Policy Research Working Paper 10367

The Macroeconomic Implications of a Transition to Zero Net Emissions

A Modeling Framework

Stephane Hallegatte
Florent McIsaac
Hasan Dudu
Charl Jooste
Camilla Knudsen
Hans Beck

WORLD BANK GROUP
Macroeconomics, Trade and Investment Global Practice &
Climate Change Group
March 2023

Policy Research Working Paper 10367

Abstract

Analyzing the macroeconomic consequences of a transition to a net-zero economy creates specific modeling challenges, including those related to the non-marginal nature of the required transformation, the role of technologies, and the replacement of fossil fuel-based assets with greener ones. To address these challenges, this paper proposes a hybrid modeling approach that starts from a set of sectoral techno-economic scenarios to construct an illustrative resilient and net-zero decarbonization trajectory. It then assesses the macroeconomic implications by linking sectoral dynamics to two macroeconomic frameworks: a multisector general equilibrium framework and an aggregate macrostructural model. This approach combines the advantages of multiple tools and captures the various dimensions of the transition, including the need to tackle simultaneously multiple market failures beyond the carbon externality. The paper illustrates this methodology with Türkiye's objective to reach net zero emissions by 2053. The multisector general equilibrium framework suggests that the transition could contribute positively to Türkiye's economic growth despite the large investment needs, especially when indirect mitigation benefits are taken into account and if labor market frictions can be reduced. Improved energy efficiency in the transportation and building sectors drives the growth benefits in the short and medium terms. The growth benefits depend on how transition investments are financed: if they crowd out other productive investments, the benefits are significantly reduced and can even become slightly negative in the long term. The macrostructural model focuses on implications for public debt and the current account, using two extreme scenarios in which additional investments are triggered by higher productivity or a set of budget-neutral incentives (taxes and subsidies). The model concludes that the transition would have moderate impacts on the current account and public debt. With budget-neutral incentives, there is a small increase in gross domestic product (GDP) growth, the debt-to-GDP ratio increases by 1 to 3 percent, and the current account remains unchanged thanks to the reduction in fuel imports.

This paper is a product of the Macroeconomics, Trade and Investment Global Practice and the Climate Change Group, and a background paper for the Türkiye Country Climate and Development Report. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at shallegatte@worldbank.org, fmcisaac@worldbank.org, hdudu@worldbank.org, cjooste@worldbank.org, cknudsen@worldbank.org, and hbeck@worldbank.org.

The Macroeconomic Implications of a Transition to Zero Net Emissions: A Modeling Framework[1]

Stephane Hallegatte,[a] Florent McIsaac,[a] Hasan Dudu,[a] Charl Jooste,[a] Camilla Knudsen,[a] and Hans Beck[a]

[a]World Bank

Keywords: Macroeconomic modeling; climate change; technological change
JEL Classification: E60; Q43; Q54

[1] This analysis is part of the analytical work for the Country Climate and Development Report (CCDR) on Türkiye and benefited from the contributions of the entire CCDR team, especially the many colleagues who developed the sectoral roadmaps on which this work is based. It also benefited from the multiple reviews done on the CCDR. The authors thank in particular the peer reviewers of the CCDR who provided insightful comments that enhanced the quality of this paper. We also thank Etienne Espagne for his helpful comments. All remaining errors and opinions are our own. The authors thank the multi-donor Climate Support Facility for funding part of this work.

1 Introduction

Achieving climate objectives requires a non-marginal and sustained technological transformation of economic systems, including changes in supply, demand, and productivity technologies, generating multiple and prolonged micro and macro disruptions. Low-carbon development would have a particularly large negative impact on specific sectors, potentially leading to abrupt (financial) asset revaluation and loss of jobs (Battiston, Mandel, Schutze, & Visentin, 2017) (van der Ploeg & Rezai, 2020) or (NGFS, 2021). On the other hand, sectors with end products and business models that support the transition, such as industries producing batteries, renewable energy, and insulation materials, could benefit from such a transformation. And all sectors could be hurt by changes in relative prices or benefit from higher energy and material efficiency, low-cost energy from renewable sources, or higher labor productivity thanks to improved air quality. All these changes will generate significant macroeconomic fluctuations, through supply and demand shocks, relative prices, and international trade. To explore the macroeconomic risks and opportunities of the zero-carbon transition, one requires both a sectoral disaggregation analysis with an explicit representation of production technologies, and a general equilibrium framework to understand the spillover effects across sectors and their consequences for labor and capital markets.

To shed light on how transition risks and opportunities will materialize, the literature has used various economic models (including Computable General Equilibrium models) and integrated assessment models (IAMs) to construct and evaluate long-term climate mitigation scenarios. These models have become central tools in the international climate policy debate for more than three decades, beginning with the seminal work of (Nordhaus, 1992). Despite steady qualitative and quantitative improvements over the last three decades, the models are subject to severe criticisms from researchers regarding methods, uncertainty, and reporting of results.[2] Among the most common criticisms, it has been noted that the usual climate economic models tend to ignore (1) pre-existing distortions and non-climate market failures that open the possibility for win-win opportunities when climate policies (both price- and non-price-based policies) also accelerate economic growth;[3] (2) the role of technological changes with the possibility that greener technologies achieve higher productivity than already mature technologies, as is currently observed for renewable energy or electrified transportation;[4] and (3) macroeconomic feedback and trade-offs resulting from the large investments or labor market transitions needed to achieve the transition.[5] While the first two limits are likely to lead to overestimating the cost of the green transition, the last one may lead to an underestimation of the same.

This paper proposes a hybrid framework that addresses some of the points raised by these criticisms. Conceptually, our approach is based on three ideas:

First, we refrain from constructing a single integrated model that would combine all the required dimensions and mechanisms, using instead a set of connected tools. We combine in particular sectoral techno-economic roadmaps or scenarios that have a granular representation of

---

[2] Important recent contributions are (Keppo, et al., 2021), and (Stern, Stiglitz, & Taylor, 2022), among others.

[3] See (Hallegatte, Heal, Fay, & Treguer, 2012), (OECD, 2017), or (The New Climate Economy, 2018) for more information.

[4] See for example on the link between energy prices and productivity (Calì, Cantore, Iacovone, Pereira-López, & Presidente, 2022) (Amann, Nicola, Calí, Todorov, & Cheng, 2021), and on the Porter hypothesis (Ambec, Cohen, Elgie, & Lanoie, 2013).

[5] An example illustrating the importance of the labor market is in (Guivarch, Crassous, Sassi, & Hallegatte, 2011).

technologies and the capital stock (e.g., the building stock or the fleet of vehicles) but little representation of behaviors and economic mechanisms, with macroeconomic models with a simplified representation of production processes but that impose macroeconomic consistency and represent the behaviors of economic agents. The combination of economic models and technological roadmaps also enables considering the interplay between price and non-price interventions, and not only the price-based policies that are easiest to consider in economic models. As real-world climate policies largely rely on subsidies, regulations, and direct public investments, assessing their macroeconomic implications would not be possible with an economic framework able to represent price-based policies only.

Second, we do not try to identify an optimal decarbonization pathway and move away from the usual intertemporal cost-benefit analysis of balancing transition and physical risks through a well-coordinated price mechanism, for which the discount rate[6] and the calibration of the damage function play a key role.[7] Instead, we explore the implications of plausible decarbonization scenarios consistent with the country's own climate targets (here, Türkiye's objective to achieve net zero emissions in 2053).

And finally, we aim at a better consideration of the many market failures that act as barriers for an efficient and smooth decarbonization process, but also create opportunities for short-term synergies between climate and development policies. This is the case for instance of weak capital markets that cannot provide the financing needed for growth, but also for energy efficient or renewable energy technologies, or with distortive tax systems, inadequate regulations, or monopolistic behaviors that prevent some high-productivity lower-emissions technologies to enter markets. With a single climate market failure and an optimal baseline, a green transition requires diverting resources away from investments that necessarily yield higher rates of return to the economy (Batten 2018). Moreover, decarbonization is typically modeled as an adverse supply shock, pushing higher production costs, and negatively impacting economic output through the inflation channel (Pisani-Ferry 2021). Therefore, under these assumptions, climate mitigation action necessarily leads to net economic costs.[8] In contrast, the use of techno-economic sectoral scenarios in our approach allows the inclusion of market imperfections in the baseline, making it possible to explore opportunities for synergies between climate and development objectives (Lipsey & Lancaster, 1956).

In practice, we start from sector-level decarbonization pathways, describing explicitly the changes in supply and demand, productive capital, and technologies, and then the required (public or private) investments and implications for economic costs and benefits (e.g., reduction in fuel consumption from the power and transport systems). These investments, costs, and benefits may be triggered by price and non-price policies or interventions. While the sectoral scenarios do not

---

[6] See for example (Pindyck, 2013).

[7] The long-term costs of climate change are expected to be significant. However, their estimation is the subject of active academic debate (see for e.g., (IMF, 2022)). Consequently, analyses based on their estimates are subject to high uncertainty.

[8] Carbon price estimates vary widely due to uncertainties in factors including technological progress, fuel prices, policy actions, and preferences. Stiglitz et al. (2017) conclude that the economic literature points to the need for a cost of carbon dioxide emissions of $50 to $100 per metric ton by 2030 for a pathway consistent with the Paris agreement climate goals. If clean technologies progress faster than economic models project, the costs of decarbonization could be substantially lower (Stock and Stuart 2021).

necessarily describe the policies needed to achieve the transformation, their coupling with the macroeconomic models does not make it necessary to assume that all changes are driven by price policies.

These investments, costs, and benefits are then fed into macroeconomic models to explore the feasibility of the illustrative scenario and its implications for growth and other macroeconomic variables as well as household welfare and employment at the sectoral level. The focus of the macroeconomic analyses is to ensure consistency across the various sectoral scenarios, to identify positive or negative spillovers across sectors, and highlight the economic trade-offs that mitigation policies could entail. We analyze these potential trade-offs in our basic framework using two types of models, first a multi-sector computable general equilibrium (CGE) model to highlight the intra-sectoral consequences of the transition. We then use a more aggregate framework to discuss the macro-fiscal consequences. As an illustration, we apply this methodology to Türkiye.

Section 2 presents the net zero path used in the macroeconomic simulations. Section 3 discusses the integration of this path into a multi-sector CGE model. Then, Section 4, in the same vein as Section 3, discusses a similar integration but to a more aggregate macroeconomic model. Finally, Section 5 concludes.

2 Bottom-up approach to define illustrative sectoral roadmaps to achieve net zero GHG

We illustrate the methodology by applying it to Türkiye, which ratified the Paris Agreement in October 2021 and committed to the 2053 net zero emissions target. This climate target will be used to anchor the analysis. The left side of Figure 1, prior to 2020, shows Türkiye 's GHG emissions history in which the energy sector (i.e., power, transportation, building, and industrial sectors) is the largest contributor to the nation's GHG emissions, accounting for three-quarters of total emissions.

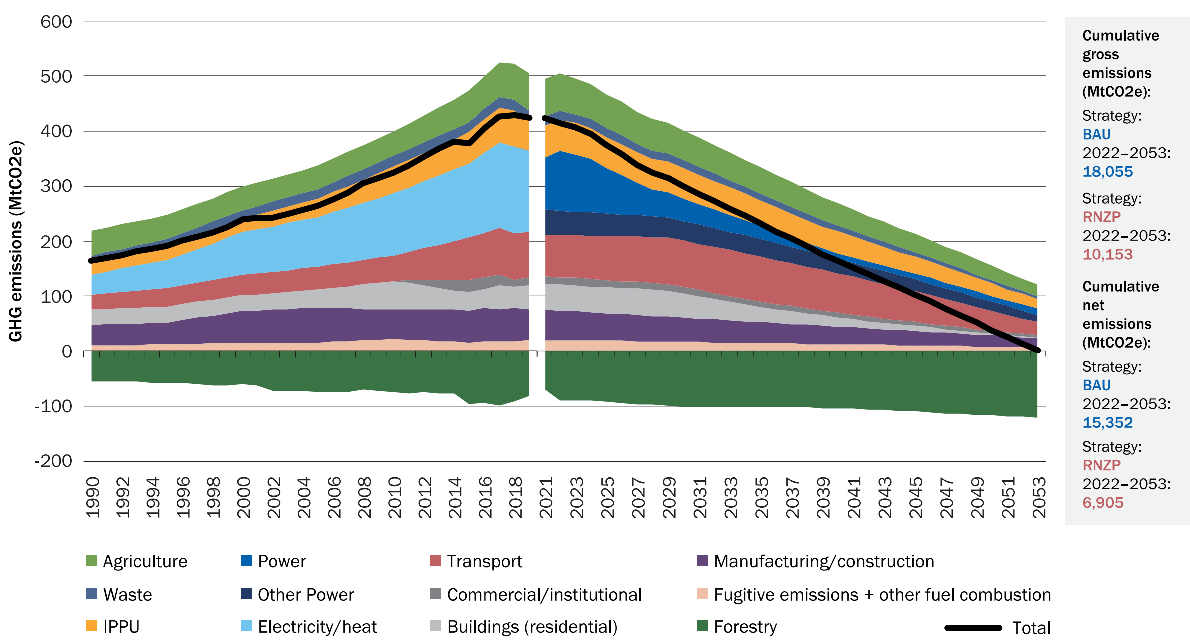


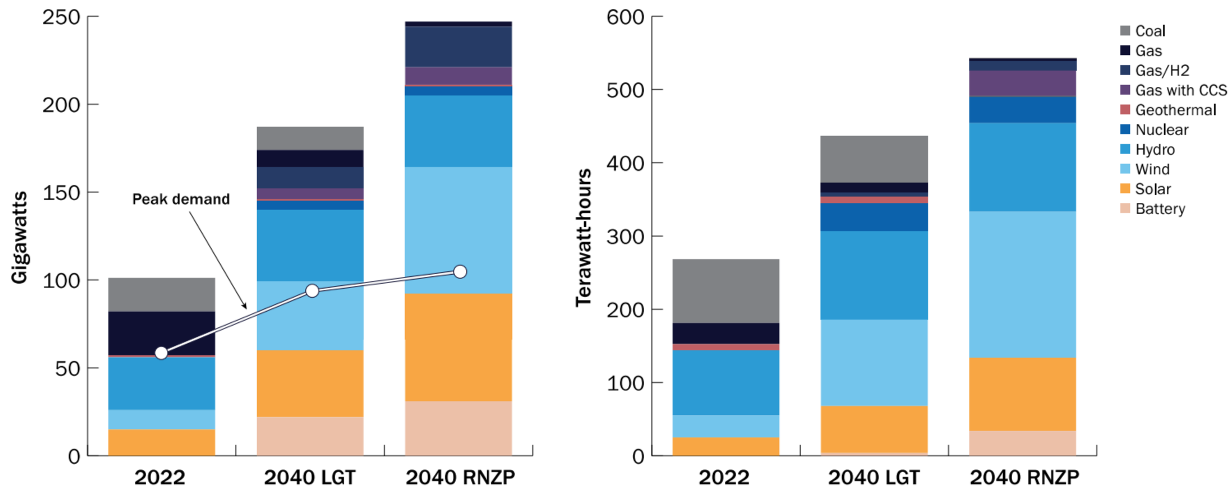
Figure 1: Historical emissions (left) and RNZP scenario (right). Source: CAIT and CCDR

We design a Resilient Net Zero Scenario (RNZP), shown in the right side of the figure, after 2022, constructed from a variety of individual sectoral technoeconomic models for a set of emitting sectors (i.e., power sector, transport, buildings sector, and forest landscapes) and more simplified roadmaps for industry and agriculture.

The RNZP assumes that Türkiye achieves its 2053 net zero emissions target through the combination of sectoral transformations (see illustrative example in Figure 2):

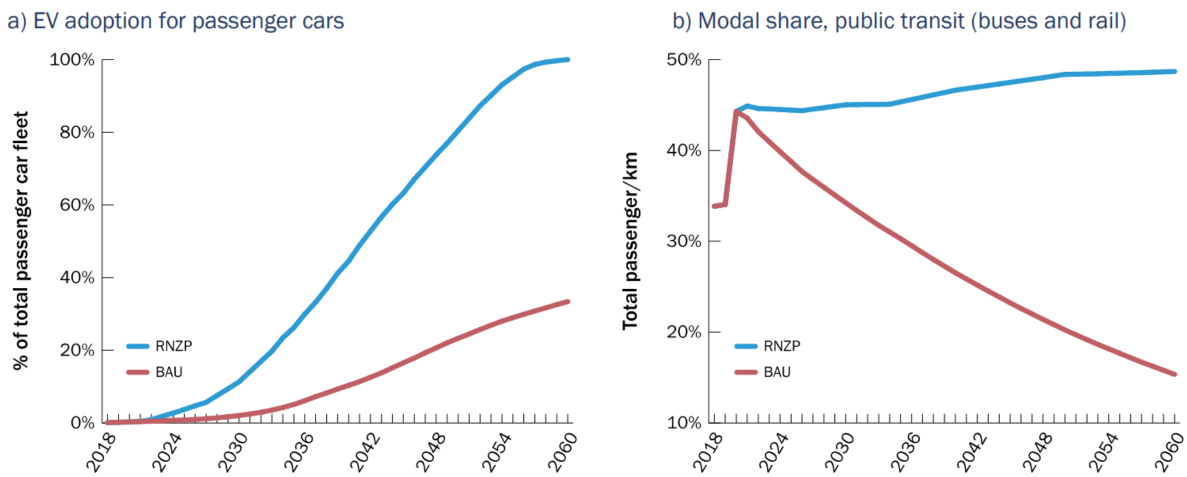
- **Power sector.** Deep decarbonization of the power sector, which requires large public and private investments but reduced consumption of fossil fuels (including imported oil, gas, and coal) and operational cost for the power sector. The baseline and decarbonization scenarios for the power sector are generated by the least-cost power sector planning model EPM (Chattopadhyay, de Sisternes, & Oguah, 2018), which provides the least-cost investments and dispatch of power generation for various technologies (coal, gas, oil, solar, wind, hydropower, etc.), to meet a constraint in terms of emissions (here, a 90% reduction by 2040 in the decarbonization scenarios, compared with the baseline scenario without carbon constraint). The model also calculates the consumption of various fuels, distinguishing imported and domestically produced fuels, the operational costs, and simple estimates for air pollution costs. Importantly, the electricity demand in the power sector simulations considers the demand from the appropriate scenarios for the building and transport sector (i.e., it takes into account the efforts in energy efficiency and the role of electrification).
- **Buildings.** A combination of resilience, energy efficiency and electrification in residential buildings, which reduces energy consumption from the building sector and fossil fuel imports, mitigate economic and human risks from earthquakes, and is co-financed by the public and the private sectors. The baseline and decarbonization scenarios for the building sector are generated with a simple scenario tool that reproduces the evolution of the fleet of buildings, based on changes in construction norms for new buildings, and a rate of building retrofits for existing buildings. New and retrofitted buildings can have different energy consumption (in kWh/m2/year), use different technologies (e.g., coal, gas, or electricity), and have different resilience to earthquakes. The model also calculates the consumption of various fuels, distinguishing imported and domestically produced fuels, the operational costs, and average human and economic losses from earthquakes.
- **Transportation.** A combination of modal shift, energy efficiency, and electrification in transport, which also affect total energy consumption, the energy mix used in transportation, as well as energy costs for households and firms as well as imports. The baseline and decarbonization scenarios for the transport sector are generated with a simple scenario tool that distinguishes passenger and freight, and urban and intercity transport. It reproduces the evolution of the infrastructure (e.g., roads, railways) and the fleet of vehicles (internal combustion engine and electric vehicle, but also trains, trucks, as well as air and maritime transport). It also calculates the consumption of various fuels, distinguishing imported and domestically produced fuels, the operational costs, and simple estimates for air pollution costs, as well as congestion and road fatalities.
- **Forestry.** A change in current practices to maximize carbon sequestration from forest landscapes, assuming a combination of natural growth in protected areas and activity-based carbon removals from reforestation and afforestation.
- **Rest of the economy.** Generic emissions reduction efforts in the rest of the economy (industries, agriculture, waste management, and water management). In industries, after

assuming unchanged IPPU emission until 2030, the sectoral scenarios separate the emissions reduction from electrification from the high-temperature and process-based emissions, which are assumed to be avoided thanks to carbon capture and sequestration.



Source: World Bank staff estimates
Notes: Gas/H2 = hydrogen gas; CCS = carbon capture and storage.

Note: LGT = least-cost with current government targets (BAU)



Source: World Bank staff estimates

Figure 2. Illustrative technological sectors roadmaps for the power sector (upper panels) and the transport sector (bottom panel).

The main assumptions and scenarios that were used to build the elements in the right side of Figure 1 are presented in the technical background of (CCDR, 2022). For each of the sectors, the sectoral roadmap provides estimates of the *additional* investment needs in the RNZP scenario, compared with a baseline achieving the same output (i.e., the same electricity generation, or the same housing or transportation service) but without emission reduction.[9] The sectoral roadmaps also provide

[9] Since this scenario includes resilience consideration, investment needs are adjusted to account for the additional costs of building more resilient infrastructure and buildings, and the economic benefits of doing so (through reduced maintenance and repair costs, based on (Hallegatte, Rentschler, & Rozenberg, 2019)).

estimates of various costs and benefits (e.g., reduced fuel consumption of energy and transportation systems, gains from improved air quality). These investments, costs and benefits are then fed into macroeconomic models to explore the feasibility of RNZP and its implication for growth and other macroeconomic variables as well as for household welfare and employment at the sectoral level.

In the RNZP, the scenarios for the four sectors are complemented by an economywide carbon tax that starts from USD 11 in 2022 and gradually reaches USD 211 dollars by 2040, with 2018 prices and triggers the needed emission reductions in the rest of the economy. This carbon tax level is calculated by the model endogenously to keep the emissions in line with the net zero target.

Below we present two complementary ways of linking sectoral information to a macroeconomic framework. The first, through multisectoral interactions, places the analysis in the interaction between sectors and the structural transformation of the production network (section 3.1). The second focuses on the fiscal impact of investment needs and the interactions with the aggregate behavior of the economy, including monetary dynamics (section 3.2).

3 From sectoral to macro: A multisectoral hybrid approach

3.1 CGE Modeling: A focus on the production structure

This first analysis is based on the single country CGE model MANAGE (mitigation, adaptation, and new technologies applied general equilibrium model), developed at the World Bank, that relies on the neoclassical structural modeling approach.[10] In what follows we will briefly explain the production structure of the MANAGE model and its calibration (see Appendix 1 for more details on the demand side of the model). Then, we will turn to how the CGE is fed the sectoral technoeconomic scenarios.

Prior to incorporating the decarbonization pathway to the MANAGE model, all production activities (38 sectors and products) in the MANAGE model are profit maximizers under technologies with constant returns to scale. All markets in the model are perfectly competitive implying that prices are equal to marginal costs in the equilibrium**.** We use a nested production function with constant elasticity of substitution (CES) technology (see Figure 3 for the full nesting structure) that describes how the economic system transforms inputs into outputs and adds value.

The nested production structure allows accounting for difference in elasticities of substitution between factors. All nests in Figure 3 use a CES technology with different substitution elasticities.

[10] Most model assumptions are derived from (van der Mensbrugghe, 2020) that provides an extended documentation of the model's assumptions.

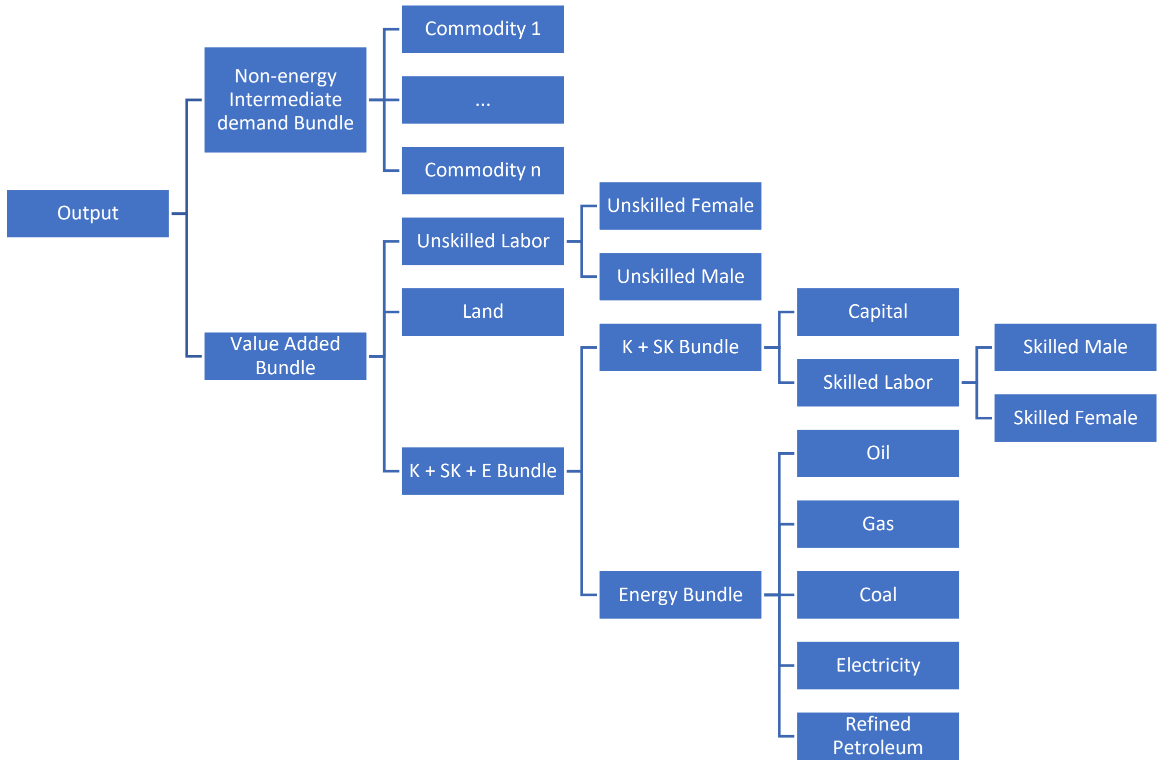


Figure 3: Schematic structure of the CGE MANAGE model (K: Capital; SK: Skilled Labor; E: Energy)

This production structure allows for an endogenous energy intensity of production, which fluctuates with carbon pricing policies. For example, an increase in carbon pricing will endogenously encourage energy substitution of capital as firms invest in energy efficient technologies to reduce production costs. The MANAGE model also has a vintage capital structure where old and new capital are treated differently in terms of substitutability with energy. The new capital is substitutable for energy while the old capital is a near complement: it means that existing productive assets need a certain amount of energy to produce, while there is flexibility to invest in new assets with higher energy efficiency in response to an increase in energy prices. In other words, the vintage capital structure captures semi-putty/putty relationships between inputs with more elastic behavior in the long run compared to the short run.

Power production in this version of the MANAGE model distinguishes seven types of power generation activities: nuclear,[11] coal, gas, oil, hydro, solar, and wind. The electricity generation mix follows the results of an Electricity Planning Model, see (Chattopadhyay, de Sisternes, & Oguah, 2018).

---

[11] Although Türkiye does not have an active nuclear power plant as of 2018, a new plant is currently being built. To be able to incorporate nuclear into the model baseline and scenarios, we introduced a very small nuclear power activity in the base year based on an average cost structure from the GTAP power database and followed the expected growth of share of nuclear in power mix in the baseline and scenarios.

The supply of labor and land is determined by a supply function that is sensitive to the average real wage and land price respectively. On the one hand, labor supply is also segmented across sector groups by introducing a constant elasticity of transformation (CET) function that allocates labor supply across sector groups based on relative wages across sector groups and an elasticity of substitution. The movement of labor between these sector groups is therefore limited (or rigid). On the other hand, the supply of capital, or the "new" capital stock that is fully mobile across sectors, is twofold: investment and the fraction of the existing capital stock released by recessionary sectors (limiting capital mobility across sectors).

3.2 Mechanics of hybridization and assumptions

To combine the granularity possible with sectoral roadmaps into the general equilibrium framework, we integrate the sectoral analysis into the macroeconomic modeling (Figure 4).

Running the RNZP scenarios using the MANAGE model involves calibrating the parameters and elasticities to replicate the emissions reductions determined in the sectoral analysis (e.g., one consequence of the net-zero transition is that the total supply and then total demand of emitting sectors, like coal, will have to decrease to zero). This procedure mimics the technological structural change of the model, but based on the sectoral scenarios. Importantly, this structural change is not free: it has a cost that takes the form of investment needs, possibly combined with other costs and benefits identified in the sectoral scenario. To capture these costs, we also introduce into the CGE the investment and other costs required to achieve these emissions reductions.

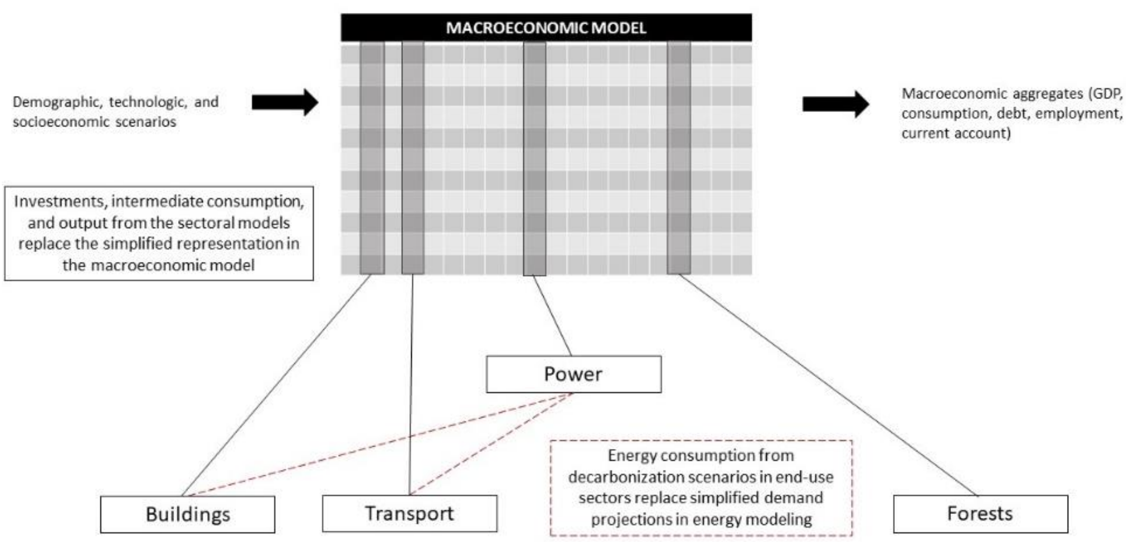


Figure 4: Integration of sector-level and macroeconomic analyses

We present below a conceptual overview of the recalibration process to mimic the RNZP. Denoting $x = (x_i)_i$ the input vector, $Y(.)$ the production function, and $p = (p_i)_i$ the real price of inputs, the profit maximization program of the producer,

$$\max_x Y(x) - p.x$$

Leads to

$$\epsilon_i := \frac{x_i}{Y(x)} \times \frac{\partial Y}{\partial x_i}(x) = \frac{p_i x_i}{p.x}$$

Where $\epsilon_i$is the output elasticity of the production factor, x_i . This argument holds when producers do not face further constraints than the production technology, $Y(.)$. Suppose that such constraints exist and are captured by a smooth function $f(.)$. The new program becomes

$$\max_x Y(x) - p.x \;\; s.t. f(x_i) = 0.$$

When the input x_i is interpreted as an input with non-zero emission intensity, the function $f(.)$ can be interpreted as a carbon budget constraint or any other non-price policy that would be priced in by the sector. The previous results now involve a shadow (e.g., carbon) price given by the (normalized) Lagrange multiplier, λ, of the new constraint, $f(.) = 0$:

$$\epsilon_i = \frac{x_i \left(p_i - \lambda \frac{\partial f(x_i)}{\partial x_i} \right)}{p.x - \lambda x_i \frac{\partial f(x_i)}{\partial x_i}}.$$

Isolating x_i yields the following

$$x_i = \frac{(p.x)_{\neq i}}{p_i - \lambda \frac{\partial f(x_i)}{\partial x_i}} \left[\frac{\epsilon_i}{1 - \epsilon_i} \right].$$

From this equation, there are only two possibilities for the economy to phase out input of production x_i: either the shadow price (e.g., of carbon), λ, converges to $\pm\infty$ [12] or the technological parameters ϵ_i (derived from Y_i) converges to zero. To achieve net zero emissions with a non-infinite carbon price, as represented in the sectoral roadmap, the technological parameters need to go to zero and this is what the hybridization process allows.

Changing the technological parameters only would imply that emission reductions happen "for free", which is not the case: the sectoral roadmaps have costs and benefits, and in particular large investment needs. To introduce investment needs reported by each sector, we assume that domestic savings will adjust to finance them. To do this, we set domestic investment levels to the sum of (i) the investment levels *in the baseline scenario;* and (ii) the *additional* investment needs reported by the sectoral analyses. As domestic investment is fixed, we allow savings to increase to ensure an investment-savings balance. This implies that the cost of the transition is passed on to consumers in the form of lower domestic consumption and higher domestic savings, both by households and firms. This necessarily means that returns to capital are lower as firms' savings increase and thus the amount of capital income transferred to households is reduced.

For the sector, the recalibration process and investment needs modeling take place as follows:

- **Power sector**: Taking the results derived from a least-cost modeling of the power system, the productivities of the different power generation activities are to be adjusted to reproduce the trajectory of the sectoral model. We introduce investment requirements into

[12] In such a case, price dynamics could diverge because of technological parameters in the price aggregator.

the model as an exogenous shock. The additional investment, relative to a baseline, is paid for by an increase in public and private savings which, in turn, reduces total consumption in the economy. However, we do not add all power sector investments to the capital stock to account for the fact that the low-carbon transition would require the earlier retirement of some fossil fuel power plants. We assume that only 75% of additional new investments needed to shift from the baseline to the RNZP would be added to the capital stock, with the 25% delivering only climate-related benefits.

- **Transport**: Taking the transport decarbonization trajectory shown in the RNZP scenario, we adjust the share of electricity and fossil fuels in total road transport sector energy demand and household consumption to reflect electrification of the sector. We also increase the energy efficiency of fossil fuel use in the transportation sector to reflect efficiency gains from fleet modernization and shifts to more efficient modes such as rail. Investment needs for the transition in the transportation sector are introduced into the model in the same way as the energy scenarios.
- **Buildings:** We follow the same approach as for transport in buildings. Until 2030, we only allow for the adjustment of energy efficiency gains in the service and household sectors to achieve the reported emission levels. After 2030, when electrification starts in the sector scenario, we adjust the share of electricity in intermediate demand in the service sectors and in household consumption. Investment demand is assumed to be primarily for the building sector. Unlike the power sector scenario, we assume that investment in the construction sector would only transform the building stock of the baseline and that, therefore, would not increase the capital stock or the productive capacity of the whole economy, compared with the baseline. (It means that we disregard gains in terms of comfort and health from more efficient buildings.)
- **Forest landscapes:** We increase the capacity of forests to sequester carbon, consistent with the findings of the forest landscape analysis. This is achieved by subsidizing the forest service sector that provides services for improved forest management. Therefore, unlike the other scenarios, the forestry scenario does not change investments but rather imposes the costs of the green transition through increased subsidies paid by the government. This is consistent with the sectoral analysis, in which the investment needs in the sector are relatively low at the macro level. In other words, in the CGE model, we assume that the carbon sequestration intensity of forests can be increased through better forest management, measured in the model as an increase in the supply of forest services from the existing capital stock in the forest sector.

In the macroeconomic simulations of the RNZP, we run the scenarios in two steps: First, we calibrate the model to replicate the results of the sectoral analysis; Second, we use these calibrated parameters in the general equilibrium framework (which will lead to slightly different results at the sectoral level, when macroeconomic effects, such as cross-sectoral effects, are considered). Table 1 presents the main channels of linkages between sectoral models and the CGE model. This is not a full integration of the sectoral scenarios with the general equilibrium simulations, in the sense that there is no two-way coupling: the sectoral scenarios are not modified in response to the outcome of the CGE. However, since the sector scenarios are technoeconomic roadmaps describing the evolution of the sector (without representing the behaviors and policies responsible for this evolution), this does not create inconsistency.

The results of the power sector model suggest a significant growth in renewables; hence we target the power mix from the power model results to calibrate the productivity of power activities by considering the investment costs for renewable expansion and early retirement of coal plants. For buildings, main drives are the electrification of heat demand and energy efficiency gains thanks to retrofitting so we change the energy efficiency and share parameters of the CES function for the energy nest in the production function of services sectors and power demand by households to match the share of fossil fuels in power demand suggested by the model for buildings. For transport, we change the share parameters of the energy nest to match the electrification suggested by the transport model and allow energy efficiency of transport sector to adjust achieve remaining reductions in emissions by the sector. For carbon sequestration, we assume that the increases would be due to better forest management which is part of the forestry sector in the CGE model. Hence, we target the sequestration suggested by the land use model and allow subsidies to the sector to adjust.

Sector	Storyline	Exogenous (i.e., change in CGE parameters informed by the sectoral scenarios)	Endogenous (i.e., changes in CGE parameters to match the sectoral scenarios)	Additional investments or costs to trigger the transition
Energy	Renewables grow	Power mix (from power model)	Productivity of power activities	Investment for renewables & early coal retirement
Buildings	Heat is electrified; energy efficiency improves	Share of fossil fuels in energy demand	Energy Efficiency	Investment for retrofitting
Transport	Transport is electrified; shift to public transport; railways	Electricity demand by transport	Energy efficiency and transport sector productivity	Investment in transport infrastructure
Land Use	Sequestration increases due to better forest management	Output of forest management activity	Subsidies to forest management activity	Subsidies
Other Sectors	Carbon saving technological change and CCS	Emission per unit of FF used/output produced decrease	Emission coefficients	Investment for technological change (USD40 per ton reduced)

Table 1: Main storyline assumptions

Not all emissions are considered by the sectoral techno-economic scenarios. Emissions from sectors not specifically modeled (agriculture, manufacturing, IPPU, waste and fugitives) account for about 40% of total emissions excluding LULUCF and are assumed to decrease by 68%-69% because of RNZP emission reductions. These emissions are therefore represented by the CGE model: for these emissions, reductions are triggered by an increase in the price of carbon, which provides an incentive to reduce emissions-intensive inputs (e.g., fossil fuels, fertilizers, etc.) and to invest more in emissions-reducing technologies. Reductions in emissions-intensive inputs are determined endogenously by increases in the relative prices of these inputs.

One challenge is to represent radical technological change in the sectors not covered by a sectoral scenario, especially in the industrial sector. For instance, hydrogen-based steel production is an emerging technology that is not expected to be commercially available at scale before 2030 but may allow emission reductions at a cost of \$38–\$77 tCO2e (Vogl and Nilsson 2018). Carbon capture usage and storage (CCUS) is expected to play the role of backstop technology. It has the potential to capture up to 99 percent of industrial process emissions at a cost of \$60–\$100 per tonne of CO2 equivalent (tCO2e) (Bataille 2019).

In the absence of a sectoral roadmap for the industrial sector, these technological changes are introduced in the CGE in a very simple way that will require further work. First, it is assumed that firms pay to reduce residual emissions further and achieve emissions reductions consistent with the RNZP. To do so, they pay an annual price equal to the level of the carbon price until this price reaches \$40/tCO2e. Beyond this price level, backstop technologies like CCUS become more attractive, but firms need to invest in these technologies. The investment needed to deploy these technologies is calculated based on the abatement cost per ton (here \$40/tCO2e), a capital lifetime of 20 years, and a nominal interest rate of 17% (the average key policy rate in Türkiye in 2018). Together these assumptions result in an investment needs equal to \$200 per annual ton reduced. Since the cost of these changes in technologies is highly uncertain, we also run a sensitivity analysis with a cost of \$120 per ton CO2e following (Bataille, 2019), which implies an investment need of \$600 to reduce annual emissions by one ton. Differences between the two scenarios are small, due to the relatively low amount of emissions in these sectors, and we only report here the results in the main scenario.

3.3 The implications of key model assumptions

Using the RNZP scenario assumptions, we run a set of scenarios to discuss the influence of macroeconomic assumptions and policy (labor market frictions and renewable energy subsidies) in unlocking the economic potential of RNZP as well as to address transition trade-offs (carbon taxes and crowding out) or co-benefits (linked to air pollution).

Labor market frictions: In its reference scenarios, the CGE model assumes an imperfect labor market with limited movement of labor between sectors. To explore the importance of this assumption, we run an additional scenario in which we assume perfect mobility. This simulation quantifies the impact of labor market frictions on the effectiveness of mitigation policies, the short-run welfare costs of the transition, and the importance of complementary policies to facilitate the transition of workers from declining sectors to the rest of the economy.

Renewable energy subsidies: The government subsidizes renewable energy production to hold electricity prices constant to explore the contribution of lower (or higher) electricity prices to growth. This additional simulation highlights the importance of electricity tariffs in the decarbonization transition, since it requires the electrification of most of the economy.

Crowding out: The amount of investment required for the transition is large and there is no guarantee that it will be fully financed by increased domestic savings. Also, it is interesting to separate in the macroeconomic implications what arises from changes in technologies (e.g., higher energy efficiency) and from macroeconomic shifts (e.g., increase in investment vs. consumption). Therefore, we perform a sensitivity analysis by changing the assumption on how the investments are financed. In the baseline scenario, we assume that the additional investments needed for the green transition are exogenous and financed by an increase in domestic savings. In this scenario, we assume that investments are endogenous and that savings rates are fixed. Therefore, sectoral investment needs would be financed by domestic savings to the extent that public and private savings increase. Since private savings are a function of household and business incomes, which do not increase significantly or even decrease relative to the baseline, investment increases only to the extent that public savings increase due to increased government revenues from the carbon tax. The remaining funding required for sectoral investments would come *at the expense of investments in other sectors* (e.g., investments in the electricity sector would reduce investments in other sectors, leading to a crowding out effect of public and private investments). This scenario represents a worst-case scenario in macroeconomic terms, where the decarbonization is done at the expense of economic-growth investments.

Air pollution 'co-benefits': A large literature suggests that reductions in air pollution increase labor productivity. We take this into account in the model by linking labor productivity to air pollution levels. The literature suggests that a 1 percent decrease in PM2.5 concentration would increase labor productivity by 0.3 percent (Jooste, Loch Temzelides, Sampi Bravo, & Dudu, 2022). In this scenario, we assume that this relationship is effective in both the baseline and the scenario. When mitigation policies reduce air pollution, labor productivity begins to increase relative to the baseline scenario. Note that the change in PM2.5 is estimated by the CGE, and not taken from the sectoral scenarios.

3.4 Results

Figure 5 shows that the RNZP scenario would contribute positively to Türkiye's economic growth compared with the baseline and in spite of the large investment needs, especially co-benefits are taken into account and if labor market frictions can be reduced.

Improved energy efficiency in the transportation and building sectors through the decarbonization scenarios drive the growth benefits in the short and medium term. The growth benefits of the transition are enhanced by considering the indirect benefits of reduced air pollution or the removal of friction in labor markets, making it easier for people in the most affected sectors to find employment in expanding sectors such as renewable energy. The growth benefits of the transition depend critically on how the investments needed for the transition are financed. If the investments needed to implement mitigation measures divert funds from other investments (i.e., crowd out investments in the rest of the economy), the benefits are significantly reduced in the short to medium term and can become negative in the long term.

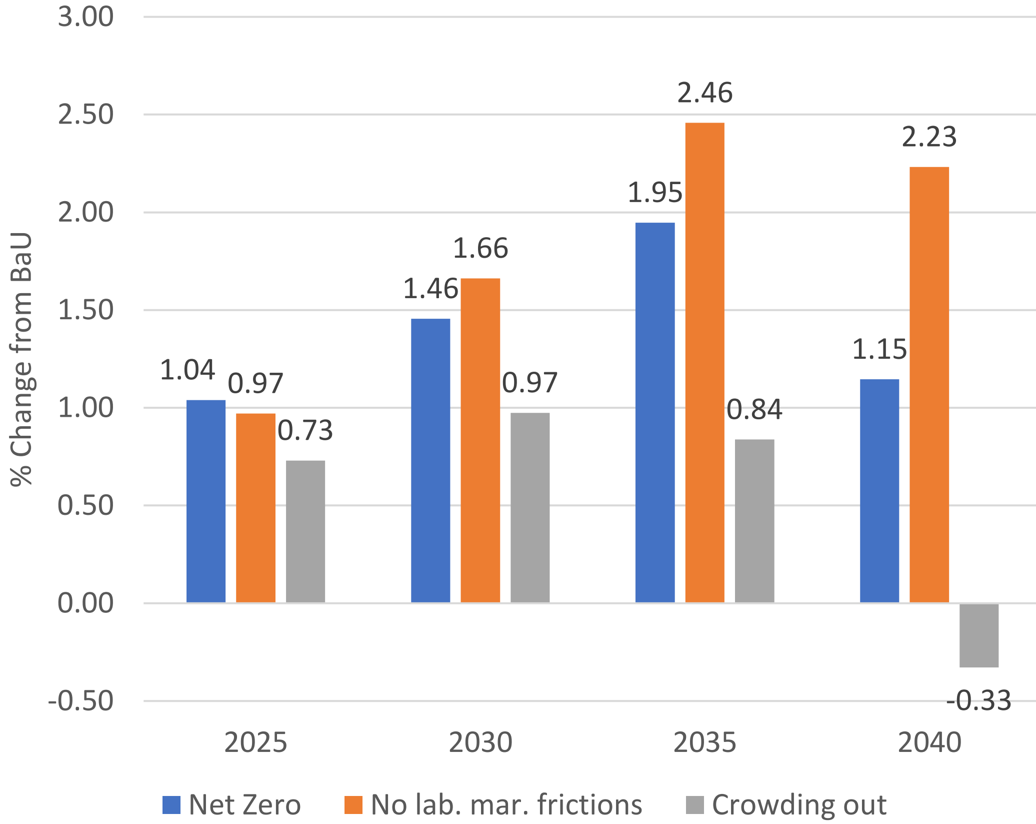


Figure 5: percentage point differences in GDP relative to the baseline

The negative impact on growth is primarily due to higher electricity prices. The increase in electricity price comes from (1) the decarbonization of the power system, which has no cost over the short-run, but becomes more costly when the share of renewable energy becomes very high, which requires expensive dispatchable non-carbon generation (here, gas with CCS) to maintain the system stability; (2) the large increase in electricity demand after 2030 (figure 6), due to electrification of buildings and transportation (with heat in building dominating). In the RNZP scenario, power demand would increase by 50% over the reference case in 2040, leading to a 20% increase in electricity prices. One magnifying factor in the price increase is the slow expansion of renewable energy, caused by labor market rigidities (e.g., skills mismatch, etc.). When these rigidities are removed, electricity prices fall even though demand is 76% higher than in the baseline scenario.

This finding can be generalized to all constraints on renewable energy expansion (e.g., ill-designed market regulations, financing issues, land market issues, etc.). For example, mobility of capital or others factor of production or structural factors such as ability of firms to substitute an intermediate input or factor of production as well as substitutability of different commodities with each other would be critical to determine the final impact. If capital is not fully mobile as assumed in our scenarios, that might prevent firms or consumers from changing their demand for specific commodities (e.g. fossil fuels) quickly enough to adapt to the new market conditions when the mitigation policies are started to be implemented.

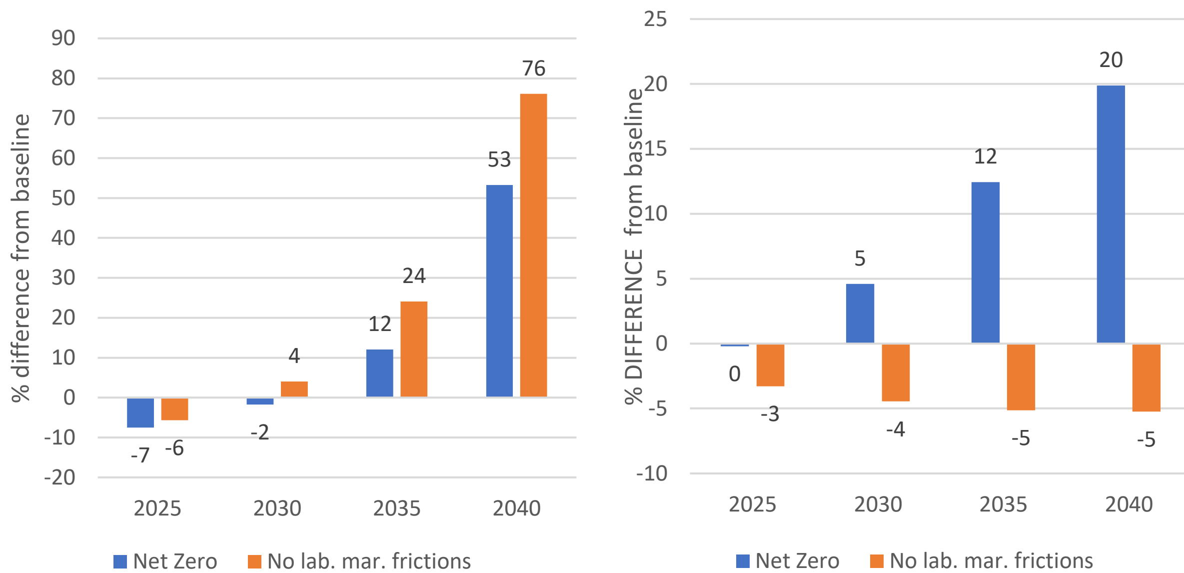


Figure 6: Electricity demand (left) and price (right)

The impact of higher electricity price is significant in all scenarios. The annual growth rate falls back to the baseline average of 4.5 percent or even below after 2037 when the demand for additional electrification increases (see figure 7). Thus, although GDP is higher in level compared to the reference case, the growth rate is lower as early as 2035 in some scenarios. Supply also contributes to fluctuations in electricity prices as the switch from fossil fuels to renewables occurs, filling the gap left by stranded fossil assets. Increasing the supply of low-carbon electricity by removing barriers to system expansion would mitigate inflationary pressure on prices. Our simulations show that labor market frictions and subsidies for renewable energy production support more robust economic growth, in particular through more affordable electricity. This result highlights the importance of well-designed electricity tariffs to protect the rest of the economy and facilitate its electrification.

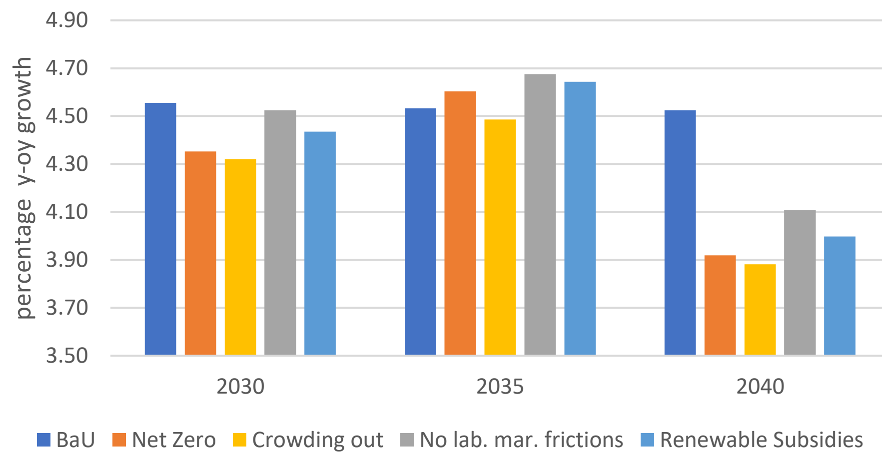


Figure 7: GDP growth rates

The transition would cause a shift in the structure of Türkiye's economy towards the services sectors. In our scenarios, the contribution of manufacturing, especially emission intensive manufacturing and non-power energy sectors, to the GDP would decline while that of services would grow in the short and medium term and stay slightly above the baseline levels by 2040. One reason is that the CGE production system has no option to fully decarbonize the industrial sector. This finding hints at a clear policy suggestion to focus on non-emission intensive high-tech sectors to boost industrialization in the country while focusing on emission saving technological change in other sectors. This result suggests that an important next step in the analysis would be to produce an additional sectoral scenario for the industrial sector, including a more granular representation of possible shifts toward low-carbon technologies based on green hydrogen, ammonia, or CCS. The impact of decarbonization on industrial production also depends on trade relationships, since the country competes with others in the production of carbon-intensive products (such as steal or fertilizers).

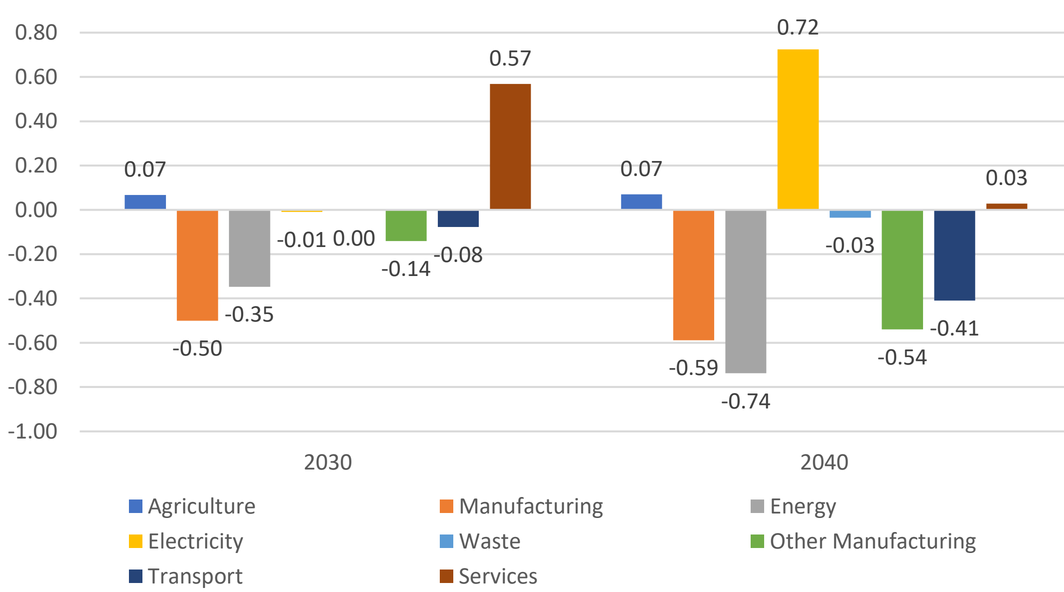


Figure 8: Change in contribution of sectors to GDP (pp difference from baseline scenario)

RNZP would increase and then reduce employment between 2022 and 2040 but would generate up to 70,000 jobs overall in cumulative net terms, primarily in the construction, agriculture, and renewable energy sectors, as well as in the upstream sectors that support them (see figure 9). Job gains are higher in the early years, reaching 270,000 jobs in 2037, before most of the job gains are partly offset by the downturn in economic activity (due to the higher electricity price). Construction jobs would increase significantly due to increased investment demand for the transition, as the building sector scenario includes major investment in retrofitting and new buildings. The increase in agricultural employment is due to the competitive advantage the sector gains by being exempt from the carbon tax.

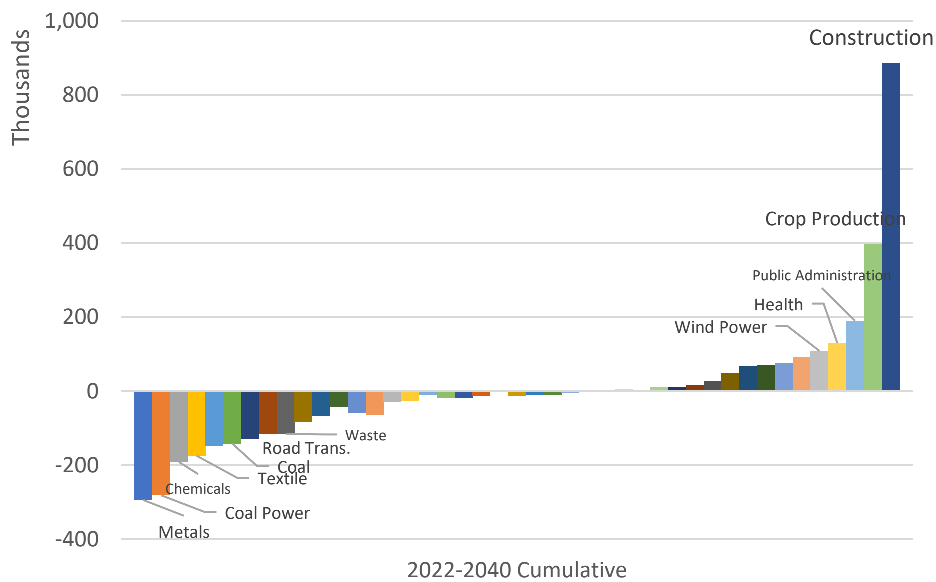


Figure 9: Cumulative net employment 2022-2040 of the RNZP scenario relative to baseline

While the transition will also put pressure on inflation as food and manufactured goods prices rise, service sector prices would fall (see figure 10). Services are generally less emissions intensive and the shift to electricity for transportation and heating protects them from the price impact of the carbon tax. However, this is not enough to offset the negative impact of the food and manufacturing sectors on the CPI. The increase is particularly present in the long run, as higher carbon prices begin to drive up supply-side costs, and higher electricity prices feed through to headline prices. However, these price increases remain moderate, especially compared with inflation in recent years in the country.

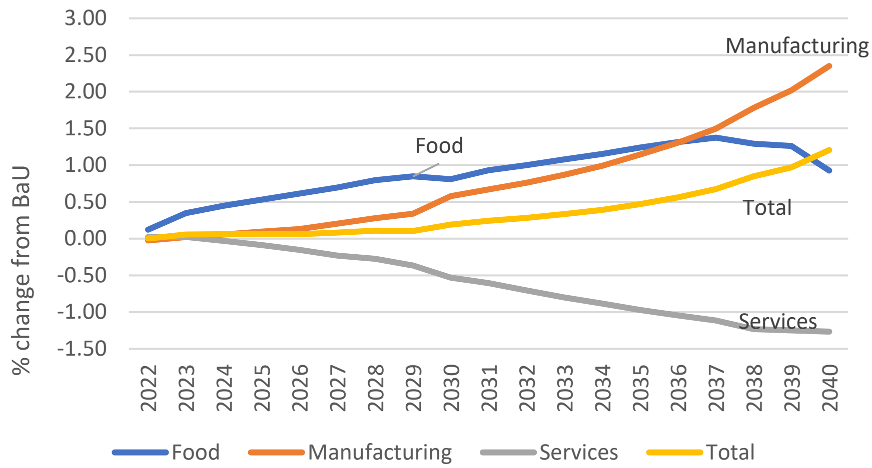


Figure 10: CPI by commodity groups of the RNZP relative to baseline

The impact of the green transition on government revenues depends primarily on the level of the carbon tax. Since liquid fuels are already heavily taxed and are a major source of revenue for the government, reducing fossil fuel use as part of the transition implies significant revenue losses. An adequate level of carbon tax could offset the revenue losses from liquid fuels. Although it would not achieve the net zero trajectory. A carbon tax of $211 in 2040 would generate revenue equivalent to 2.3 percent of GDP and thus provide more fiscal space to manage the transition and its negative effects, including job retraining or unemployment compensation.

The transition would be progressive in terms of household welfare.[13] When carbon tax revenues are used to stimulate investment and thus growth (see the net zero scenario in figure 11), poorer households would be better off due to increased employment and thus wage income, while richer households would be worse off due to lower returns to capital (as using the revenues for investment would stimulate the supply of capital and thus make it cheaper) and higher energy intensity of their consumption. In contrast, shifting carbon tax revenues to households through cash transfers would ease the transition until 2030s, but would reduce and eventually reverse the growth benefits, increase the return to capital, and thus have a regressive welfare impact by 2040. Hence, Türkiye needs to strike a balance between supporting growth in the long run by boosting investments and supporting households in the short run to avoid welfare losses. Carefully designed and targeted social protection programs are hence crucial for a just transition without harming growth.

[13] The welfare measure we use is equivalent variation, which is the amount of money that must be given or taken from a group of households to make them indifferent between the baseline and the scenario.

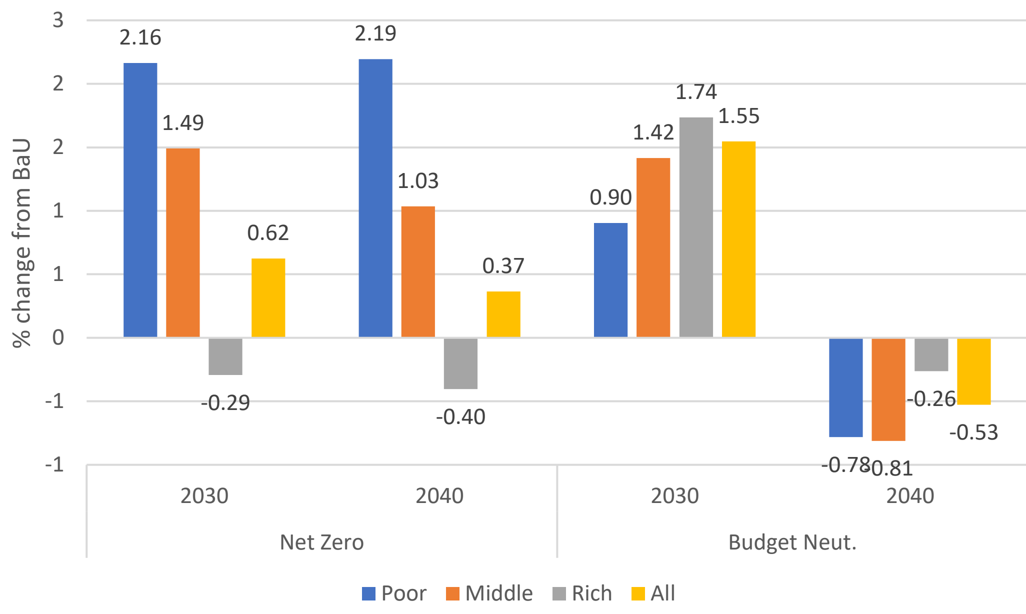


Figure 11: Welfare impacts

4 From sectoral to macro: A macrostructural approach

This section places the analysis at the aggregate level, focusing on the fiscal impact and including monetary dynamics. To do so, we complement the work with the CGE by focusing on these effects using the World Bank's macrostructural model MFMod, which has a more granular representation of monetary and fiscal issues.[14] The model assumes that households smooth their consumption paths in an optimal manner and that private investors use cost and return signals to allocate investment amounts. Monetary policy responds to deviations in inflation expectations from target inflation. The set of fiscal expenditure options include transfers to households, government compensation of employees, net acquisition of non-financial assets (investment) and use of goods and services. The model is an open economy characterization of Türkiye's economy.

4.1 Mechanics of hybridization and assumptions

To support Türkiye's growth and development objectives over the next two decades, the RNZP scenario's cumulative additional investments are of about USD 313 billion, while cumulative saving fuel expenditures amount to about US$182 billion (until 2040).

Based on the capital structure used in an application of MFMod to evaluate the macroeconomic risks from floods and earthquakes in Türkiye (Hallegatte, Jooste, & McIsaac, 2022), the model includes exogenously the additional investment needs from the sectoral scenarios, for the same four sectors (power, transport, building, and forestry).

For infrastructure capital (including buildings), we assume that 50 percent is funded by the government. The remaining 50 percent will be taken up by the private sector. This increase in

[14] See (Burns, Campagne, Jooste, Stephan, & Bui, 2019) and (Hallegatte, Jooste, & McIsaac, 2022).

private investment can be triggered in two different ways, which we examine through two scenarios:

- One scenario (TFP scenario) assumes the reforms and investments boost TFP relative to the baseline to incentivize more private investment. These reforms may not be costly, for instance if done through better rule of law, better institutions, investments in human capital, and improved market regulations.
- One scenario (Carbon tax incentive scenario) assumes specific fiscal incentives, in the form of carbon prices and subsidies for energy.
- Efficiency infrastructure investments, which would encourage private investments. These incentives may be neutral for public finances, combining taxes and subsidies. In our simulations, non-infrastructure investments by the private sector are crowded out. We also include fuel savings in the simulation, in addition to the market impacts determined in the model itself (see Appendix 2).

These two scenarios are extreme cases, and a realistic pathway would probably be an intermediate case.

4.2 Hybridization results

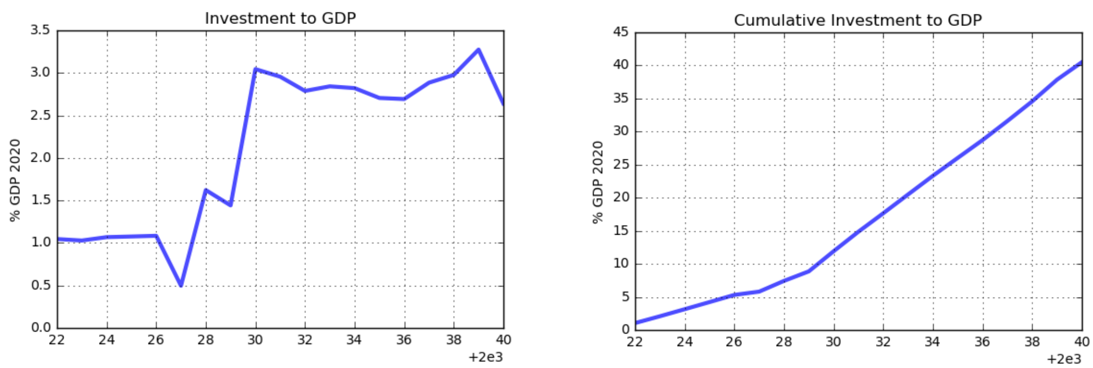


Figure 12: Annual and cumulative Investment needs relative to GDP

Figure 12 shows that, unsurprisingly, the TFP scenario significantly boosts GDP. While the overall capital stock from investment remains fixed, the TFP impact generates overall economic benefits by making existing factors of production more efficient. The TFP scenario presents a rapid increase in public debt (50% of infrastructure investments are financed by the government). The increase in public debt in this scenario starts from a low baseline in terms of debt-to-GDP, and the crowding-out effects are therefore smaller than they would have been if the debt-to-GDP ratio were high. The increase in TFP also lowers marginal costs, which reduces pressure on inflation (and hence on monetary policy). In this case, the fiscal space associated with lower marginal costs and more efficient public investment has strong economic spillovers. The increase in aggregate demand generates an increase in imports. The current account balance deteriorates accordingly. However, without the impact of fuel savings, the current account balance would have deteriorated further (counterfactual, right panel of figure 13).

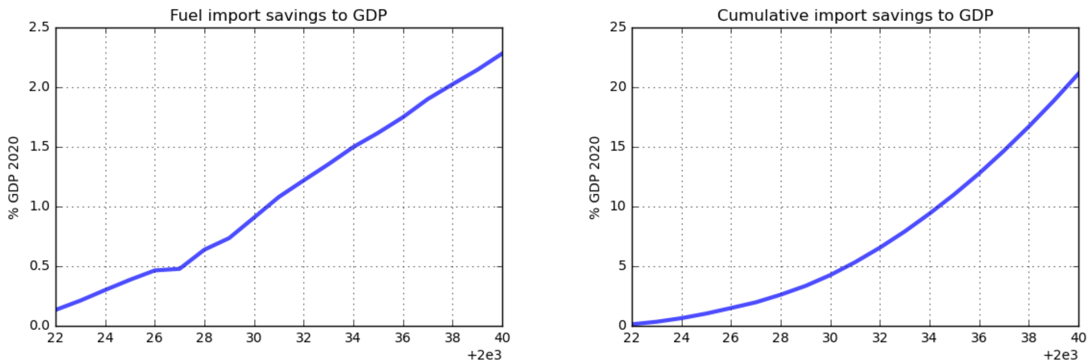


Figure 13: Annual and cumulative Fuel import savings relative to GDP

In the Carbon tax incentive scenario, the financing of the carbon tax subsidies goes through a different channel, and the benefits in terms of GDP are smaller, but still positive. The economic benefits in terms of GDP are small, as the carbon tax directly affects households at all levels. The carbon tax suppresses some aggregate demand, even though it leads to a reduction in emissions. The carbon tax is recycled through subsidies to the private sector to invest in the sectors identified in the RNZP sectoral roadmaps. The increase in investment offsets the losses to households from the tax. Debt still increases in this scenario, but primarily through government discretionary infrastructure spending. Combined with fuel savings, this scenario leads to a small current account surplus.

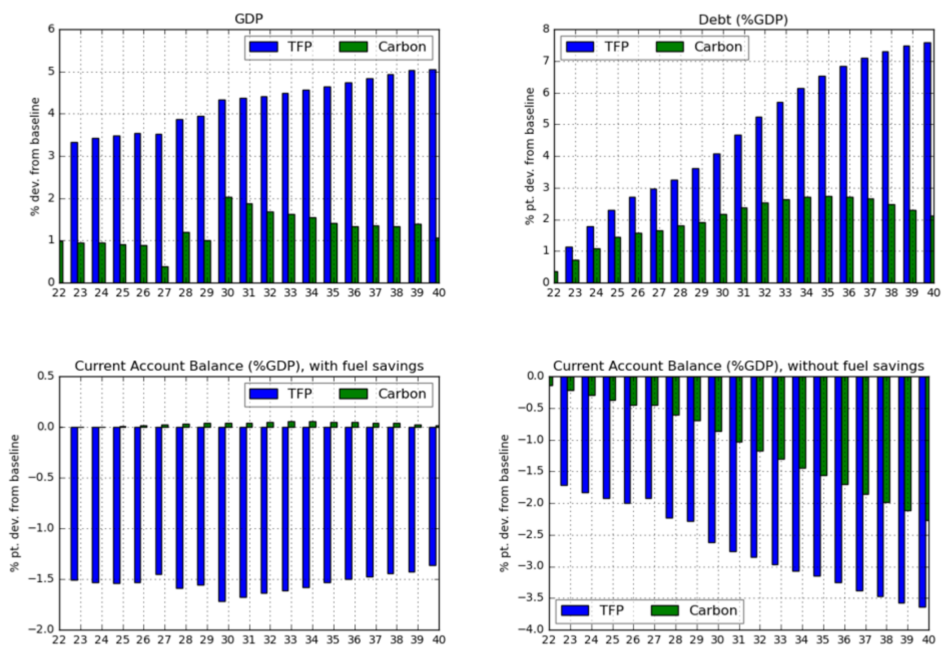


Figure 14: Simulation results

5 Conclusions and limitations

Using a set of illustrative resilient and net-zero sectoral scenarios, we showed two complementary ways to integrate these sectoral results into macroeconomic frameworks. First, by using a CGE model to analyze multi-sectoral interactions. Second, by using a macrostructural model to study aggregate output in macro terms.

This model design allows for a thorough discussion of macro assumptions, including rigidities implicit in the development context. We refrain from assuming an ex-ante optimal baseline (in the sense of intertemporal optimization) to which climate action can only add an additional constraint and thus deadweight costs. Instead, the use of technoeconomic sectoral scenarios allows us to include a non-optimal starting point (e.g., the existence of a potential for energy efficiency) and shift the discussion to economic rigidities that, once unlocked, could further stimulate economic activity in the context of decarbonization.

In an application to Türkiye, we find in the two frameworks that the decarbonization transition would increase GDP growth and employment, even without considering the benefits of avoided climate change impacts. These benefits arise mostly from energy efficiency, technology upgrades, and fuel cost reductions, and are magnified by the macroeconomic impact of additional investments. However, this growth benefit would be reduced if carbon pricing revenues are not recycled in a way that supports private sector investment and if additional investments in RNZP crowd out other investments. The benefits of growth are also significantly lower after 2035, as decarbonization of the electricity system gradually drives up electricity prices, leading to slower growth by 2040. This result highlights the importance of electricity tariffs, to make sure an economy that becomes fully electrified is not impaired by the added cost of system stability when the share of renewable energy becomes very high.[15]

While the additional investments needed are large, their overall impact on fiscal and external balances is relatively small. The analysis shows that the additional investments increase capital and related imports but are offset in the current account by savings on oil and gas imports. In addition, government debt levels increase by 1 to 3 percentage points of GDP relative to the baseline scenario, as government revenues from the carbon tax help offset borrowing for investment needs. This provides an indication of the room for maneuver available to the government if it chooses to save less and take on a larger share of the total investment needed in capital and innovation to support the transition. Macroeconomic stability is essential to preserve this fiscal space. In terms of the external balance, the negative effect of increased investment on the current account balance is offset by the reduction in oil and gas imports in the RNZP, relative to the baseline scenario. The reduction in oil and gas imports would also reduce exposure to energy supply and price volatility due to geopolitical risks.

The approach proposed in this paper combines the strengths of multiple modeling tools and maintains transparency in the processes driving the results. However, it does not capture all the possible significant feedback loops between the sectoral modeling and the macroeconomic framework. In the application to Türkiye, this approximation is acceptable since sectoral integration does not create a large macroeconomic deviation. In a more thorough analysis, the technoeconomic scenarios could be adjusted based on the new macroeconomic environment, and results passed on to the macroeconomic framework, but this iterative process was not considered necessary in this application.

[15] In our scenarios, this stability is ensured by gas with carbon capture and sequestration, even though options after 2035 may include other solutions, including green hydrogen or pumped hydropower.

6 References

Amann, J., Nicola, C., Calí, M., Todorov, V., & Cheng, C. F. (2021). Switching it up: The effect of energy price reforms in Oman. *World Development, 142*, 105252,.

Ambec, S., Cohen, M. A., Elgie, S., & Lanoie, P. (2013). The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Review of Environmental Economics and Policy, 7*(1), 2-22.

Bataille, C. (2019). Physical and policy pathways to net-zero emissions industry. *Wiley Interdisciplinary Reviews: Climate Change, 12*(1).

Battiston, S., Mandel, A., Schutze, F., & Visentin, G. (2017). A climate stress-test of the financial system. *Nature Climate Change, 4*, 283-288.

Burns, A., Campagne, B., Jooste, C., Stephan, D., & Bui, T. (2019). The World Bank MacroFiscal Model Technical Description. *olicy Research Working Paper; No. 8965. World Bank, Washington, DC.*

Calì, M., Cantore, N., Iacovone, L., Pereira-López, M., & Presidente, G. (2022). Too much energy The perverse effect of low fuel prices on firms. *Journal of Environmental Economics and Management, 111*, 102587.

CCDR. (2022). *Country Climate and Development Report for Türkiye.* Washington, D.C.: World Bank.

Chattopadhyay, D., de Sisternes, F., & Oguah, S. K. (2018). World Bank Electricity Planning Model (EPM): Mathematical Formulation World. *ESMAP*.

Guivarch, C., Crassous, R., Sassi, O., & Hallegatte, S. (2011). The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy, 1*, 768-788.

Hallegatte, S., Heal, G., Fay, M., & Treguer, D. (2012). FROM GROWTH TO GREEN GROWTH - A FRAMEWORK. *NBER WORKING PAPER SERIES*.

Hallegatte, S., Jooste, C., & McIsaac, F. (2022). Macroeconomic Consequences of Natural Disasters : A Modeling Proposal and Application to Floods and Earthquakes in Turkey. *Policy Research Working Papers*.

Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). *Lifelines: The resilient infrastructure opportunity.* Washington, D.C,: World Bank Publications.

Hertel, T. (2001). Notes on Final Demand in the Presence of Non-homothetic, Weak Separability. *GTAP lecture note.* West Lafayette: Purdue University.

IMF. (2022). *World Economic Outlook Countering the Cost-of-Living Crisis.* Washington, D.C.: International Monetary Fund.

Jooste, C., Loch Temzelides, T. P., Sampi Bravo, J. R., & Dudu, H. (2022). Polution and Labor Productivity: Evidence from Chilean Cities. *Policy Research Working Paper Series 10236*.

Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., . . . Wagner, F. (2021). Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. *Environmental Research Letters, 5*(16), 053006.

Lipsey, R., & Lancaster, K. (1956). The general theory of second best. *The Review of Economic Studies, 24*(1), 11-32.

NGFS. (2021). Annual report.

Nordhaus, W. D. (1992). An Optimal Transition Path for Controlling Greenhouse Gases. *Science, 258*(5086), 1315-1319.

OECD. (2017). *Investing in Climate, Investing in Growth, A synthesis.* Paris, France: OECD.

Pindyck, R. (2013, September). Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature, 51*(3), 860-72.

Stern, N., Stiglitz, J., & Taylor, C. (2022). he economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change. *ournal of Economic Methodology, 29:3*, 181-216.

The New Climate Economy. (2018). *UNLOCKING THE INCLUSIVE GROWTH STORY OF THE 21ST CENTURY: ACCELERATING CLIMATE ACTION.* Washington, D.C.: The New Climate Economy.

van der Mensbrugghe, D. (2020). The Mitigation, Adapation and New Technologies Applied General Equilibrium (MANAGE) Model, Version 2.0g. *GTAP Technical Paper, TP/20/xx. Center for Global Trade Analysis, Purdue University West Lafayette, IN*.

van der Ploeg, F., & Rezai, A. (2020). The risk of policy tipping and stranded carbon assets. *Journal of Environmental Economics and Management, 100*(C).

7 Appendix

1 CGE Model additional feature

The model consists of a ten representative household types according to income deciles. Households are the owners of factors of production. They supply labor depending on the real wages: higher wages induce more labor supply. That means we ignore the wealth effect on labor supply which would require reducing the labor supply for very high levels of real wage rate. Income sources other than factor income for households are income and transfers from government and rest of the world. Households spend their income on consumption, savings and direct taxes. The distribution of consumption across commodities is determined by a two-level utility function. At the first level, a Constant Difference in Elasticities (CDE) utility function determines the consumption of aggregated commodities. The use of CDE allows better representation of income effects on household demand by allowing consumption shares to change as income and prices change (Hertel, 2001) unlike other functional forms like Linear Expenditure System (LES) or CES demand functions which assume that expenditure shares are independent from the household income and are constant. The aggregate groups are food, manufacturing, energy, services and transport. So, the first level utility function distributes household consumption spending across those broader categories. Then a second level CES nest distributes the spending on each aggregate consumption among commodities in that group. For example, energy group consists of coal, refined petroleum, coke, electricity, and natural gas.

Government does not have a behavioral assumption and is completely neutral. It collects taxes, receives transfers from rest of the world and domestic agents and then spends them on saving, government consumption and investment, transfers to rest of the world. Government can borrow from domestic institutions or from rest of the world but must pay interest on debt in following periods. All tax rates are fixed at base year levels. The volumes of government current and investment spending are also fixed. This implies that government savings (primary balance) is endogenous and adjust to clear the government balance. The gap between government investment demand and public saving is satisfied through foreign and domestic borrowing. Alternative government closures can be considered for the simulations of fiscal reforms. For example, there can be a target for the government budget balance and a 'swing' fiscal instrument, such as personal income taxes, adjusts to achieve the target.

Rest of the world (ROW) exports from and imports to Türkiye according to CET and Armington specification respectively.[16] Both specifications assume that domestic commodities are not perfect substitutes with traded commodities. Thus, imports and exports are determined based on the difference between domestic prices and world prices which are assumed to be fixed in line the small open economy assumption. ROW also makes transfers to domestic agents and receives transfers from them. These transfers are assumed to be constant share of GDP. Last, ROW account

[16] This model considers only one trade partner, the Rest of the World. However, the model code is flexible enough so that additional trading partners can be added in a two-level nested structure.

invests in Türkiye, which corresponds to F/X flows for investment purposes (e.g., FDI, short term capital movements etc.).

The model follows a savings-driven closure where aggregate investment is flexible and equals the available volume of saving. Foreign saving is exogenous and fixed as a share of GDP, while government and household savings are endogenous. In effect, the rate of return on capital adjusts to equalize investment to the saving. Hence, the model has the crowding out effect where government investment displaces private investment.

The model dynamics follows the neo-classical growth framework (Solow-Swan growth model) implying that the long-run growth rate of the economy is determined by three main factors: capital accumulation, labor supply growth, and increases in productivity. The stock of capital is endogenous, while the latter two are exogenously determined. The capital stock in each period is the sum of depreciated capital from the previous period and new investments. For each type of labor, the maximum stock of labor available in each period grows exogenously based on population projections by age cohort and cohort-specific participation rates. The technical progress specific to sector and production factors are calibrated to replicate the GDP growth in the baseline and equals that calibrated level in simulations.

On the data side, the model is calibrated to replicate the 2018 Social Accounting Matrix (SAM) for Türkiye, which consists of the 2018 macro-aggregates, the 2012 Input-Output (I-O) table, and household surveys. It includes 38 sectors and products, 6 factors of production, and 10 types of households by income deciles. The SAM also distinguishes between public and private investment demand and includes seven electricity activities that produce a homogeneous electricity product: coal, gas, nuclear, hydropower, wind, solar and other. The single electricity sector in the original I-O table is divided based on the GTAP electricity database with ad-hoc adjustments for the Turkish electricity balance tables. Nuclear power is introduced with a small share in electricity supply based on the average cost structure of nuclear power activities in the GTAP power database.

2 MFMOD additional feature

The World Bank's macrostructural model, MFMod is used in quantifying the economy-wide impacts of the energy efficient infrastructure investment. The customized standalone model for Türkiye extends the investment channels along the several dimensions. (1) Capital stock is differentiated by public and private contributions and (2) capital stock is differentiated between infrastructure and non-infrastructure capital,[17] and (3) the time horizon is extended to 2040.

In the model, investment decisions are based on the difference between returns and the cost of capital. Specifically, the dynamic investment equation is a function of past investment decisions (to reflect the "sticky" nature of asset decisions) and the marginal Tobin's Q ratio, which reflects the return vs. the cost of capital. In the long-run, the investment to capital ratio is a function of long-run economic growth plus the rate of capital depreciation. The private sector infrastructure equation is written as:

[17] In (Hallegatte, Jooste, & McIsaac, 2022), they use a modified version of the model to explore the vulnerability to floods and earthquakes. http://hdl.handle.net/10986/37060

$$\frac{I_t}{K_{t-1}} = \beta \frac{I_{t-1}}{K_{t-2}} + (1-\beta)\left[\frac{\Delta \ln(A_t)}{\alpha} + \Delta \ln(WPOP_t) + \delta_t\right] + \gamma\left(\frac{MPK_t}{UCC_t}\right) + \varepsilon_t$$

The investment-to-capital ratio $\left(\frac{I_t}{K_{t-1}}\right)$ is a function of previous investment decisions. In the long-run this ratio converges to long-term growth (TFP adjusted for the labor share in income plus growth in working-age population) and the capital depreciation rate. In the short-run, investments increase if the marginal product of capital (MPK_t) is higher than the cost of capital (UCC_t). The error term is independent and identically distributed ($\varepsilon_t \sim i.i.d$). Thus, any measure that raises expected growth in the long run will generate higher investment. The real cost of capital is a function of the short-term interest rate (proxied by the average interest rate on government debt (r_t^B)) and adjusted for corporate income taxes (τ_t^{CIT}):

$$UCC_t = \frac{P_t^I}{P_t^Y}\left(\frac{r_t^B + \delta - E_t\pi_t}{1-\tau_t^{CIT}}\right)$$

While public sector choices in the model are discretionary, private investment choices are behavioral based on firm-level optimization. As a result, there are multiple ways of representing the increase in the private sector investments, and the policies or public interventions in place to incentivize those investments. Here, to explore the implication of higher investments, two scenarios are used with different (and contrasted) assumptions on how the private sector incentives generate the investment amounts:

1. **TFP Scenario.** An increase in total factor productivity (A) from FDI flows and investment climate reforms (these are taken as a given). In the TFP scenario, an improvement in productivity in infrastructure will generate the necessary investment amounts required to reduce emissions. The TFP boost need not come at an economic cost (i.e., better rule or law, better institutions, a reduction in entry barriers are not always expensive), even though it may also include investments. This efficiency boost will also lower marginal costs, which benefit producers directly, but also consumers through lower end-user prices. Higher aggregate demand (from investment, lower costs) will increase imports. However, note that this import rise is offset by a reduction in fuel imports due to the "efficiency" factor of the new investments.

2. **Fiscal incentive scenario.** Government transfers to the private sector, where transfers are financed by raising additional revenues through a carbon tax calibrated on the CGE simulations presented in the first section of this paper. The economic transmission mechanisms are different in the case of raising funds via a carbon tax and then transferring those revenues as a subsidy to the private sector. The carbon tax drives a wedge between fossil fuel and renewable energy demand. It is assumed that the carbon price is passed onto the end-user, which implies a rise in aggregate prices in the short run. The government collects revenues from the carbon, which is then transferred to the private sector via a subsidy in energy efficiency infrastructure investment. The subsidy lowers the cost of capital for this type of investment relative to the return to capital.

Another important assumption concerns the productivity of the new investment. The question is whether the investments necessary for the RNZP are producing economic value in addition to emissions reductions, or only emissions reductions. Some of these investments are additional because they correspond to an additional cost to produce the same service. For instance, buildings can be more expensive because of electrified heat and better insulation. But at the same time, these investments have significant benefits beyond emission reductions and energy efficiency. In the building example, better insulated buildings tend to be more comfortable, provide better health (because of better ventilation and less indoor pollution), and in the case of the Türkiye RNZP, the investments also allow for higher resilience to heat waves and earthquakes.

To provide the most conservative estimates, the simulations in this note assume that these investments provide energy efficiency gains, but do not generate new capital stock, but rather reflects adjustments to the existing stock of capital. In other words, all co-benefits are ignored, except energy efficiency. In the model, to ensure that capital stock does not rise, the infrastructure investment is offset by reducing non-infrastructure capital investment (for both public and private investment). However, the efficiency component of capital should also be considered when analyzing the output responses of this investment. The economic production function is a Cobb-Douglas technology:

$$Y_t = A_t F(N_t, u_t^K K_{t-1})$$

While the efficient investment spending does not add to the existing stock of capital (K_t), it does modify its efficiency (u_t^K), and hence may increase output in the medium to long run horizon. Furthermore, second round effects will imply changes to both factor prices, which will have implications for labor too. To reflect the crowding out effect (for capital to remain constant) requires an increase in the cost of capital for other types of investments.