model

A significant challenge related to linking of the d-PLACE and TR^{3}E models originated from the differences in the classification and measurement of transport activity in both models. For this reason, the scope of information exchange is smaller than in the case of d-PLACE and MEESA link. In the TR^{3}E model, activity is expressed in person- or tonne-kilometers, while in the d-PLACE model – in constant-price monetary units. In addition, in the TR^{3}E model, transport is divided into passenger and freight, while in the d-PLACE model transport activity is divided between the household sector and the transport services sector - the latter includes both freight and passenger transport. In the TR^{3}E model, transport activity is determined on the basis of GDP projections from d-PLACE. The structure of the means of transport adjusts, inter alia, to the marginal cost of emission abatement in the non-ETS sector determined in d-PLACE, and to electricity and hydrogen prices from MEESA (forwarded to TR^{3}E via d-PLACE). The d-PLACE model, on the other hand, matches energy consumption and emissions with the results from the TR^{3}E model. Given the methodological differences, activity levels in both models are currently not reconciled. The results from the TR^{3}E model are used in the d-PLACE model to recalibrate the structure of energy sources and their emission intensity, which has influence on transport costs. Currently, capital cost of transport fleet is not aligned between models.

The correspondence between TR^{3}E to d-PLACE classifications is shown in Annex I.

4.3. Linking agriculture model with the CGE model

The original agriculture model, developed within Climate CAKE, contained the farm module, which allowed to project changes in quantities supplied, induced by climate policy. In order to link it with CGE model in the same fashion as other sectoral models, the agriculture model was converted into a partial equilibrium model by adding a market module. The purpose of this addition was to enable the model to project (and take into account) changes in prices of agricultural commodities.

In the market module the set of prices of agricultural products is derived from equilibrium conditions that equate demand and supply for every such product. In practice, the model starts by setting the relation between supply and prices (the supply curves) and the relation between demand and prices (the demand curves). Changes of supply predicted by the farm module are used to shift the supply curves. Those shift lead to a new equilibrium with new set of prices. This information is then re-entered in the farm module which again predicts changes in supplies. The iteration between the two modules continues until price convergence is obtained.

The demand curves are consistent with the micro-founded demand system (i.e., derived from the optimisation problem of representative consumer in the national economy). As such, it is aligned with the principles of microeconomic theory. Therefore, the model is robust to pitfalls of some numerical models that derive their predictions from the economic patterns of the past not taking into account that those patterns evolve over time together with the changes in the environment of economic actors (the Lucas critique). The derivations are based on the assumption of rational behaviour and rational expectations of economic agents.

Once the market module is combined with the farm modules, the model allows to determine changes in the structure and volume of agricultural production for a given marginal abatement cost projected by the d-PLACE model. The changes lead to a reduction of CH_4 and N_2O emissions, which are then reflected in d-PLACE. Contrary to the energy and transport sector models, EPICA is a model for Poland only. However, it is assumed that changes in emission intensity obtained for Poland apply also in the other EU countries.

5. Iterative solutions: results and discussion

In this section we show and discuss illustrative results from the simulations using the interlinked models. Here we focus on the interaction between the models and selected variables only – for a broader analysis of scenarios' assumptions and results see the report "*Poland net-zero 2050*", Pyrka et al. (2021).

5.1. Targeting results from sectoral models in the CGE model

It is worth pointing out an asymmetry between the models operating in the link mode. From the perspective of sectoral models, the inputs, coming from the CGE model (such as prices of emission allowances, energy demand etc.) are naturally exogenous variables. In contrast, virtually all inputs to the CGE model, transmitted from sectoral models, are naturally endogenous variables from the CGE model's perspective.

For example, price of a given product is represented, in the CGE setting, as a sum of unit costs of capital, labour and intermediate inputs (plus taxes, minus subsidies, where applicable), therefore it is naturally an endogenous variable. However, in the link mode, we are willing to target, in the CGE model, the energy price (more specifically, price of electricity and district heating bundle) derived from the energy system model, MEESA. To target the price, we need to adjust the quantity of one or more inputs per unit of output, that is, we need to adjust the technology of energy generation, as represented in the CGE model. In this specific case, we chose to adjust input of fixed capital per unit of energy produced. In principle, the adjustment of unit capital input can be endogenous, in which case energy price targeting is strict, or exogenous, in which case energy price targeting is approximate. We use the latter option, since endogenous technology adjustment is not explicitly allowed in the MPSGE (Mathematical Programming System for General Equilibrium analysis) framework, in which the d-PLACE model is programmed. Consequently, the change in unit use of capital input is calculated in such a way, that energy price in d-PLACE would match the price from MEESA, *given input prices from the previous d-PLACE iteration*. In the current d-PLACE iteration, though, energy price would eventually deviate somewhat – albeit typically not by much – from the target, due to movements in input prices in general equilibrium, invoked by, inter alia, change in energy demand as a response to the price change.

In general, in most cases, matching the d-PLACE outcomes with the results from sectoral models is approximate. In this way, relevant values in a current iteration of the CGE model run – such as demand for specific fuels from the energy and transport sectors, emission levels, prices of electricity, district heating and hydrogen – might differ from the values obtained in a previous iteration in the sectoral models. However, as the fluctuations of results die out in subsequent iterations (as the solutions converge), the approximation becomes more and more exact too. With ideal convergence it should therefore not matter whether the targeting in a single iteration is based on endogenous or exogenous adjustments of technologies etc.

5.2. Scenarios and the scope of result analysis

Below we present selected results from simulations using interlinked models, for three scenarios, denoted BAU, REF and NEU. The BAU scenario assumes roughly 42% GHG emission reduction in the EU in 2030 compared to 1990 and 60% reduction in 2050. REF assumes the same reduction as BAU until 2030 and roughly 80% emission reduction by 2050 compared to 1990. NEU scenario assumes 55% reduction by 2030 and 90% reduction (excluding LULUCF). In each scenario the overall target is split into a single reduction target for EU ETS as a whole, and country-level non-ETS reduction targets. For instance, in the case of NEU scenario we assume 93% reduction for EU ETS and 73% in Poland in non-ETS sector in 2050 compared to 2005. Detailed assumptions of those scenarios are discussed in the report “Polska net-zero 2050”, Pyrka et al. (2021). The above setting results in a single price of emission allowances for all sectors and countries participating in the EU ETS, and country-specific emission prices for non-ETS sectors.

D-PLACE distinguishes 3 individual EU countries (Poland, Germany and France), 6 aggregate regions of the EU, the EFTA region, and 9 non-EU countries or aggregate regions. MEESA features almost the same regional aggregation of countries participating in the EU ETS as d-PLACE, except that EFTA countries are aggregated with other regions, rather than distinguished as a separate regions. TR^{3}E distinguishes individual EU27 states and UK (so results are aggregated when transferred from TR^{3}E to d-PLACE, or mapped from country aggregates to individual countries when transferred in the reverse direction), while EPICA is a model for Poland (although emission intensities resulting from that model are also used as a proxy for other EU countries). Since sectoral models do not cover regions outside EU (EU ETS), the results for rest of world rely on the CGE model only.

Our general experience from simulations using the linked models is that the highest variation between iterations characterizes emission prices (carbon taxes), as well as emission volumes in energy and transport sectors. Note that total emissions do not vary due to the binding emission caps. Consequently, in Figures 2-4 we report emission prices (marginal abatement costs) in the EU ETS and non-ETS, emission volumes in relevant sectors. In addition, we show output and price of the energy sector (electricity and district heating generation). The EU ETS emission allowance price by definition applies to all countries, whereas all the other illustrative results shown in Figures 2-4 are for Poland.

Table 2. Time scopes and steps of models in the link mode

Model	Time scope	Time step	First year using inputs from other models
d-PLACE	2014-2050	5-year (except 1-year between 2014 and 2015)	2015
MEESA	2015-2050	5-year	2025
TR^{3}E	2015-2050	1-year	2015
EPICA	2015-2050	5-year	2015

Source: CAKE/KOBiZE own study

The models differ slightly in terms of time-span and time-steps, as shown in Table 2. In the simulations, information exchange between the models starts in 2015, with one exception of the energy system model MEESA that uses external inputs starting from year 2025. Rather than using the outcomes of d-PLACE simulations for the years 2015 and 2020, MEESA is calibrated to a relatively detailed set of most recent data, unlike e.g. d-PLACE which uses detailed data for the benchmark year 2014 and is “moved” to 2020 using a few aggregate drivers only.

In the figures 2-4, we present simulation results for the years 2020-2050, with five-year time steps. Results for iteration 0 are based on standalone d-PLACE model, without yet using the inputs from sectoral models. Apart from that initial solution, results from the final six iterations of each scenario run are reported, numbered $N-5,\dots,N$. We do not report all iterations, because during the simulations the models' link was subject to improvements and tweaking, after which the solving process was restarted from previous iteration rather than from iteration zero. As a result. However, the final six iterations under each scenario were already performed using a consistent link setting.

All results reported below are taken from d-PLACE directly. Recall that they are not exactly the same as in sectoral models in the previous iteration, due to (i) CGE model's endogenous response to the changes imposed based on inputs from sectoral models, and (ii) because some variables (e.g. energy and district heating prices) are matched in terms of their dynamics (index), not the levels.

5.3. Results from linked models and standalone CGE

EU ETS. Most of all, it is obvious from the results that that using the information from sectoral models leads to a substantial revision of the results from the standalone CGE model. In particular, assessments of the marginal abatement cost in the EU ETS in a standalone model tend to be much higher than in the linked mode in the long run (years 2040-2050), especially in the case of high emission reduction ambition. This implies that consideration of individual technologies in the energy system model framework allows to identify more/cheaper abatement options than implied by a nested CES production function (with fairly standard nesting structure and parametrization) employed in the d-PLACE model. In contrast, in the short-run (until 2030) the integrated assessment of EU ETS CO_2 price tends to be higher than the standalone CGE assessment, which corresponds with the relative rigidity of the existing energy system, and the time needed for low-carbon transition. This rigidity is reflected in various constraints in the energy system optimization model. Whereas does differentiate the strength of responses to policy shocks between short- and long-run.

Even with significantly lower emission prices in the long run (2040-2050), emissions in the energy sector in Poland are also lower than in the standalone CGE model, under NEU[3] and REF[4] scenarios. In fact, the model shows negative net emissions in that sector in the final years of the simulation horizon, as a result of the use of BECCS technology.

Non-ETS. In contrast to EU ETS, marginal abatement cost (emission price) in the non-ETS tends to be higher according to the linked models than according to standalone CGE. It implies that transport and agriculture models, taken together, "see" emission abatement as more difficult/costly than the CGE model in the default setting. For example, the decrease in emissions of the transport services sector (covering freight transport as well as public or commercial

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[3] Neutrality scenario in the report "Polska net-zero 2050", Pyrka M, et al. (2021), assuming 90% reduction by 2050 (relative to 1990) and achievement of net-zero emission levels by inclusion of the LULUCF sector and using technologies to remove GHG emissions from the atmosphere (e.g. BECCS).

[4] Reference scenario in the report "Polska net-zero 2050", Pyrka M, et al. (2021), assuming 80% reduction by 2050 (relative to 1990), excluding the LULUCF sector.

passenger transport) is significantly slower in the first half of the simulation period in the models' link mode than in the standalone CGE mode. Even though the reduction later accelerates under NEU and REF scenarios, emissions are still relatively high in the link mode. Note that the transport model TR^{3}E tracks the stock of vehicles, with its decommissioning and gradual replacement which justifies the rather sluggish responses to emission pricing. In contrast, in the household sector, models linking leads to a slight reduction in emissions under NEU and REF scenarios, implying that switching to electric or hydrogen-fuelled private vehicles is a little faster, although note it happens at higher emission costs than faced by households in the standalone CGE simulation. In the case of agriculture, emissions are lower in the link mode than in the standalone CGE mode (at higher emission prices). In conclusion, it is primarily transport services being the bottleneck for emission reduction in the non-ETS sector.

Energy prices and demand. Linked-models and standalone CGE results differ considerably in their projected paths of demand for and price of electricity and district heating. The growth of electricity and district heating prices until 2030-2035 is much sharper in the linked models than in the CGE model alone[5] (note that the prices, transferred from MEESA to d-PLACE, are based on average unit system costs of energy generation, rather than e.g. marginal costs). To explain this outcome, let us acknowledge that the energy model accounts for the fact that low-carbon transition is stretched over time, and so in the short run there are limited opportunities to counteract the rising emission prices. In contrast, the d-PLACE model, which does not reflect capital vintages, does not distinguish between short-run and long-run adjustments of the economy to policy shocks. In particular, in Poland the rapid energy price growth in the first 10-15 years of the simulation period is largely due to the rising emission prices under high dependence on coal which cannot be phased-out immediately. Energy price growth is inhibited in subsequent years, after coal has mostly been removed from the energy mix.

Interestingly, and perhaps counterintuitively, in the linked models the price of electricity and district heating is substantially higher than in the standalone CGE (for example, around 40% higher in the year 2050, under the NEU scenario), while the emission price – that is, marginal abatement cost – is substantially lower (by as much as 80%). Firstly, one should note the differences in the course of changes in marginal abatement cost in the energy sector over time, as represented by the CGE and the energy model. In is an implicit assumption in the d-PLACE model that lowest cost abatement options are utilized immediately (with an exception of a few technologies modelled with explicit upper bound on their potentials) as the emission price increases. This is shown in marginal abatement cost rising slowly in the first years, while increasing sharply in the final years of the simulation. In MEESA, the limits on the pace of technology spreading lead to a more steady increases in marginal costs of emission abatement over time – it increases more quickly in MEESA than in d-PLACE in the first years, but more slowly

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[5] This is the result found for Poland. In the rest of the EU countries the prices of electricity and district heating grow more steadily. Still, they exhibit some slowdown after 2030-2035, although not as obvious as in the case of Poland.

in the final years. In such a case, average abatement cost in the energy model might be higher than in the CGE model, even though the marginal abatement cost in the final years is lower. Secondly, the decrease in the rate of return on capital, observed under ambitious emission reduction scenarios, drives down electricity prices in the standalone CGE simulation, especially in the later years, when energy generation technology is highly capital intensive. On the other hand, MEESA assumes a fixed discount rate. We treat the problem of reconciling capital cost assumptions between models as a case for further research.

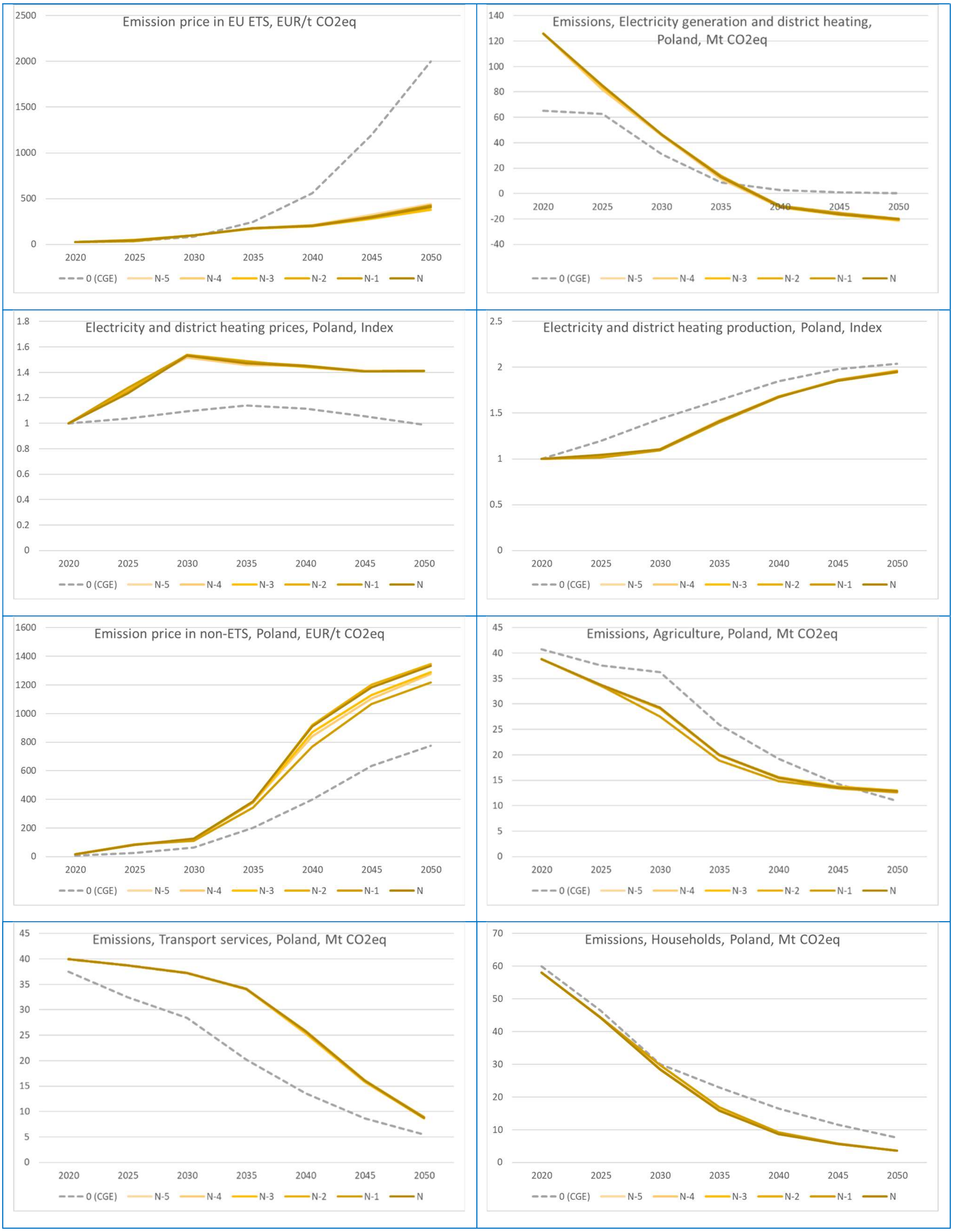
5.4. Variation of results between iterations

In general, the linked models provide reasonably robust solutions from subsequent iterations. Graphically, they display as fairly narrow and stable bundles of time-paths of solutions for various model variables, clearly distinctive from the initial (iteration zero) paths provided by the CGE model alone.

Nevertheless, some variability between iterations does occur, especially for emission prices, as well as emissions levels in individual sectors. Looking closer at the results for selected single years often reveals oscillations roughly between two states (values). Although this point definitely deserves a further study, we tentatively attribute this behaviour to a relatively high sensitivity of the models' responses to the inputs from other models. In particular, the sensitivity of emission prices in the CGE model to even moderate changes in emission levels in the emission intensive sectors, stemming from the modification of their production technologies (in accordance with the sectoral models' results) seems quite high, impeding the convergence process. Furthermore, it is worth pointing out that the energy system model MEESA is a forward-looking, linear model, which implies that (i) a change in e.g. the emission price in one year affects the solutions for all periods, and (ii) sometimes a slight change in e.g. emission prices may make the energy model jump to a qualitatively different solution (say, a technology that was inactive now exceeds the break-even point and starts operating). Put alternatively, the energy system model implicitly features a step-wise marginal abatement cost "curve". We deem it a factor that impedes convergence – perhaps strict convergence is unattainable in some situations.

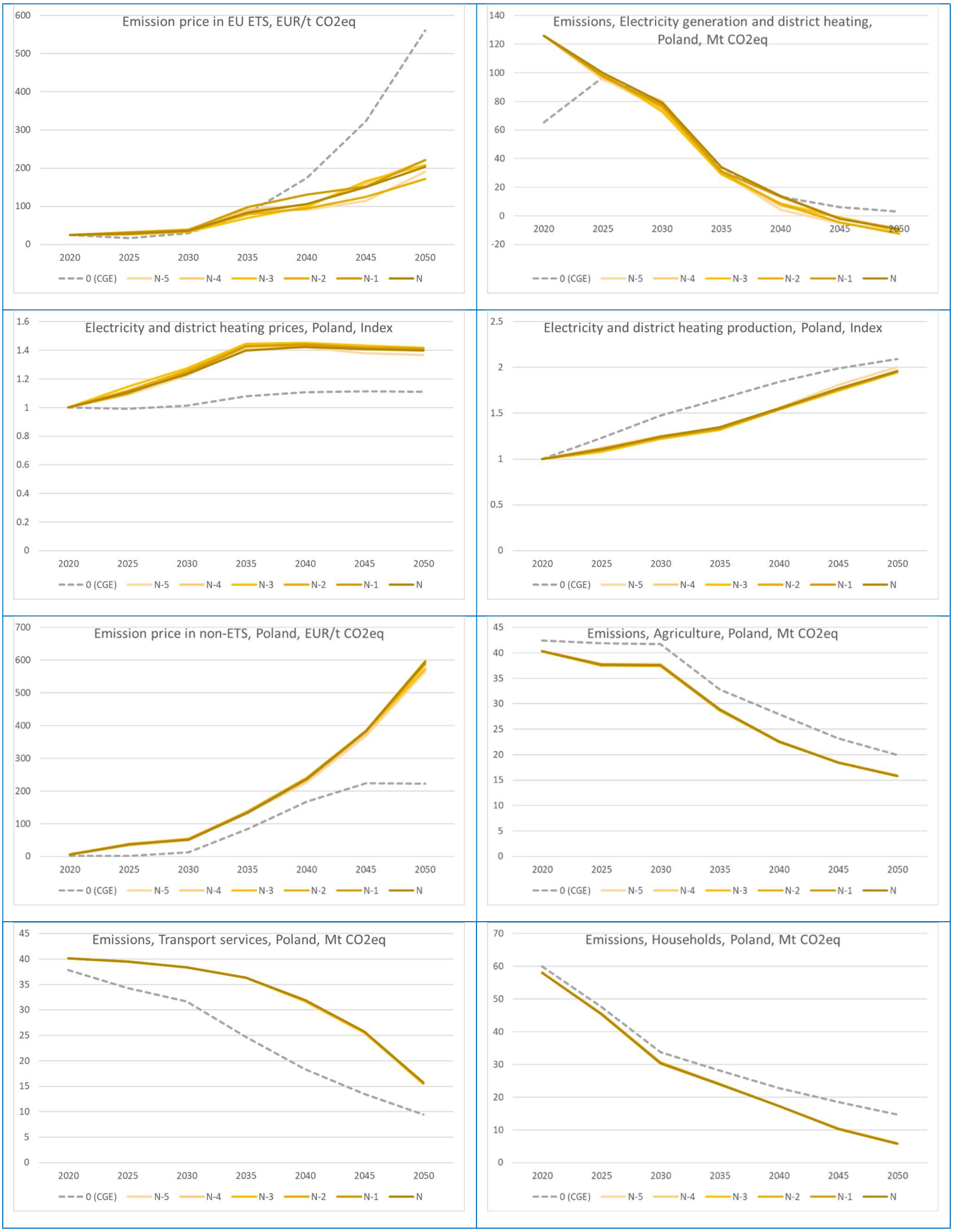
We have found that averaging the results exchanged between models helps stabilize the results from subsequent iterations (reduce the volatility). It was also a helpful strategy in a few cases in which solutions from the linked models diverged. Currently the inputs to the d-PLACE model are calculated as an average from energy system and transport models results from the previous two iterations. In the opposite direction, the outputs from d-PLACE are also averaged – in this case a weighted average was used, with 0.7 weight on the current, and 0.3 on the previous iteration. The design of the averaging, the choice of weights etc., will still be subject to testing and tweaking in order to find a setting in which convergence is achieved most effectively. Note that averaging is only the means to improve convergence and it should not, in principle, affect the final results.

Figure 2. Selected results from NEU scenario iterations



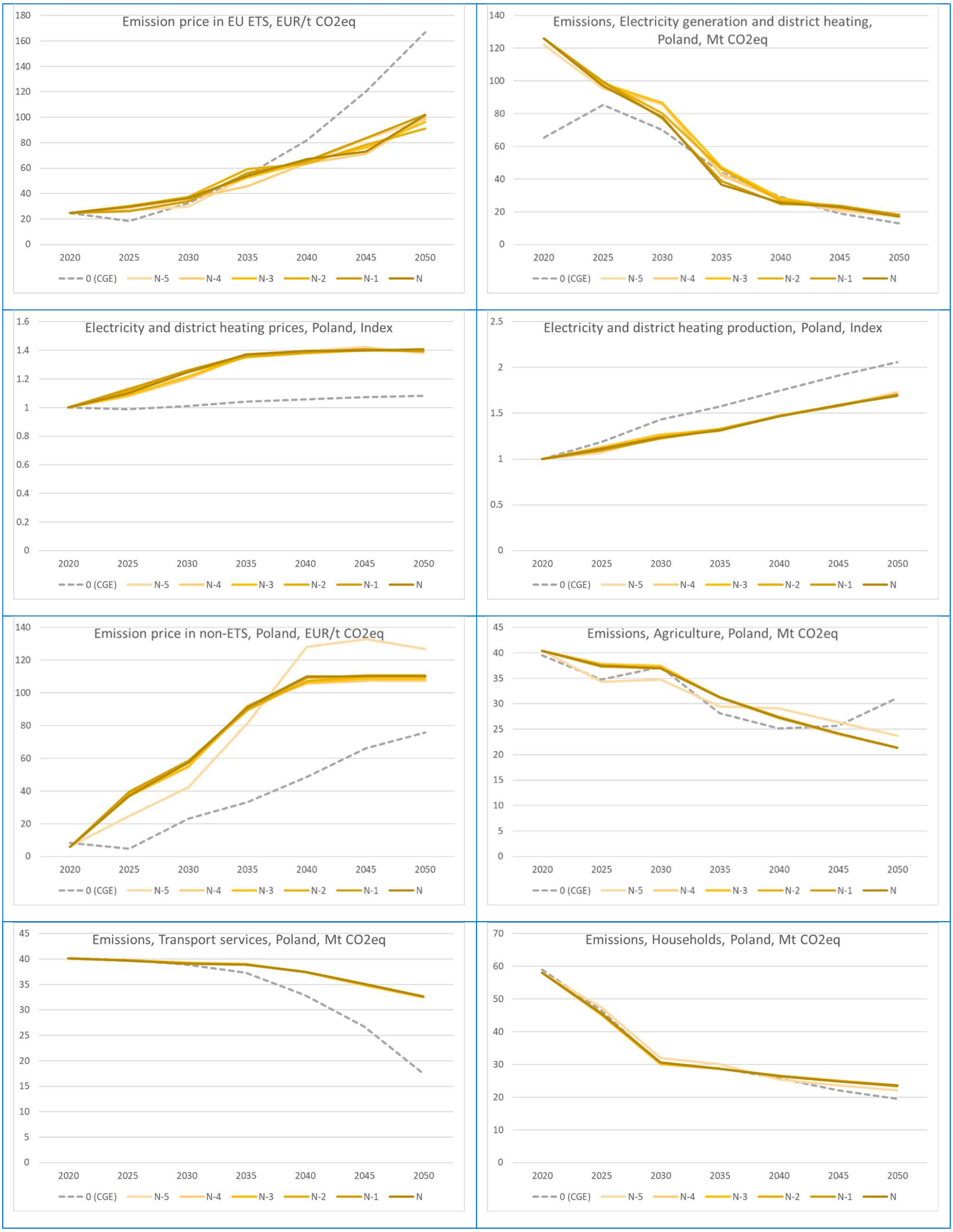
Source: CAKE/KOBiZE own study

Figure 3. Selected results from REF scenario iterations



Source: CAKE/KOBiZE own study

Figure 4. Selected results from BAU scenario iterations



Source: CAKE/KOBiZE own study

6. Planned developments

The current setup of the models link covers the most important channels through which carbon prices are reconciled across sectors. Nevertheless, models integration is an ongoing task and can be advanced in numerous ways. Below we list several topics for further developments:

- Improving speed and robustness of convergence of model results. Analyzing conditions under which models converge or diverge, and a possibility of non-unique solutions.
- Reconciling activity levels between the CGE and the transport model.
- Aligning investment and capital costs, between the CGE model and the transport model, possibly facilitated by separation between purchase and operation of vehicles, as well as split between public and freight transport in the CGE model.
- Reconciling activity levels between the CGE and the agriculture sector model.
- Considering conceptual differences and relationship between capital rental rate (d-PLACE) and discount rate (MEESA) with a view to reconciling these quantities in the integrated models.
- Aligning changes in agricultural production, prices and trade projected by d-PLACE and EPICA; using EPICA projections to estimate changes in emissions in agricultural sectors outside Poland.
- Linking EPICA and TR^{3}E models in order to align the demand for biofuel components from agricultural sector and emission intensity of transport fuels.
- Automating the solutions and reporting.

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Annex I

Table 3. Mapping from TR^{3}E to d-PLACE classifications.

TR^{3}E classification				d-PLACE classification				
	Transport type	Fuel type		Sector		Share*		Energy form
car_ele	passenger car	electricity	psg	trn	c	0.14-0.43	0.57-0.86	ele
car_hybrid	passenger car	petrol/ electricity	psg	trn	c	0.14-0.43	0.57-0.86	oil
car_petrol	passenger car	petrol	psg	trn	c	0.14-0.43	0.57-0.86	oil
car_lpg	passenger car	lpg	psg	trn	c	0.14-0.43	0.57-0.86	oil
car_cng	passenger car	cng	psg	trn	c	0.14-0.43	0.57-0.86	gas
car_diesel	passenger car	diesel	psg	trn	c	0.14-0.43	0.57-0.86	oil
car_H2	passenger car	hydrogen	psg	trn	c	0.14-0.43	0.57-0.86	hgen
train_diesel	passenger train	diesel	psg					
train_ele	passenger train	electricity	psg					
metro	metro, tram, urban light rail	electricity	psg					
bus_ele	passenger bus	electricity	psg	trn		1		ele
bus_diesel	passenger bus	diesel	psg	trn		1		oil
bus_cng	passenger bus	cng	psg	trn		1		gas
bus_petrol	passenger bus		psg	trn		1		oil
bus_lpg	passenger bus	lpg	psg	trn		1		oil
bus_H2	passenger bus	hydrogen	psg	trn		1		hgen
mbk	motorbike / powered 2-wheelers	petrol	psg	c		1		oil
avia_domest	domestic passenger aviation	petrol/diesel	psg					
avia_intraeu	intra -EU passenger aviation	petrol/diesel	psg					
avia_extraeu	extra - EU passenger aviation	petrol/diesel	psg					
ldv_ele	light duty vehicle	electricity	fgt	trn		1		ele
ldv_diesel	light duty vehicle	diesel	fgt	trn		1		oil
ldv_cng	light duty vehicle	cng	fgt	trn		1		gas
ldv_petrol	light duty vehicle		fgt	trn		1		oil
ldv_lpg	light duty vehicle	lpg	fgt	trn		1		oil
ldv_H2	light duty vehicle	hydrogen	fgt	trn		1		hgen
aviaf_domieu	domestic and intra EU freight aviation	petrol/diesel	fgt					
aviaf_extraeu	extra - EU freight aviation	petrol/diesel	fgt					
hdv_dom	domestic heavy duty vehicle	diesel	fgt	trn		1		oil
hdv_int	domestic heavy duty vehicle	diesel	fgt	trn		1		oil
hdvd_H2	domestic heavy duty vehicle	hydrogen	fgt	trn		1		hgen
hdvi_H2	international heavy duty vehicle	hydrogen	fgt	trn		1		hgen
hdvd_ele	domestic heavy duty vehicle	electricity	fgt	trn		1		ele
hdvi_ele	international heavy duty vehicle	electricity	fgt	trn		1		ele
trainf_ele	freight train	electricity	fgt	trn				ele
trainf_diesel	freight train	diesel	fgt	trn				oil
water	coastal shipping and inland waterways	petrol/diesel	fgt					

Source: CAKE/KOBiZE own study

Note: part of energy use in the transport sector is not linked to TR^{3}E (water and air transport).

** Shares are region specific.*