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GREEN TRANSITIONS IN COAL-DEPENDENT ECONOMIES: A HYBRID COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS OF THE CZECH NATIONAL ENERGY AND CLIMATE PLAN

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Green Transitions in Coal-Dependent Economies: A Hybrid Computable General Equilibrium Analysis of the Czech National Energy and Climate Plan

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Abstract:
This paper assesses the long-term macroeconomic and environmental impacts of climate policies in the Czech Republic, a coal-dependent economy, under the EU's Fit-for-55 package. Using a hybrid dynamic Computable General Equilibrium (CGE) model, we integrate a bottom-up electricity module with technology-specific detail and a discrete choice module capturing consumer preferences for vehicle technologies. The model, formulated as a mixed complementarity problem in GAMS, accounts for capacity constraints in power generation and endogenizes vehicle fleet evolution based on choice probabilities. We evaluate two scenarios: With Existing Measures (WEM), reflecting current policies, and With Additional Measures (WAM), which includes coal phase-out, expanded renewables, and the introduction of ETS2. Results show that WAM leads to more than 60% reduction in power sector CO2 emissions by 2040 and 80% battery electric vehicle (BEV) adoption by 2050. However, green investments under WAM do not balance out structural shifts—especially in fossil-related sectors— negatively influencing GDP. This integrated top-down and bottom-up modeling approach offers a robust framework for evaluating economy-wide effects of climate action. Findings inform

cost-effective and socially balanced decarbonization strategies for Czech and EU policymakers.

JEL: C68; D12; D58; H22; H23; Q43; Q52; R42
Keywords: Hybrid CGE model; Green Transition; Climate policies; Energy and transport

1. INTRODUCTION

Environmental policies play a critical role in addressing climate change and promoting sustainable development, but they also entail significant economic and social implications. At the EU level, the European Commission requires all Member States to formulate and regularly update National Energy and Climate Plans (NECPs), outlining their strategies to reduce greenhouse gas (GHG) emissions in line with the EU's commitments under the Paris Agreement (Williges et al., 2022). These plans align with the EU-wide targets set out in the Fit-for-55 package (European Commission, 2021), which comprises a range of legislative initiatives aimed at achieving a 55% reduction in GHG emissions by 2030 and climate neutrality by 2050.

The Czech Republic's NECP sets ambitious objectives, including reducing fossil fuel use to 50% by 2030, achieving a full phase-out by 2050, and eliminating coal from electricity and heat production by 2033. It also envisions a transition towards alternative fuel vehicles (AFVs), expanded renewable energy deployment, and full integration into the EU Emissions Trading System.

Over the past three decades, the Czech Republic has made substantial progress in improving environmental quality, particularly by reducing emissions from large and medium combustion sources. Nevertheless, persistent air quality challenges remain, largely driven by fossil fuel use in electricity generation and transport (Czech Ministry of Industry and Trade, 2023). These challenges are closely linked to the structure of the Czech economy, which is among the most industrialized in the EU and exhibits one of the highest emission intensities per unit of GDP[1] (Friedlingstein et al., 2024). The continued reliance on coal power and carbon-intensive industrial activities—particularly lignite—highlights the difficulty of achieving rapid decarbonization while maintaining economic stability.

In response, the Czech NECP provides a strategic roadmap to reduce emissions across key sectors, building on two main policy frameworks: the State Energy Concept (SEC) (Ministry of Industry and Trade, 2024) and the Climate Protection Policies (Ministry of the Environment, 2017). Core measures include the EU Emissions Trading System (EU ETS), expansion of renewable electricity generation, development of nuclear energy (including both large-scale and modular reactors), and investment in clean mobility and transport infrastructure.

Electricity generation in the Czech Republic remains dominated by coal-fired power plants and nuclear energy, with facilities such as Dukovany and Temelín playing a central role. Renewable sources, including hydro, solar, and wind, contribute a smaller but growing share. Of the 77.2 TWh of electricity produced in 2023, coal and nuclear each accounted for roughly 40%. An overview of electricity generation by source is shown in Figure 1.

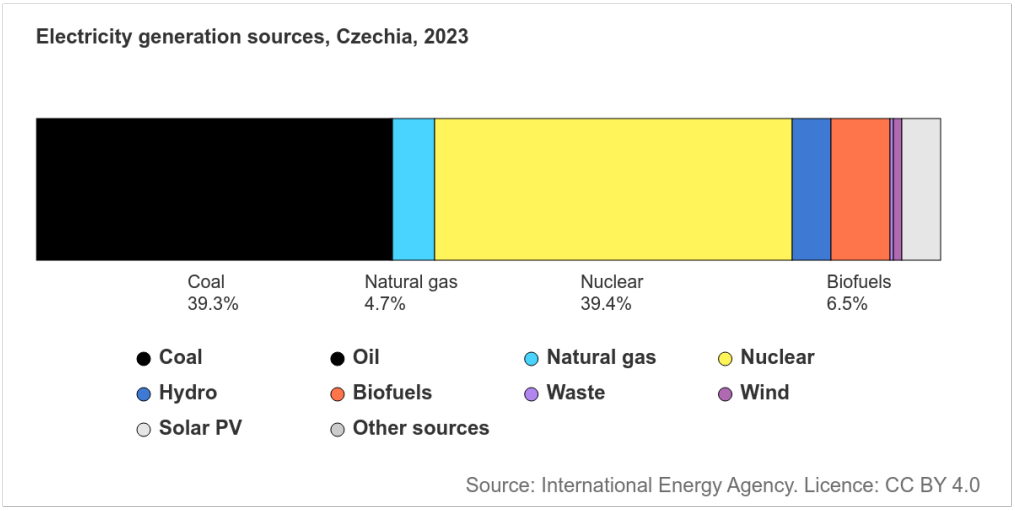

Figure 1: Electricity Generation by Sources, 2023

The planned phase-out of coal presents both challenges and opportunities. While it necessitates a significant expansion of alternative energy sources—particularly nuclear and renewables—it also raises concerns related to grid stability, investment costs, and the integration of variable renewable energy. The Czech electricity system remains strongly interconnected with neighboring countries, allowing imports and exports to help balance supply and demand.

[1] Carbon intensity was 0.29 CO_2 kg/$ in the year 2022.

The transport sector remains a major contributor to air pollution, as internal combustion engine vehicles (ICEVs) still dominate both passenger and freight transport. Although electric vehicle (EV) adoption is increasing, barriers such as limited infrastructure, high upfront costs, and consumer preferences continue to slow the transition. Public transport electrification and modal shifts towards rail face similar challenges, requiring substantial investment and policy support.

Beyond sectoral transformations, decarbonization policies will have broader macroeconomic implications. Carbon pricing—particularly through the expansion of the EU ETS—will affect production costs, household expenditures, and investment decisions. While revenue recycling mechanisms may mitigate distributional impacts, they may also create sectoral winners and losers. Capturing these economy-wide feedback effects requires a framework that accounts for macroeconomic interactions, energy system constraints, and behavioral responses.

Although several ex-ante studies have examined the impacts of the Fit-for-55 package on the Czech economy, they tend to focus on specific sectors (Rečka et al., 2023) and on short- to medium-term horizons, typically up to 2030. As a result, they may not fully capture broader economic interactions and long-term effects.

When policy changes affect a single sector with limited spillovers, partial equilibrium (PE) models are appropriate, as they capture interactions between producers and consumers, including strategic behavior. However, for economy-wide policies, general equilibrium (GE) models—such as input-output (IO) and computable general equilibrium (CGE) models—are more suitable, as they identify indirect and unintended effects across sectors (Smith and Zhao, 2020; Carbone et al., 2022). Among these, CGE models are particularly well suited for analyzing the medium- to long-term macroeconomic impacts of climate and energy policies (Koutsandreas et al., 2021).

Despite their advantages, CGE models are often criticized for their limited technological detail in the energy sector (Böhringer, 1998). Aggregation can obscure sectoral heterogeneity, leading to "aggregation bias" in assessments of decarbonization policies (Cai and Arora, 2015). In standard CGE models, the electricity sector is typically represented in aggregated form, with changes in the energy mix modeled through factor substitution rather than explicit technological shifts (Faehn et al., 2020).

To address this limitation, hybrid modeling approaches have been developed, integrating bottom-up (BU) technological detail into top-down (TD) CGE frameworks. These approaches have been applied to sectors such as electricity (Peters, 2016), transport (Cai et al., 2023), and steel production (Vercoulen et al., 2023). By combining macroeconomic consistency with technological realism, hybrid models enable a more comprehensive assessment of climate policies.

Traditionally, TD models such as CGEs capture macroeconomic outcomes, including impacts on public finance, competitiveness, and employment, while BU models—such as Energy System Optimization Models (ESOMs)—provide detailed representations of technologies, resource potentials, and energy system dynamics. However, BU models typically lack feedback mechanisms that capture broader economic adjustments (Hourcade et al., 2006). Hybrid models overcome these limitations by integrating both approaches, often by embedding BU detail within a CGE framework (Krook-Riekkola et al., 2017). Methodologically, this integration can take the form of soft linking, hard linking, or fully integrated modeling (Böhringer and Rutherford, 2008). Soft linking involves iterative exchange of information between separate models, hard linking uses automated integration, and fully integrated approaches combine both frameworks within a single system.

Motivated by these considerations, this paper investigates the system-wide implications of key elements of the Fit-for-55 package as reflected in the updated Czech NECP. To this end, it employs a hybrid dynamic CGE model of the Czech economy, based on the Austrian framework of (Miess et al., 2022), with an integrated electricity sector following Böhringer and Rutherford (2008). The model also incorporates a discrete choice module for transport technologies (Truong and Hensher, 2012), capturing consumer preferences across conventional vehicles (petrol and diesel) and AFVs, thereby explicitly modeling consumer choice as a driver of endogenous technological change.

This paper contributes to several strands of literature. First, it provides a system-wide assessment of the Czech NECP. Second, it adds to the limited literature on environmental policy evaluation in the transport sector (Noll et al., 2022). Third, it advances the literature on sector coupling by integrating the power and transport sectors within a unified hybrid CGE framework, highlighting their interactions as a key mechanism for decarbonization (Brown et al., 2018).

The remainder of the paper is structured as follows. Chapter 2 presents the methodological framework, Chapter 3 describes the scenarios, Chapter 4 discusses the results, and Chapter 5 concludes.

2. METHODOLOGY

2.1 The core CGE model

We employ a dynamic hybrid CGE model implemented in GAMS as a Mixed Complementarity Problem and solved using the PATH solver, based on the Austrian CGE model of Miess et al. (2022). On the production side, the model distinguishes 24 different cost-competitive sectors, all employing labor, capital, and materials as inputs in their production. The nesting structure of the producing sectors is shown in Figure 2. The dynamics of the model follow the simple Ramsey model in a steady state, where savings are endogenous according to an intertemporal and optimal choice of household agents to trade off current consumption and future investments via their savings decision. Investment in the model is financed through endogenous household savings within the intertemporal Ramsey framework. The representative household determines the optimal allocation of income between current consumption and savings over time, which governs capital accumulation and the level of investment in each period. Lump-sum transfers from ETS revenues increase household disposable income and may therefore influence the optimal consumption–savings decision. Labor is assumed to remain constant over time, and the labor market follows the standard full employment assumption. Capital and labor are assumed to be homogeneous across sectors, and the Czech economy is modeled as a small open economy, with the shares between imported and domestically produced goods assumed fixed, and exports growing exogenously according to the steady-state growth path. The closure rule for the public sector follows a zero deficit rule.

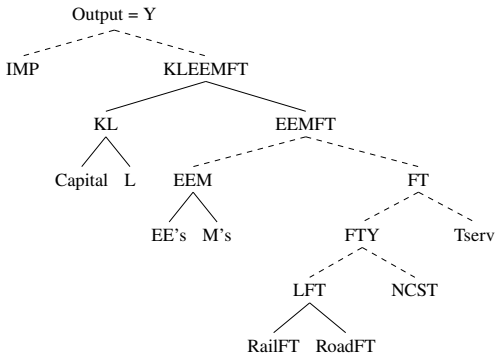

Figure 2: Nesting structure of production sectors.
Dashed lines denote Leontief nests. Abbreviations: IMP – imported inputs; KL – capital–labour composite; KLEEMFT – top-level production nest combining capital, labour, energy, materials and freight transport; EEM – energy and materials composite; EE – energy inputs; M – material inputs; FT – freight transport; FTY – freight transport composite; LFT – land freight transport; RailFT – rail freight transport; RoadFT – road freight transport; NCST – non-land transport; Tserv – transport services.

2.2 Electricity sector

Böhringer and Rutherford (2008) show that formulating an economic equilibrium as a mixed complementarity problem (MCP) allows bottom-up activity representations to be embedded directly within a top-down general equilibrium framework. This approach is especially useful for the electricity sector, where heterogeneous generation technologies operate under technology-specific constraints while supplying a homogeneous electricity good.

In our model, each electricity generation technology tec is represented as a separate activity that supplies the electricity market. The activity level E_{tec} denotes electricity generation by technology tec. For each technology, production is governed by the following unit-profit condition:

$$\Pi^{E}_{tec} = p_{\mathrm{ELE}} - \sum_{m} a^{Y}_{tec,m} p_m - a^{K}_{tec} r_K - a^{L}_{tec} p_L - \sum_{f} a^{F}_{tec,f} p_f - \mu_{tec}, \tag{1}$$

where $a^{Y}_{tec,m}$ denotes the material input coefficient, a^{K}_{tec} is the capital input coefficient, a^{L}_{tec} refers to the labor input coefficient, $a^{F}_{tec,f}$ is the energy input coefficient (e.g. coal, oil or gas inputs), and μ_{tec} is the complementary shadow value of the technology-specific generation constraint. In MCP form, the unit-profit condition is written as:

$$0 \geq \Pi^{E}_{tec} \perp E_{tec} \geq 0.$$

Electricity generation by each technology is subject to an upper bound reflecting the maximum annual net electricity output that can be delivered by that technology:

$$E_{tec} \leq \overline{E}_{tec},$$

with associated complementarity condition:

$$0 \leq \mu_{tec} \perp \bar{E}_{tec} - E_{tec} \geq 0.$$

The parameter $\bar{E}_{tec}$ represents an upper bound on annual electricity generation expressed in model-consistent activity units. The generation limits are calibrated using net electricity generation projections from the TIMES-CZ energy system model. In the benchmark equilibrium, the value shares of the electricity generation technologies in the social accounting matrix (SAM) are calibrated to be proportional to the observed net generation shares. Following Sue Wing (2008), the electricity sector is disaggregated into two activities: transmission and distribution, and generation, with generation split into eight technologies with the use of a Positive Mathematical Program (PMP) Howitt's (1995) that allocates capital, labor, energy, and material inputs across these activities in a way that is consistent with engineering cost data and with the micro-consistent structure of the SAM.

For future periods, the TIMES-CZ projections of net generation by technology are translated into upper bounds on generation activities by scaling benchmark activity levels proportionally. In this way, projected percentage changes in technology-specific electricity generation are imposed as quantity constraints within the CGE model, while electricity prices, input demands, and economy-wide adjustments remain endogenous.

When a generation constraint binds, the associated shadow price μ_{tec} is positive and generates a scarcity rent. These rents are reflected in the equilibrium electricity price and propagate through production, consumption, and welfare outcomes in the rest of the economy. Aggregate electricity supply is obtained by combining generation from individual technologies into an electricity-generation composite, which enters the final electricity supply activity together with transmission, distribution, and other fixed requirements in a Leontief structure. Market clearing requires the total electricity demand to equal the aggregate electricity supply.

Electricity generation technologies are associated with technology-specific capital stocks that evolve endogenously through investment and depreciation. Transmission and distribution infrastructure, on the contrary, follows the same investment mechanism as any other aggregate production activity, with capital accumulation determined through the general intertemporal Ramsey closure rather than through a separate bottom-up expansion module. The dynamic closure follows a forward-looking Ramsey framework in which a representative household chooses intertemporal savings, while investment is allocated across capital categories associated with production activities, including individual electricity generation technologies. As a result, both capital use and capital accumulation are activity-specific. At the same time, the electricity module remains a bottom-up representation embedded in general equilibrium: generation technologies are modeled as constant-coefficient activities that compete in a common electricity market, while their intertemporal adjustment is shaped by profitability and equilibrium factor-price signals, subject to technology-specific generation constraints. Endogenous capital accumulation therefore affects the cost and scale of technology use over time, but the admissible generation path of each technology remains restricted by the exogenous upper bounds calibrated from TIMES-CZ, thereby preserving consistency with externally specified technology pathways while allowing prices and macroeconomic adjustment to remain endogenous.

2.3 Transport sector

Transport, comprising the public and freight sectors, is disaggregated into public (PT), rail freight, road freight, non-land transport (water, air, pipe), and support services for transportation.

RoadFT services are a Leontief composite of a CES aggregate of the fuel mix of the road freight transport fleet (RoadFTMix), and the aggregate of the remaining production factors (KLEEM).

Given the explicit representation of different non-private transport activities/technologies, and the substitution/complementary possibilities between them, we employ the production nesting structure in Figure 3.

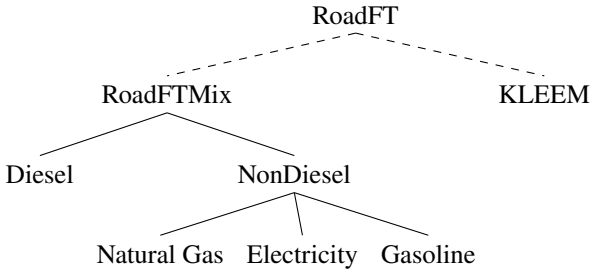

Figure 3: Nesting Structure of RoadFT sector. Dashed lines denote Leontief nests.

2.4 Discrete choice model for private individual transport

The CGE model is coupled with the endogenous demand for low-emission, energy-efficient technologies based on heterogeneous consumer preferences derived from a discrete choice model estimated using survey data specifically designed for this purpose.

Figure 4 shows the nesting structure of the consumption of the representative household. At the top nest, the agent substitutes between the consumption of mobility and non-transport goods. In the mobility nest, households substitute between an individual transport (IT) and public transport (PT) composite, ITPT, and other forms of transport, which mainly represents long distance travel by air. In the model split decision branch, the ITPT nest, the representative consumer substitutes between PT and IT. Expenditures on the individual transport composite comprise expenses of new vehicle purchases and to operation costs of the existing vehicle stock (such as fuels, service and maintenance, taxes).

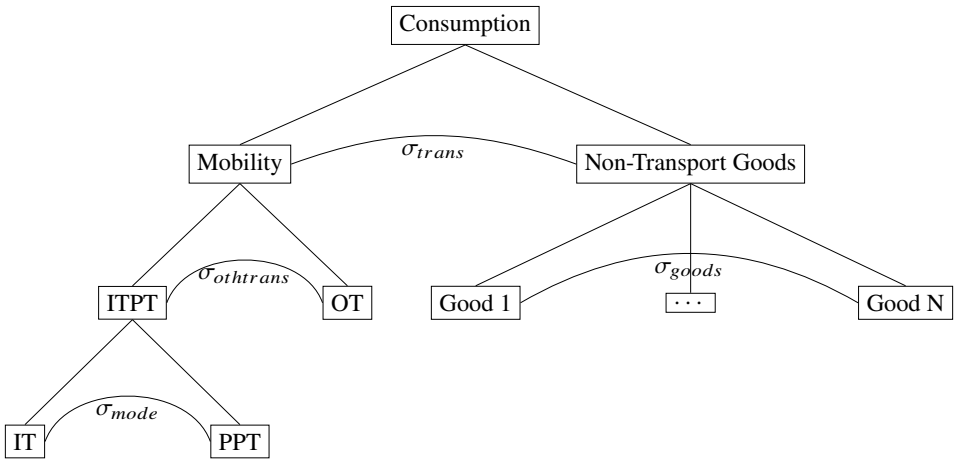

Figure 4: Nested structure of household consumption

Vehicle purchases are determined by our representative household's preferences, and the purchase price of vehicle technologies and their technological characteristics. Given the lack of possibility to substitute between purchasing a vehicle and using it, expenditures on the use of the vehicles are a linear function of the size of the vehicle stock. The cost share between vehicle purchase and use components is determined endogenously over time. Any increase in vehicle purchases that exceeds the number of decommissioned vehicles will lead to an increase in vehicle stock. In order to depict these developments correctly, we incorporate a discrete choice model and a vehicle fleet accounting model into the core CGE model. A schematic illustration of the procedure is provided in Figure 5. The summary of the integration process is provided in Appendix A A complete description of the integration procedure of the discrete choice model in the CGE is presented in Miess et al. (2022).

The purpose of the discrete choice model is to determine the market share of vehicle technologies – petrol[2] and diesel[3] cars representing conventional (CV) vehicles, plug-in hybrids (PHEV) and battery electric vehicles (BEV) – when

[2]Petrol cars category includes CNG, LPG and hybrid petrol vehicles (HEV-B) as well.
[3]Diesel cars category includes hybrid diesel vehicles (HEV-D).

it comes to vehicle purchase decisions that then translate to new registrations.

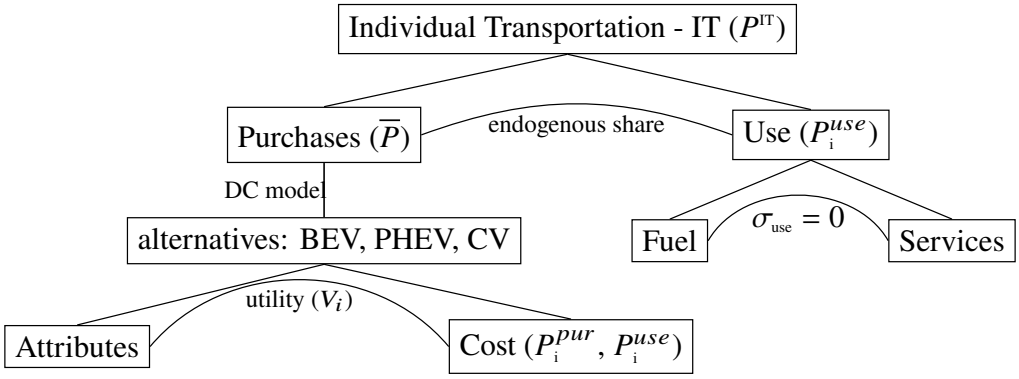

Figure 5: Individual transport consumption structure (DC model of the purchase decision)

The utility parameters of households are estimated using a mixed logit model based on specific characteristics of vehicles, such as the purchase price, fuel costs, and the driving range for BEVs. Mixed logit estimation outputs a vector of specific utility parameters for each variable. When multiplied by the initial levels of the variables, we get the indirect benefit of acquiring a vehicle of a certain type (Truong and Hensher, 2012). Based on indirect benefits, the probability of choice for all four vehicle types is derived, representing the market shares in car purchases, which, when multiplied with the aggregate demand of households for individual transport, determines the demand for Petrol, Diesel, PHEV, and BEV. In addition to consumer preference, vehicle market shares also depend on the development of the purchase price, changes in taxation, or the price of fuel and electricity.

2.5 Vehicle Stock and Flow Model

Private vehicle ownership and use are modeled entirely on the household consumption side of the CGE framework, rather than as part of market-based transport production as in the case of the road freight transport sector. Conceptually, households combine vehicle purchases and vehicle use to generate a flow of "individual transportation services," in close analogy to the way energy services are derived from energy-using durable goods and energy inputs. By contrast, industrial activities related to vehicle components production and assembly are represented as conventional production sectors, characterized by a standard KLEEM CES technology. The demand for different vehicle technologies (Petrol, Diesel, PHEV, and BEV) determines the number of new vehicle purchases that enter the fleet in each period. The demand for fuel, maintenance, and repair is evolving in line with the evolution of the vehicle fleet. While the number of newly registered cars corresponds to the purchasing decisions of households, the stock of each of the five types of cars develops according to the standard process of accumulation and depreciation. Therefore, the stock of vehicles at time *t* is equal to the stock in the previous period *t-1* plus the number of newly registered vehicles minus the depreciation of worn-out cars.

2.6 Emission Trading System module

The ETS module in the CGE model incorporates carbon pricing mechanisms based on the approach described by Liu et al. (2021). CO_2 emissions are determined by multiplying sector-specific emission coefficients[4] by fossil energy consumption in both intermediate input sectors and final demand from coal and petroleum gas. Emissions arise from fossil energy use, but carbon pricing applies only to emissions from intermediate consumption by economic sectors.

The carbon tax for a specific sector is determined as follows:

$$CTAX_i = tc_j \cdot \sum_j E_{i,j} \cdot \theta_j, \quad j = \text{coal, petroleum, gas} \tag{2}$$

where $CTAX_i$ represents the carbon tax levied on sector i, tc_j is the carbon price of a ton of CO_2 emissions, $E_{i,j}$ denotes the consumption of fossil fuel j in sector i, and θ_j is the CO_2 emission coefficient for fossil fuel j.

[4]Emission coefficients are calculated by the authors based on the data from the REZZO database (Czech Hydrometeorological Institute (CHMI), 2025)

The total carbon tax collected from a specific fossil fuel type is the following.

$$CTAX_j = tc_j \cdot \sum_i E_{i,j} \cdot \theta_j, \quad j = \text{coal, petroleum, gas} \tag{3}$$

Summing across all sectors and fuel types, the total carbon tax revenue is determined and subsequently redistributed within the economy to mitigate economic distortions and enhance social welfare.

To translate the carbon tax into price adjustments, an ad valorem tax rate, t_j^{carb}, is calculated as:

$$t_j^{carb} = \frac{CTAX_j}{PQ_j \cdot QQ_j} \tag{4}$$

where PQ_j and QQ_j are the price and domestic demand for fossil fuel j, respectively. This tax mechanism directly impacts fossil fuel prices, affecting energy consumption patterns and incentivizing shifts toward cleaner energy sources.

As part of the 2023 revisions of the ETS Directive, a new emissions trading system named ETS 2 was created, separate from the existing EU ETS 1. This new system will cover and address CO_2 emissions from fuel combustion in buildings, road transport, and additional sectors (mainly small industries not covered by the existing EU ETS). Although it will be a 'cap and trade' system like the existing EU ETS 1, ETS 2 will cover emissions upstream. Fuel suppliers, rather than end consumers, such as households or car users, will be required to monitor and report their emissions.

In the present modeling framework, CO_2 emissions from the power sector are treated differently from emissions arising in other sectors covered by the EU ETS. Although electricity generation is formally part of the EU ETS, emissions from the power sector are not explicitly priced within the CGE model. This modeling choice reflects the hybrid structure adopted in this study: net electricity generation trajectories by technology are imposed based on results from the TIMES-CZ energy system model, which already incorporates the effects of ETS carbon prices on fuel switching, technology choice, and dispatch decisions in the power sector.

Introducing an additional explicit carbon price on power-sector emissions within the CGE model would therefore lead to double counting of policy effects. To ensure consistency, power-sector emissions are excluded from the ETS emissions total used to determine carbon tax revenues, and ETS revenues in the model are generated exclusively by non-power ETS sectors. Emissions from electricity generation are instead calculated ex post using technology-specific emission coefficients and reported for analytical purposes, without affecting equilibrium prices or revenue recycling within the CGE framework.

3. POLICY SCENARIO FRAMEWORK

To evaluate the macroeconomic implications of alternative decarbonization pathways for the Czech Republic, two policy scenarios are considered: a reference scenario with currently implemented policies (WEM – With Existing Measures) and a policy scenario reflecting additional decarbonization measures consistent with the ambitions of the EU Fit-for-55 package (WAM – With Additional Measures).

Rather than replicating the full set of policy instruments described in national or EU policy documents, the scenarios are implemented through a set of model-consistent shocks affecting carbon pricing, electricity generation pathways, and transport technology adoption. In particular, the scenarios differ with respect to (i) carbon pricing trajectories, (ii) electricity generation limits derived from the TIMES-CZ energy system model, (iii) coal phase-out assumptions, and (iv) the evolution of vehicle technologies in private transport.

3.1 Carbon pricing and revenue recycling

Carbon pricing is represented through the implementation of the EU Emissions Trading System (ETS). In the reference scenario (WEM), only the existing EU ETS 1 system is active. Emission allowance prices follow the harmonized trajectories recommended by DG Climate Action (European Commission, 2022). No additional carbon pricing mechanisms are introduced.

In the policy scenario (WAM), carbon pricing is strengthened through the implementation of both EU ETS 1 and the new EU ETS 2 system. ETS 2 becomes operational in 2027 with a temporary price cap of 50 EUR/tCO_2 (in constant 2020 prices) during the period 2027–2030. After 2030, the ETS 2 price converges gradually toward the ETS 1 allowance price.

Revenues from carbon pricing are recycled within the economy. In the model, ETS revenues are redistributed through a combination of reductions in labour taxation and lump-sum transfers to households. These transfers increase household disposable income and therefore influence consumption and savings decisions within the intertemporal framework of the model.

3.2 Electricity sector assumptions

Electricity sector developments are represented through a hybrid linkage between the CGE model and the TIMES-CZ energy system model. Rather than determining the electricity mix solely through endogenous substitution within the CGE framework, externally derived electricity generation pathways are incorporated directly into the model.

Specifically, projections of net electricity generation by technology obtained from the TIMES-CZ model are translated into upper bounds on electricity generation activities within the CGE model. These limits determine the maximum annual output of each electricity generation technology and therefore govern the evolution of the electricity mix over time. Electricity prices and economy-wide feedback effects remain endogenously determined within the general equilibrium framework.

In the WEM scenario, electricity generation limits follow the baseline pathway from the TIMES-CZ model, which reflects currently implemented policies. In the WAM scenario, the electricity generation limits correspond to a more ambitious decarbonization pathway. Compared with WEM, the WAM scenario implies a faster phase-out of coal-fired electricity generation, a stronger expansion of photovoltaic and wind generation, and the addition of new nuclear capacity. These developments reflect the expected structural transformation of the Czech electricity system under stronger climate policy.

3.3 Transport sector assumptions

The transport sector representation focuses on the adoption of alternative vehicle technologies in private passenger transport. Household vehicle purchase decisions determine the composition of the vehicle fleet through the discrete choice model described in Section 2. New vehicle purchases translate into changes in the vehicle stock through the vehicle stock and flow model described earlier.

In the WEM scenario, vehicle technology adoption follows baseline trends consistent with existing policies. Conventional internal combustion vehicles continue to dominate new registrations in the early part of the modeling period, while the adoption of electric vehicles gradually increases over time.

In the WAM scenario, the transition toward low-emission vehicle technologies is accelerated. In particular, the registration of new conventional internal combustion passenger vehicles is phased out from 2035 onwards. As a result, BEVs and PHEVs progressively replace conventional vehicles within the fleet.

The model does not explicitly represent hydrogen-based transport technologies or biofuels. Consequently, the transition toward low-emission mobility in the model is primarily represented through the electrification of the vehicle fleet.

3.4 Scope of sectoral coverage

Certain sectors and technologies are represented in an aggregated form within the social accounting matrix and are therefore not modeled explicitly. In particular, bioenergy technologies such as biogas or biofuels are not represented as separate activities in the model. These activities are implicitly included within aggregated energy or agricultural sectors and cannot be analyzed independently.

Similarly, the agricultural sector is represented in aggregated form and is not subject to carbon pricing in the present policy scenarios. While future climate policy discussions have considered potential extensions of carbon pricing mechanisms to agricultural emissions, such measures are not included in the current modeling framework. The scenarios therefore focus primarily on sectors currently covered by existing or planned carbon pricing mechanisms, particularly energy, industry, and transport.

4. SCENARIO RESULTS

4.1 Macroeconomic impacts

Figure 6 presents the decomposition of GDP deviations into expenditure components, expressed as percentage point contributions relative to baseline GDP. Each contribution is defined as the difference between WAM and WEM scaled by baseline GDP, while the black line represents total GDP deviation.

The results indicate a persistent negative impact on GDP under WAM, reaching a minimum of -5.5% in the mid-2040s, followed by a gradual recovery toward +0.1% in 2050.

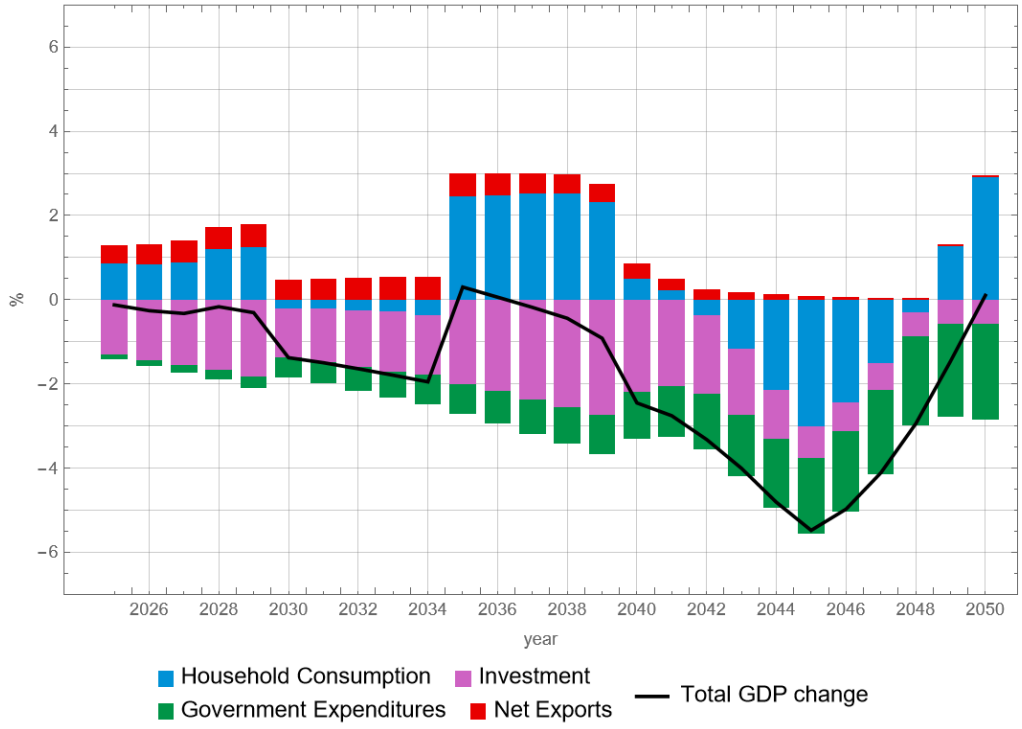

Figure 6: Relative change in GDP in WAM

The decomposition reveals strong time variation in the drivers of GDP change. In the early period (2025–2029), GDP deviations are driven primarily by negative investment contributions (-1.3 to -1.8 p.p.), largely offset by positive household consumption (+0.8 to +1.2 p.p.) and net exports (+0.5 p.p.), resulting in only modest GDP losses.

Between 2030 and 2034, all domestic demand components become negative, with investment remaining the largest contributor and government expenditures increasingly contractionary. This leads to a steady GDP decline to approximately -2%.

A temporary stabilization occurs in 2035–2039, driven by strongly positive household consumption (around +2.5 p.p.), which offsets persistently negative investment (down to -2.7 p.p.).

The deepest downturn occurs around 2045, when household consumption becomes strongly negative (-3.0 p.p.) and dominates the GDP decline. In contrast, investment becomes less negative, while government expenditures continue their gradual deterioration.

After 2045, GDP recovers mainly due to a strong rebound in household consumption (reaching +2.9 p.p. by 2050), despite increasingly negative government contributions (down to -2.3 p.p.). Net exports remain positive but economically small throughout.

Overall, the results highlight a shift in GDP drivers over time: investment dominates early dynamics, consumption drives the mid-term downturn, and the recovery is consumption-led, while government expenditures exert an increasingly negative influence.

Figures 7 and 8 present the distribution and sectoral changes in investment under WAM relative to WEM. The

results indicate strongly sector-specific responses, reflecting a substantial reallocation of capital across the economy.

Figure 7: Investment shares by industry

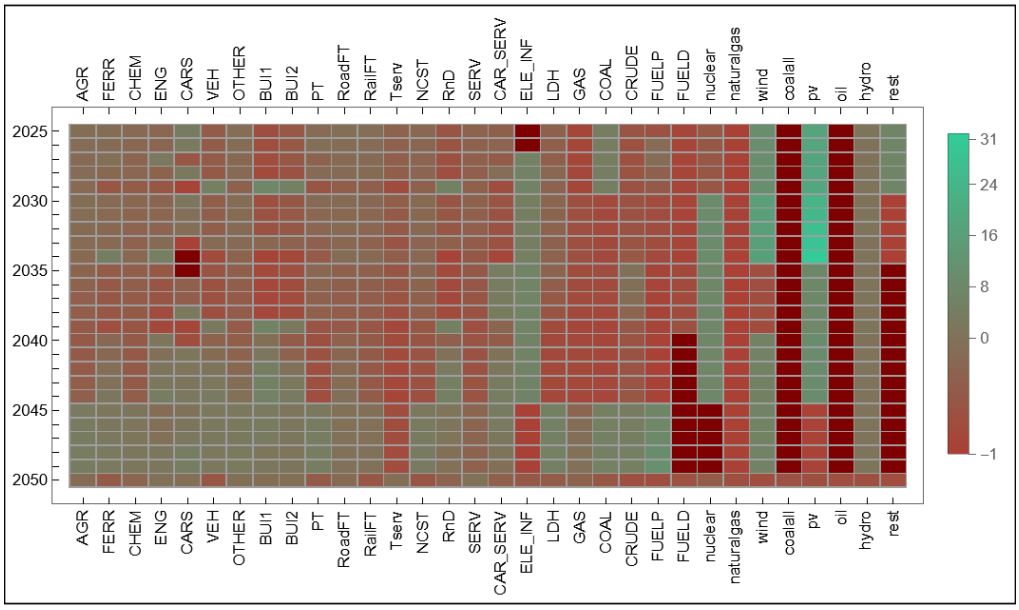

Figure 8: Relative deviation from baseline - Investment. Each cell represents the deviation from baseline (WEM) investment levels. Green hues indicate positive investment growth (policy-driven expansion), whereas red hues represent declining investment (reallocation or contraction). The intensity of the shading reflects the magnitude of the change, as indicated by the color scale.

Fossil fuel sectors (COAL, CRUDE, FUEL–Petrol, FUEL–Diesel) experience sharp investment declines, particularly after 2035, consistent with policy-driven divestment and transport electrification. Investment in natural gas also declines, albeit more gradually.

In contrast, low-carbon electricity technologies expand significantly. Renewable energy—especially solar PV and wind—shows strong investment growth, peaking around 2035, with photovoltaic investment increasing by more than 30% relative to WEM. Nuclear investment follows a similar but less pronounced pattern. At the same time, electricity infrastructure (ELE-INF) exhibits persistently positive investment, reflecting the need for grid expansion and integration of renewable generation. Coal is fully phased out after 2033 in WAM.

Transport investment shifts in line with decarbonization objectives. Public transport and rail freight expand, while road freight and private vehicle sectors (CARS, VEH) experience declining investment, particularly after 2035. Car services (CARSERV) also show moderate but persistent reductions, consistent with declining demand for conventional vehicle use.

In other sectors, responses are more muted. Construction remains broadly stable, while heavy industry (CHEM, FERR, ENG) experiences modest declines, particularly around 2035. Services and agriculture show limited changes, whereas R&D investment increases slightly, reflecting support for innovation.

Overall, the results point to a structural reallocation of investment toward low-carbon energy, infrastructure, and clean transport, with the most pronounced shifts occurring around 2035.

Figure 9 illustrates the relative changes in sectoral output under WAM compared with WEM. The results show a clear pattern of contraction in carbon-intensive sectors and expansion in electricity-related activities, reflecting the structural transformation induced by decarbonization policies.

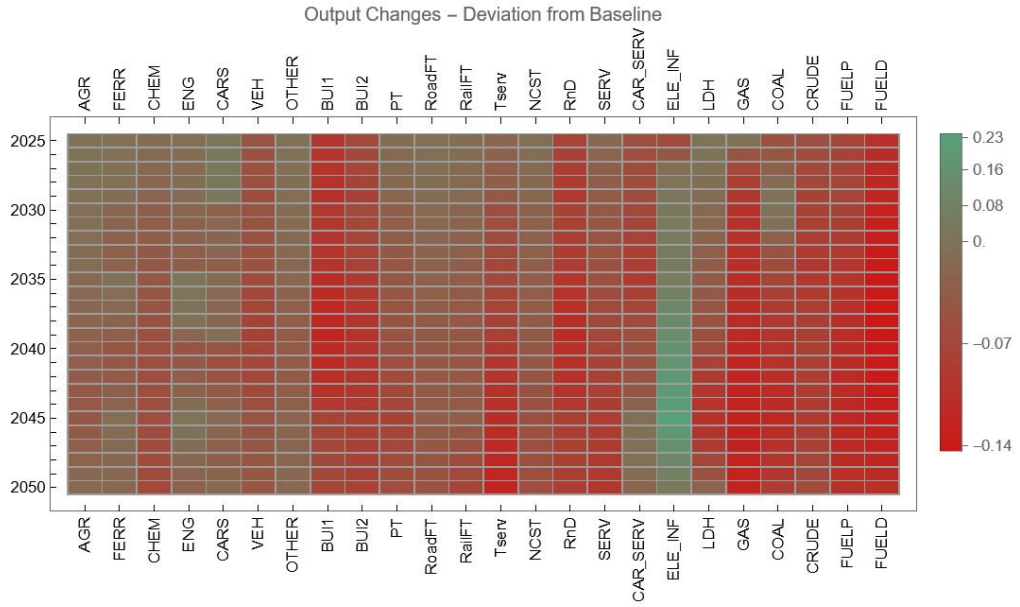

Figure 9: Relative deviation from baseline - Output

Fossil fuel sectors (COAL, CRUDE, FUEL–Petrol, FUEL–Diesel) experience substantial output declines, exceeding -14% over the simulation horizon. In contrast, electricity infrastructure (ELE-INF) exhibits the strongest growth, reaching increases of up to +23%, driven by expanding transmission, distribution, and grid integration requirements.

Construction (BUI1, BUI2) and manufacturing sectors (CHEM, ENG, VEH) show persistent output reductions, particularly after 2030, reflecting higher production costs under the EU ETS and shifting demand patterns. In transport, road freight and private transport decline moderately, while public transport and rail freight remain broadly stable, indicating a gradual modal shift.

Output changes in services and knowledge-based sectors (SERV, R&D) are limited, with R&D showing a modest early increase before stabilizing. Among energy carriers, natural gas output declines gradually, while district heating exhibits slight increases in the earlier years, reflecting changes in the energy mix.

Overall, output adjustments are less pronounced than investment shifts, but they consistently indicate a transition toward a low-carbon economic structure, with growth concentrated in electricity infrastructure and related activities.

Figure 10 shows sectoral employment changes under WAM relative to WEM. Consistent with output patterns, employment effects reflect a reallocation toward low-carbon activities.

Employment increases most strongly in renewable energy sectors, particularly photovoltaics and wind, with sustained growth in labor demand throughout the simulation period and especially between 2025 and 2035. The expansion of electricity transmission and distribution (ELE-INF) further supports labor demand, reflecting the broader electrification of the economy.

In contrast, fossil fuel-related sectors experience persistent employment declines, driven by carbon pricing and reduced demand. Sectors covered by the EU ETS show heterogeneous effects: capital-intensive industries such as chemicals exhibit relatively small reductions (generally below -1.5%), while labor-intensive sectors, notably construction (BUI1, BUI2), face larger employment losses of up to -8%.

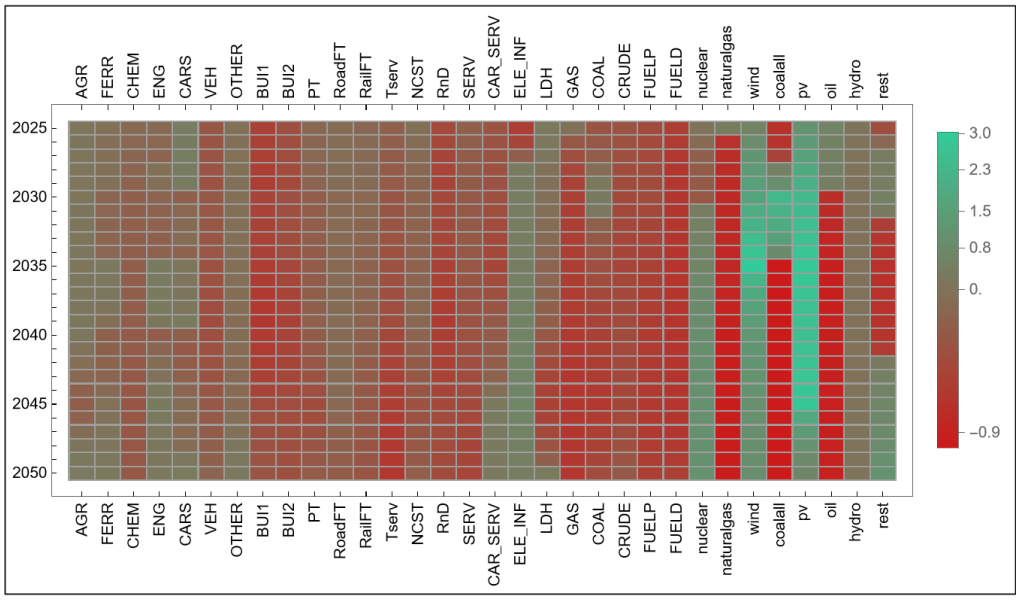

Figure 10: Relative deviation from baseline - Employment

Across the rest of the economy, employment effects are generally limited and mixed. Overall, however, the model indicates a gradual decline in aggregate labor demand, leading to a reduction in real wages and weaker incentives for labor market participation.

Household income is influenced by two opposing forces over most of the modeling horizon. On the one hand, labor income declines gradually relative to WEM as labor demand decreases. On the other hand, capital income in WAM remains higher than in WEM during the first 15 years of the simulation period (2025–2040). In addition, households receive higher lump-sum transfers due to the recycling of EU ETS revenues.

Between 2025 and 2040, the positive effects from higher capital income and transfers outweigh the decline in labor income. After 2040, however, capital income begins to decline relative to the baseline, resulting in a gradual reduction in household disposable income compared with the WEM scenario. Aggregate household consumption (Figure 11) follows a similar pattern, although the magnitude of the changes is smaller.

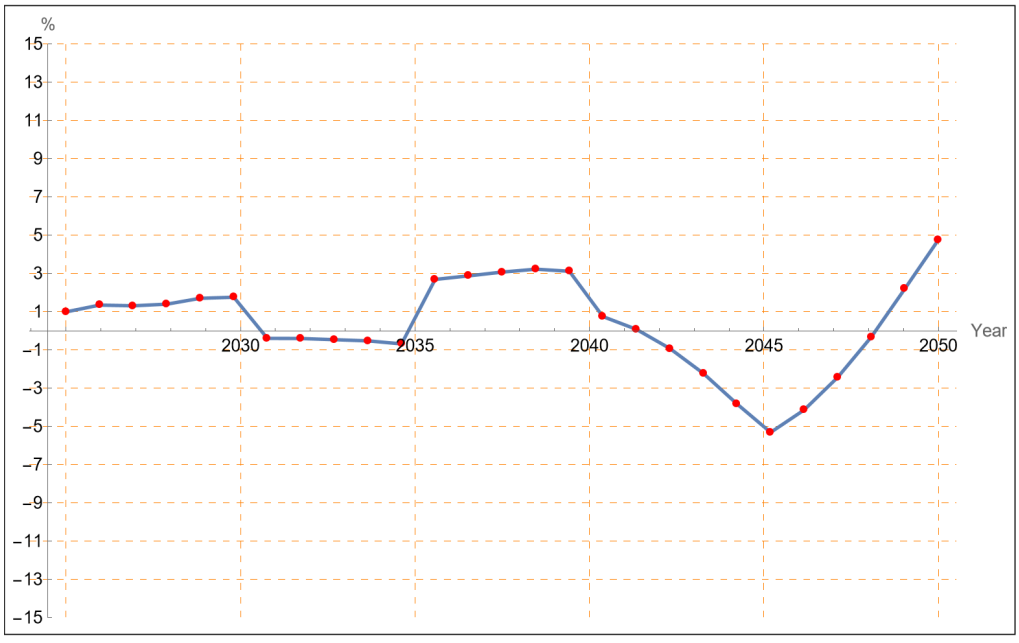

Figure 11: Relative deviation from baseline - Household Aggregate Consumption

Household consumption is measured in nominal terms. As an additional welfare indicator, we report the change in intertemporal household welfare, representing the discounted lifetime utility of the representative household. The policy scenario results in a welfare gain of approximately 0.75% relative to the baseline.

Figure 12 shows the evolution of household energy prices under WAM relative to WEM. Prices for fossil energy carriers decline over time, particularly for coal, reflecting reduced demand for carbon-intensive fuels during the transition. As consumption of these fuels decreases, their relative prices fall compared with the baseline. District heating prices exhibit a similar downward trend, driven by changes in the energy mix and the declining role of carbon-intensive inputs.

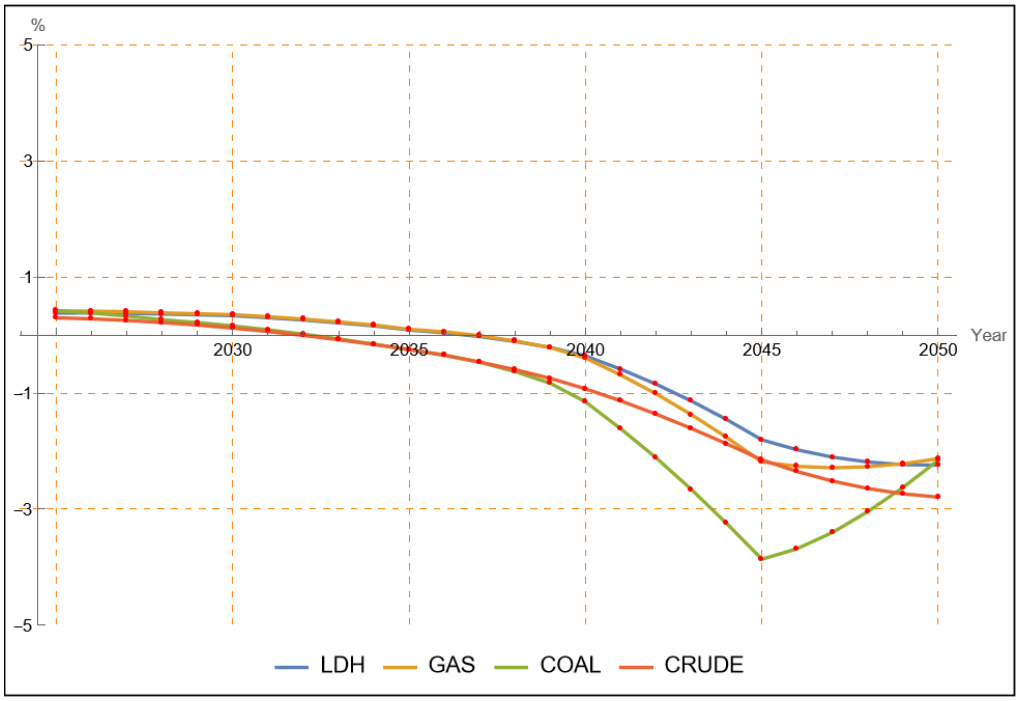

Figure 12: Relative deviation from baseline - Energy Prices

Figure 13 illustrates the evolution of tax revenues under the WAM scenario. The most pronounced effect is the sharp decline in fossil fuel-related tax revenues, with excise taxes (TYE) falling by approximately 50% by 2045, reflecting reduced output and consumption in carbon-intensive sectors.

Electrification and structural change are insufficient to compensate for the erosion of fossil fuel tax bases. Diesel excise taxes (TD) decline sharply after 2035 (by around -20%), while petrol taxes (TMO) decrease more gradually (to approximately -15% by 2045). Labor tax revenues (TL) fluctuate moderately around -5%, reflecting changes in labor income and adjustments in the recycling mechanism.

In contrast, capital tax revenues (TK) increase temporarily, peaking at around +15% in 2040, driven by investment in electricity generation and infrastructure. Consumption tax revenues (TC) remain broadly stable, indicating limited changes in aggregate consumption patterns.

These developments translate into a persistent decline in government consumption (Figure 14), which falls from approximately -1% of GDP in 2025 to nearly -9% by 2050. The decline is gradual but accelerates after 2040.

The reduction in public spending reflects the persistent shortfall in government revenues, primarily due to declining energy-related taxes. Although capital tax revenues recover later in the period, they are insufficient to offset these losses. Under the zero-deficit closure, the government adjusts expenditures rather than increasing borrowing, leading to a progressive fiscal tightening over time.

4.2 Vehicle fleet and new registrations

Figure 15 presents yearly new registrations of private vehicles by technology for both the WEM and WAM scenarios. In both scenarios, internal combustion engine vehicles (ICEVs) are gradually replaced by alternative fuel vehicles (AFVs), with a pronounced acceleration after 2035.

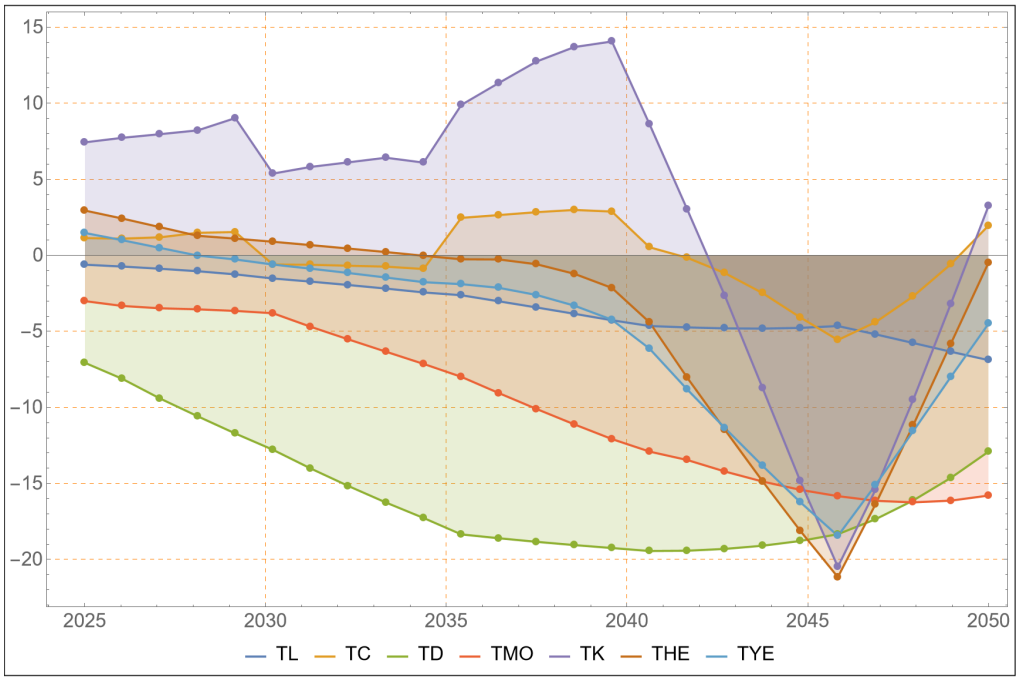

Figure 13: Relative deviation from baseline - Tax Revenue

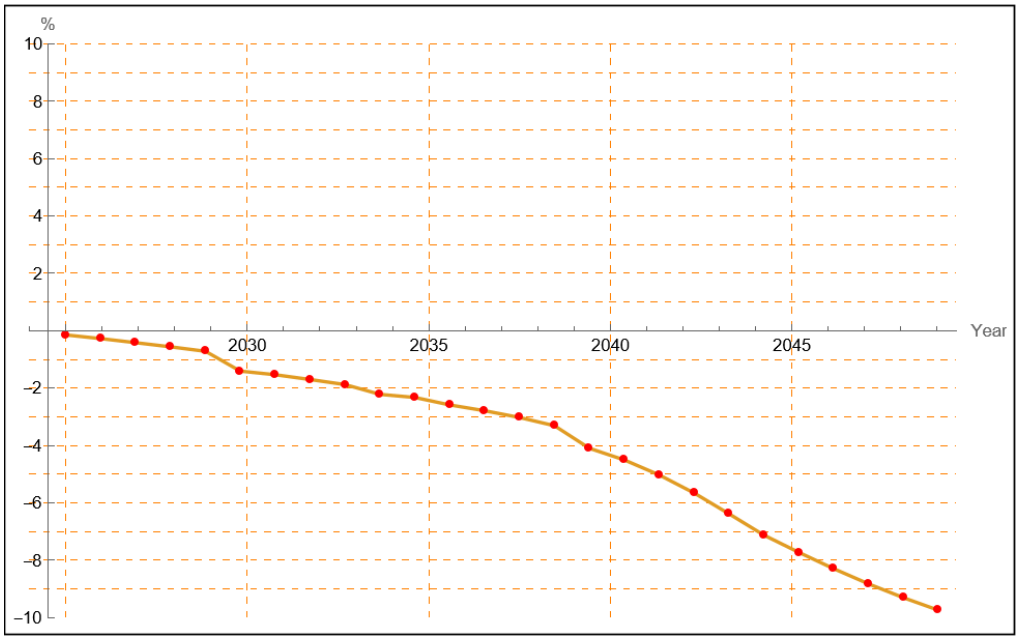

Figure 14: Relative deviation from baseline - Public Spending

Between 2025 and 2035, AFVs account for less than 5% of new vehicle registrations in the WEM scenario, while their share ranges between approximately 10% and 20% in the WAM scenario. During this period, petrol vehicles continue to dominate new purchases in both scenarios.

After 2035, the transition toward electric mobility accelerates significantly. By 2050, new vehicle registrations in both scenarios consist almost entirely of battery electric vehicles (BEVs). However, the transition occurs substantially faster in WAM than in WEM. In the baseline scenario, the replacement of ICEVs by AFVs occurs more gradually, with AFVs accounting for roughly 30% of new vehicle purchases before the transition accelerates after 2035. In contrast, in the WAM scenario AFVs—particularly BEVs—represent more than 90% of annual vehicle registrations between 2035 and 2050.

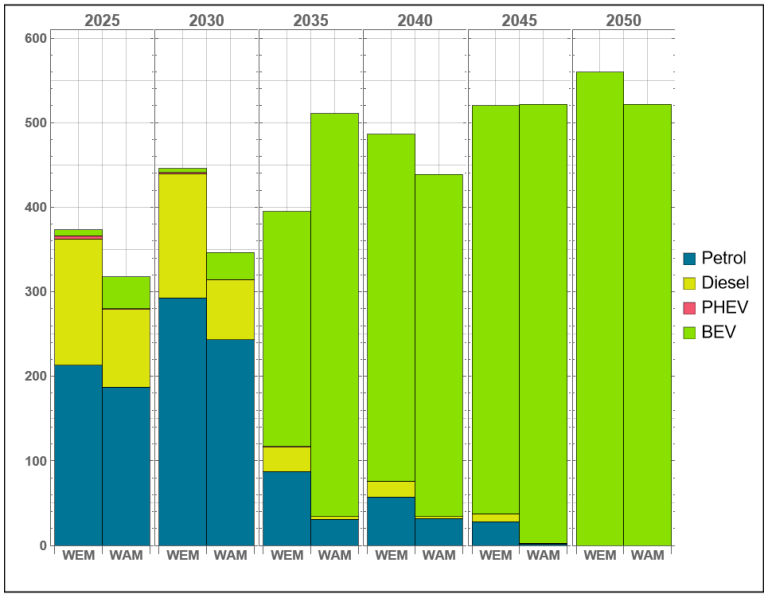

Figure 15: New registration of private vehicles by technology (thousands)

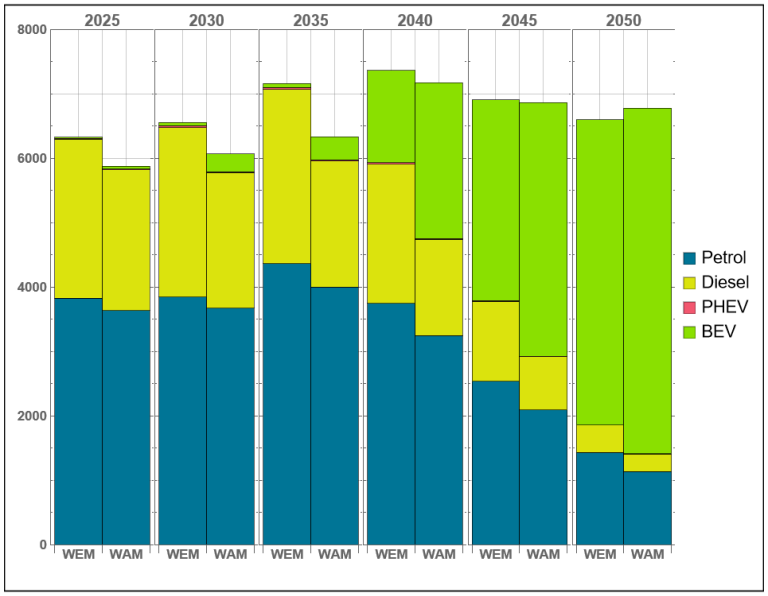

Figure 16: Stock of private vehicles by technology (thousands)

The faster adoption of AFVs in the WAM scenario is reflected in the vehicle stock evolution shown in Figure 16. As ICE vehicles are progressively replaced by AFVs through new registrations and the retirement of older vehicles, both scenarios exhibit a gradual transition toward an electrified vehicle fleet. The share of AFVs reaches approximately 50% of the total vehicle stock by 2046 in the WEM scenario and by 2044 in the WAM scenario.

4.3 Electricity supply

The evolution of electricity generation differs substantially between the WEM and WAM scenarios, reflecting alternative decarbonization pathways. Figure 17 presents generation by technology in physical units (TWh).

In both scenarios, coal-based generation declines markedly; however, under WAM it is fully phased out by 2035. Natural gas follows diverging trajectories: in WEM, generation increases from 5.2 TWh in 2025 to nearly 21 TWh by 2050, whereas in WAM it declines to 1.85 TWh by 2040 before modestly recovering to 3.4 TWh in 2050. This reflects the reduced role of fossil fuels under the policy scenario.

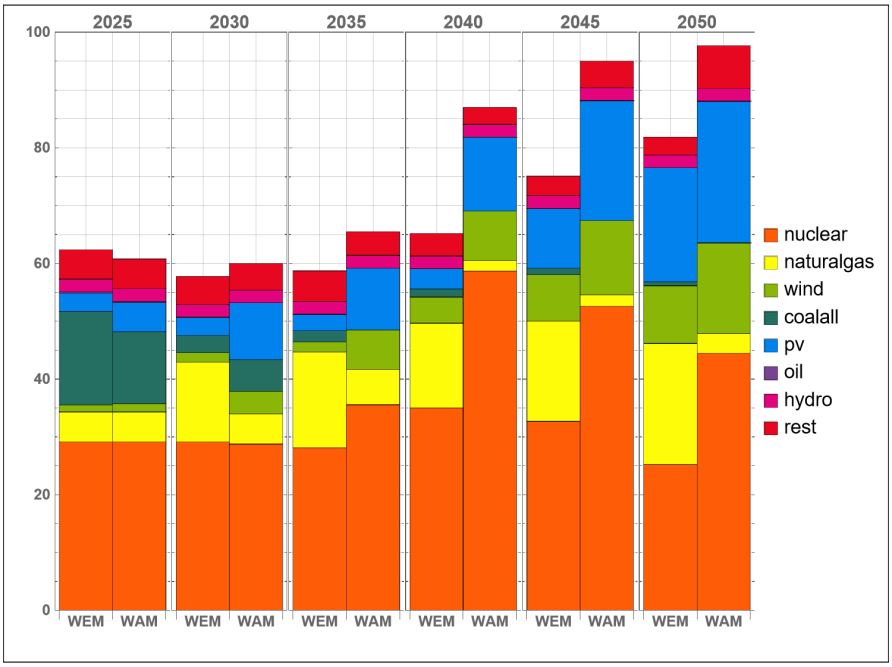

Figure 17: Electricity generation by technology (TWh)

The WAM scenario exhibits a clear shift toward low-carbon electricity sources, particularly nuclear and renewables. Nuclear generation increases from 29 TWh in 2025 to 44.45 TWh in 2050, supported by new capacities at Temelín and Dukovany, and provides a stable baseload for integrating variable renewables.

Renewable energy expands strongly. Photovoltaic generation rises from 3.1 TWh in 2025 to 24.5 TWh in 2050 under WAM (compared to 19.7 TWh in WEM), while wind increases from 0.6 TWh to 15.7 TWh (versus 10 TWh in WEM). Hydropower remains broadly constant, reflecting limited expansion potential. The residual category (biomass, geothermal, waste) grows to 7.4 TWh in WAM, but declines in WEM, indicating a more diversified renewable mix under the policy scenario.

Overall, the results show a substantial restructuring of the electricity system, driven by the phase-out of coal, reduced reliance on natural gas, and expansion of nuclear and renewable generation.

Despite this expansion, the electricity sector remains a relatively small share of total economic output. As a result, its growth does not fully offset the contraction in carbon-intensive sectors and the broader reallocation effects induced by carbon pricing.

4.4 Emissions

Year-on-year changes in CO_2 emissions are presented in Figure 18. The largest emission reductions occur in the electricity sector, where year-on-year emission reductions exceed 60% after 2040 due to the phase-out of coal-fired generation and the significant reduction in natural gas use.

Emissions from private transport decline steadily throughout the modeling period due to the higher share of BEV registrations in the WAM scenario relative to WEM. The rate of emission reductions stabilizes between 2038 and 2043, when the difference in the number of BEVs between the two scenarios reaches its peak. After this period, BEV adoption in the WEM scenario gradually catches up with that in WAM. As the AFV fleet matures in both scenarios, the pace of year-on-year emission reductions slows over time.

Emission reductions in the remaining economic sectors are less pronounced than in electricity generation and private transport, but still significant. Most sectors achieve year-on-year emission reductions exceeding 5% after 2035. ETS sectors in particular experience accelerated emission reductions after 2035–2036, reaching a maximum reduction of nearly 20% relative to WEM around 2045.

Figure 19 reports the evolution of carbon pricing revenues as percentage deviations relative to the WEM baseline. These revenues reflect the effects of carbon pricing mechanisms implemented under the policy scenario.

Overall, the results indicate that the policy scenario leads to meaningful emission reductions across multiple

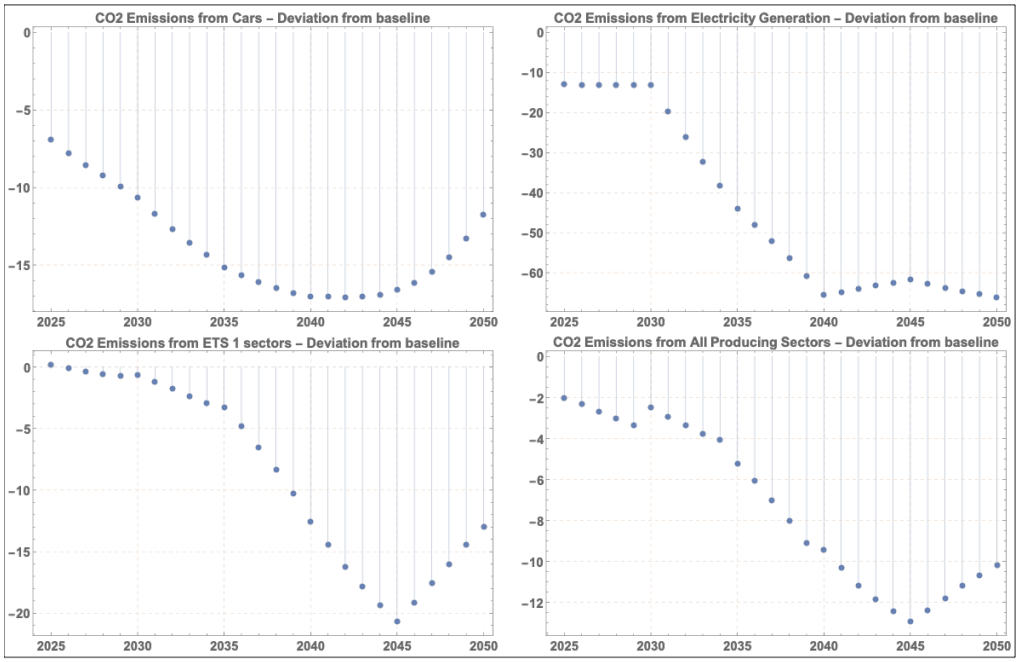

Figure 18: Relative deviation from baseline – Emissions

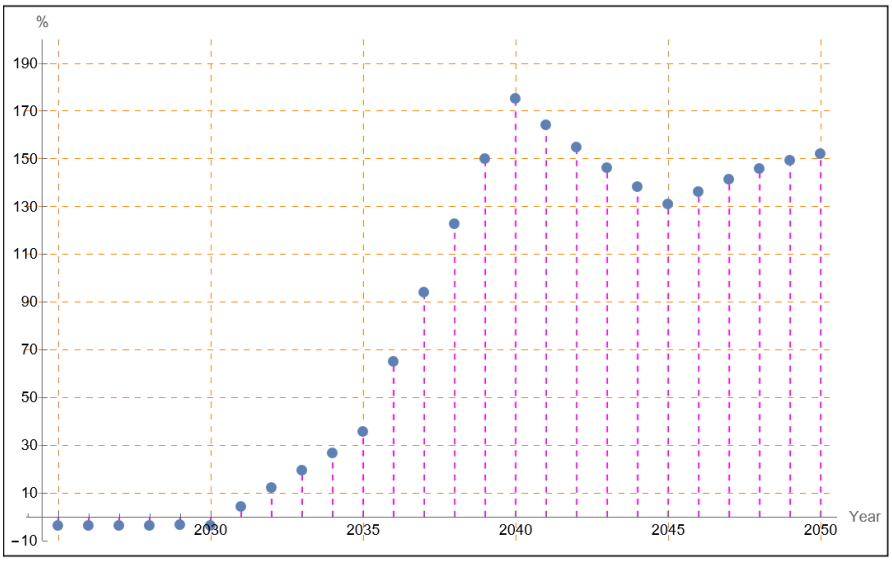

Figure 19: Relative deviation from baseline – ETS revenue

sectors of the economy. While substantial progress is achieved in electricity generation and private transport, other sectors may require additional technological advances and targeted policies in order to achieve deeper emission reductions.

The overall difference in CO_2 emissions between the scenarios becomes negative after 2033, gradually increasing from approximately -0.3% to -1.6% by 2040. In later years the difference widens further, reaching nearly -5% by 2050.

5. CONCLUSION

This study provides a comprehensive assessment of the long-term economic and environmental impacts of the Czech Republic's updated National Energy and Climate Plan (NECP) using a hybrid Computable General Equilibrium (CGE) modeling framework. By integrating detailed bottom-up representations of the electricity and transport sectors with a top-down macroeconomic structure, the model captures system-wide interactions and feedback effects that are essential for evaluating complex climate policy interventions in coal-dependent economies.

The analysis of the With Additional Measures (WAM) scenario, reflecting the ambitions of the EU Fit-for-55 package, shows that the transition requires substantial upfront investment, particularly in renewable energy infrastructure and the electrification of transport. At the same time, these policies lead to significant reductions in greenhouse gas emissions.

The evaluated policies are projected to reduce GDP by around 2% by the mid-2030s, in line with previous studies (Chateau et al., 2023). However, the impact is non-monotonic over time, with GDP declining further to a maximum deviation of approximately -5.5% in the mid-2040s, before recovering toward baseline and reaching near-zero deviation by 2050.

While increased investment in renewable energy and related sectors stimulates economic activity in certain periods, these positive effects are not sufficient to fully offset the impact of higher carbon pricing and the reallocation of resources away from carbon-intensive sectors, such as fossil-fuel-related industries. The results therefore highlight that the macroeconomic costs of the transition are transitional rather than permanent, reflecting structural adjustment dynamics rather than long-run output losses.

It should be noted that the analysis does not account for several potentially positive economic effects associated with decarbonization, including improvements in air quality and public health, energy efficiency gains, or process-based emission reductions in energy-intensive industries such as steel production.

A further limitation concerns the dynamic structure of the CGE model. The model follows an intertemporal Ramsey-type formulation calibrated to a steady-state growth path, in which households make forward-looking decisions regarding consumption and savings. This framework captures intertemporal substitution between present consumption and future investment and reflects capital accumulation decisions that are central to long-term decarbonization pathways. Intertemporal CGE frameworks of this type are widely used in climate policy analysis to study investment-driven structural change over long time horizons.

However, the perfect-foresight assumption implies that agents anticipate future policy and price trajectories and adjust optimally over time. In contrast, recursively dynamic CGE models typically assume myopic expectations and may better represent short-term adjustment dynamics under policy uncertainty. The intertemporal formulation used in this study therefore emphasizes long-run equilibrium outcomes and welfare implications rather than short-run transition dynamics. As a result, certain adjustment frictions—such as delays in investment, expectation errors, or other transitional rigidities—are not explicitly captured in the simulations.

The representation of international trade also imposes limitations on the analysis. The Czech economy is modeled as a small open economy with fixed shares between domestically produced and imported goods. While this assumption ensures consistency with the benchmark calibration and simplifies the representation of international markets, it limits the model's ability to capture potential changes in trade patterns induced by climate policies. Decarbonization policies may influence the trade balance both directly—through changes in imports of energy carriers or low-carbon technologies such as electric vehicles—and indirectly via impacts on domestic production structures and international competitiveness. Exchange-rate adjustments and global market responses are likewise not explicitly represented.

Another limitation concerns the treatment of technological change. The modeling framework does not explicitly incorporate endogenous technological learning or learning-by-doing effects for low-carbon technologies. Introducing explicit learning curves would require assumptions about future learning rates and technology cost trajectories that remain highly uncertain and may differ substantially across technologies and policy environments. Instead, technological developments in the electricity sector are incorporated indirectly through generation trajectories obtained from the TIMES-CZ energy system model, which reflect projected changes in the technology mix and implicitly capture expected technological progress in the power sector. Nevertheless, the CGE framework does not explicitly account for potential technology spillovers, productivity gains, or broader industrial benefits associated with the deployment of low-carbon technologies. Consequently, the estimated economic impacts of the transition may represent a conservative assessment.

Overall, the results indicate that ambitious decarbonization policies may involve non-negligible macroeconomic adjustment costs, particularly for carbon-intensive sectors and public finances. However, these outcomes reflect the

structural assumptions of the modeling framework and should not be interpreted as a comprehensive assessment of the overall costs and benefits of climate policy. In particular, the model does not fully capture technological spillovers, international trade adjustments, or broader welfare gains associated with environmental improvements and innovation.

The findings therefore highlight the importance of carefully designing complementary policies—such as revenue recycling mechanisms, innovation support, and industrial transition strategies—to ensure that decarbonization objectives are achieved while maintaining economic resilience and supporting broader societal goals.

Nevertheless, the analysis demonstrates the value of hybrid modeling approaches that combine detailed technological representation with economy-wide consistency. Such frameworks allow for a comprehensive evaluation of climate policies and provide valuable insights into potential decarbonization pathways.

For Czech and EU policymakers, the results suggest that a timely and ambitious transition away from coal, coupled with electrification and clean mobility strategies, can achieve substantial emission reductions. At the same time, careful attention must be paid to transition dynamics, sectoral disparities, and the sequencing of investments to ensure that economic resilience and social fairness are maintained throughout the decarbonization process.

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APPENDIX

A Integration of Discrete Choice into Household Demand

This appendix summarizes the integration of a discrete choice (DC) model into household demand within the dynamic CGE framework. The exposition follows Miess et al. (2022), but is restricted to the equations required to map choice probabilities into endogenous prices and demands.

A.1 Household vehicle choice

Households h derive indirect utility from purchasing a vehicle of type i according to

$$V_{h,i} = \sum_n \beta^n_{h,i} x^n_{h,i} + \alpha_{h,i}, \tag{5}$$

where $x^n_{h,i}$ denote vehicle attributes, $\beta^n_{h,i}$ the associated marginal utilities, and $\alpha_{h,i}$ an alternative-specific constant.

Assuming i.i.d. type-I extreme value errors, the probability that household h chooses alternative i, conditional on purchasing a vehicle, is given by the multinomial logit model

$$\mathbb{P}_{h,i} = \frac{\exp(V_{h,i})}{\sum_{j\in I}\exp(V_{h,j})}. \tag{6}$$

In the CGE model, these probabilities are interpreted as endogenous market shares,

$$\theta_{h,i} := \mathbb{P}_{h,i}. \tag{7}$$

A.2 Effective prices and aggregate purchase price

Let β^{money}_h denote the marginal utility of income, assumed identical across alternatives. The indirect utility function can then be written as

$$V_{h,i} = \beta^{\text{money}}_h P^e_{h,i} + \alpha_{h,i}, \tag{8}$$

where $P^e_{h,i}$ denotes the effective (perceived) price of vehicle type i, defined as

$$P^e_{h,i} = \sum_n \frac{\beta^n_{h,i}}{\beta^{\text{money}}_h} x^n_{h,i}. \tag{9}$$

The aggregate price of vehicle purchases is derived from the logsum (inclusive value)

$$\bar{V}_h = \ln\left(\sum_{i\in I}\exp(V_{h,i})\right), \tag{10}$$

which represents the expected maximum utility over all vehicle alternatives. Total differentiation yields

$$\mathrm{d}\bar{V}_h = \beta^{\text{money}}_h \sum_{i\in I} \mathbb{P}_{h,i}\,\mathrm{d}P^e_{h,i}. \tag{11}$$

Defining the aggregate purchase price as the probability-weighted average of effective prices,

$$\mathrm{d}\bar{P}_h := \sum_{i\in I} \mathbb{P}_{h,i}\,\mathrm{d}P^e_{h,i}, \tag{12}$$

implies

$$\mathrm{d}\bar{V}_h = \beta_h^{\text{money}}\, \mathrm{d}\bar{P}_h. \tag{13}$$

Integration yields

$$\bar{P}_h = \frac{\bar{V}_h}{\beta_h^{\text{money}}} + c_h, \tag{14}$$

where c_h is a calibration constant determined in the base period.

A.3 Mapping into household demand

Household demand for individual transportation is obtained from the unit expenditure function via Shephard's Lemma. Let $D_h^{\text{IT}}(t)$ denote unit demand for transportation services in period t. Overall demand for vehicle purchases is given by

$$\bar{D}_h(t) = D_h^{\text{IT}}(t) \frac{\Theta_h^{\text{pur}}(t)}{\Theta_h^{\text{pur}}(0)}, \tag{15}$$

where $\Theta_h^{\text{pur}}(t)$ denotes the expenditure share of vehicle purchases in total transportation expenditures.

Demand for purchases of vehicle type i follows directly from the endogenous choice shares,

$$D_{h,i}^{\text{pur}}(t) = \bar{D}_h(t) \frac{\theta_{h,i}(t)}{\theta_{h,i}(0)}. \tag{16}$$

Discrete choice probabilities thus determine both the composition of vehicle demand across technologies and the aggregate purchase price index. Monetary vehicle costs entering $P_{h,i}^e$ are endogenous equilibrium prices in the CGE model, ensuring full feedback between household technology choice and the macroeconomic equilibrium.

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