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Mitigating foreign fossil fuel shocks: The role of renewable energy and industrial electrification in The Netherlands☆

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ABSTRACT

Recent disruptions in foreign fossil fuel supply have significantly increased the price of imported gas across Europe. From a long-term policy perspective, it is essential to explore strategies to reduce an economy's exposure to such shocks. Focusing on The Netherlands, we use a computable general equilibrium model with a detailed energy matrix to quantify the potential impact of foreign gas supply disruptions at different stages of the energy transition. Our results indicate that expanding renewable energy capacity and electrifying industries reduce the economic impact of foreign gas supply shocks. Furthermore, encouraging investments that decrease industrial energy consumption can both mitigate the short-term effects of fossil fuel supply disruptions and accelerate the economy's shift away from energy dependence.

1. Introduction

European economies have recently experienced a severe fossil energy supply shock, exposing their vulnerability to fluctuations in foreign fossil fuel output. The Russian invasion of Ukraine led to an estimated 80% reduction in Russian gas exports to the European Union (EU) in 2022 (Zettelmeyer et al., 2022). The full economic aftermath of this shock to foreign fossil supply is still unfolding. The full economic consequences of this foreign fossil fuel supply shock are still unfolding. The anticipated effects of this disruption on household budgets, business production costs, and overall economic activity prompted European governments to take immediate countermeasures. These included direct interventions in domestic energy markets, reductions in energy taxes, and securing alternative sources of gas supply (European Commission, 2022a,b). Beyond these short-term responses, the EU developed the long-term REPowerEU plan, a set of policies designed to reduce the EU's dependence on Russian fossil fuels while accelerating the energy transition through increased investment in renewables (European Commission, 2022a).

This paper examines this long-term policy perspective in which reducing reliance on foreign fossil fuel supply and integrating renewables are pursued as simultaneous objectives. In doing so, we conduct a quantitative macroeconomic assessment that accounts for several factors influencing an economy's exposure to foreign fossil fuel supply shocks. These factors include the economy's dependence on foreign fossil fuel supply and the sectoral composition of the economy, particularly the significance of energy-intensive industries and their links to other sectors. Also included is the capacity of different sectors to substitute away from fossil fuels and the degree of electrification and the structure of the electricity mix.

Using the Netherlands as a case study, we analyze how these four factors interact in shaping the economic consequences of a foreign fossil fuel supply shock at various stages of the energy transition. This case is particularly relevant for exploring the interplay between fossil fuel supply shocks and the ongoing energy transition. The Netherlands is committed to rapidly shifting away from fossil fuels; however, its economy remains heavily dependent on them, in part due to the concentration of energy-intensive industries (IEA, 2020). The Dutch economy still relies on gas as the primary source of both energy and electricity production (PBL, 2021). See Fig. 10 in Appendix B.1 for more information. Additionally, the Dutch government has implemented policies to drastically reduce domestic gas production, in line with its goal to entirely cease production from the Groningen gas field

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by 2024 (Ministry of Climate Policy and Green Growth, 2023). As a result, the economy has become even more reliant on foreign fossil fuel supply in the short-term.

To capture the dynamics of the Dutch energy transition, we integrate projected energy demand and production trajectories from the Climate and Energy Outlook of the Netherlands (KEV) (PBL, 2021) with the ADAPT emission reduction scenario from the OPERA energy system model of the Netherlands (Scheepers et al., 2022). The ADAPT scenario is aligned with the Dutch government's greenhouse gas (GHG) emission reduction targets, aiming for net carbon neutrality by 2050. This scenario provides a highly detailed breakdown of energy demand and supply using a bottom-up approach in which the energy system optimizes production to meet specified emissions targets. We calibrate the macroeconomic model's baseline scenario to reflect the expected energy supply and demand outlined in the KEV and ADAPT projections.

Our paper builds upon a long-established body of literature examining the macroeconomic effects of energy shocks and the role of policy in mitigating their impact (e.g., Eastwood 1992, Hamilton 1983, Hickman 1987, Liu et al. 2015).[1] We contribute to the growing research on the potential consequences of a Russian gas shutoff, including the study by Bachmann et al. (2024), which applies the Baqaee–Fahri approach to quantify the macroeconomic impact of such shocks (Baqaee and Farhi, 2024). Bachmann et al. predicted that a halt in Russian energy imports to Germany would lead to moderate aggregate effects, with gross national expenditure declining by less than 1%. Using a similar framework, Albrizio et al. (2022) found that access to the global liquid natural gas (LNG) market dampens the shock's effects. Specifically, they estimated that the gross national expenditure in the EU would decline by 0.4% if the EU maintained access to international LNG markets; otherwise, the reduction would be 2.5%. Lan et al. (2022) further contributed by examining the lagged negative effects of increased uncertainty, in addition to the direct impact of the shock on reduced production of final and intermediate goods. They estimated that the shock would lower Germany's gross domestic product (GDP) by 1.5% in 2022 and 2.7% in 2023.

Other relevant studies include Di Bella et al. (2024), which used a partial equilibrium framework to assess the aggregate effects of the gas supply shock on EU countries. Their findings indicated varying country-level impacts, with Central and Eastern European nations being the most vulnerable, potentially experiencing GDP declines of up to 6%. The study also found that the Dutch economy is less affected, largely due to its access to alternatives (e.g., LNG imports and alternative pipeline infrastructures). The Organization for Economic Co-operation and Development (OECD, 2022) recently employed a macroeconomic simulation of a multiregion global economy to evaluate the broader effects of commodity price shocks stemming from the Russia–Ukraine war, estimating a GDP decline of approximately 1% in the Euro area. Turco et al. (2023) showed that this contraction could increase fourfold in the absence of macrostabilization policies.

Beyond the aggregate perspective, several studies have focused on sectoral impacts. One assessed the changes in gross output across various sectors resulting from a 20% reduction in direct and indirect imported energy inputs in the EU (OECD, 2022). The most significant declines in nonenergy sectors can be observed in the basic metals (−2.8%), transport (−2.8% to −1.5%), and the chemical sectors (−2.2%). Hutter and Weber (2023) conducted an empirical study using panel data from the German manufacturing sector, emphasizing the role of energy intensity. They found that the onset of the Russia–Ukraine war triggered a sharper contraction in sectors with higher energy intensities. Khudaykulova et al. (2022) contributed to this sectoral analysis from a global perspective, demonstrating that the shipping, motor, and chemical industries are particularly vulnerable to the inflationary pressures caused by the international conflict,[2].

Our paper contributes to this literature in two ways. First, rather than assessing the impact of fossil energy supply shocks under a fixed energy mix, we quantify both aggregate and sectoral effects at different stages of the energy transition during which the electricity and overall energy mix of the economy undergo significant changes. This is achieved by integrating a detailed energy transition scenario into the baseline model calibration. The scenario incorporates various elements of the transition, including industrial electrification and the evolution of the electricity mix. Second, beyond analyzing the immediate effects of a shock to foreign gas prices, we also account for the fact that as gas imports from Russia are partially replaced with more expensive alternatives, the price of imported gas remains relatively high after the shock.[3] This allows us to capture the reconfiguration of gas imports in the aftermath of the disruption and examine how this process interacts with the broader forces driving the energy transition.

For the short-term impact of the shock to imported gas prices, our findings align with the existing literature. Consistent with Di Bella et al. (2024), we observe a moderate effect of the shock at the aggregate level. From a sectoral perspective, the most energy-intensive industrial sectors experience a gradual contraction in output of approximately 2% relative to the baseline. Beyond these general findings, three specific results emerge from the distinct aspects of our analysis. First, compared with 2022, a shock to imported gas prices occurring at a later stage of the energy transition has a moderated effect on energy demand patterns and sectoral economic activity. This reflects the declining importance of gas as an energy source for households and productive sectors. In our analysis, this reduced reliance on gas is primarily driven by the energy transition, which prescribes a lower share of gas in the overall energy mix due to the expansion of renewable energy capacity and the electrification of nonenergy sectors. As a result, these sectors decrease their relative use of gas as a primary energy source.

Second, the reduced dependence on imported gas is further reinforced by the fact that gas prices do not return to preshock levels, which in turn accelerates capital accumulation in nonenergy sectors and lowers energy intensity. That is, the 2022 shock leads to a long-term decline in the energy intensity of productive sectors and accelerates the economy's transition away from gas.

Third, the response to imported gas price shocks vary across sectors. Specifically, we find that for the most energy-intensive industries, the shock results in a relatively greater contraction in output. This is because short-term substitution of gas with electricity is both difficult and limited in scope due to the comovement of electricity and gas prices. Additionally, reducing sectoral energy intensity requires capital investment, which takes time to accrue. Capital accumulation is a slow process, constrained by the availability of investment goods, and productive sectors cannot immediately scale up their use of capital. The gradual pace of capital accumulation, combined with the limited short-term substitutability between gas and electricity, leaves energy-intensive sectors particularly vulnerable to foreign fossil fuel supply shocks in the short-term.

Taken together, our results have two key implications. First, they support the conclusion that, from a long-term perspective, transitioning away from fossil fuels provides additional economic benefits by reducing exposure to foreign fossil fuel supply shocks. Second, they focus on the importance of facilitating energy-saving investments, particularly in

[1] See Brown and Yücel (2002) and Kilian (2008) for an overview of the literature.

[2] Shifting the focus to households, Zhang et al. (2023) among others, analyze the uneven distribution of the effects of an energy price shock on different income groups and regions in the world.

[3] Europe's Russian gas imports have been largely substituted by LNG imports from other countries (European Council, 2024), which has led to reduction in prices from the 2022 peak, yet imported gas prices still remain higher than the preshock level (International Monetary Fund, 2024).

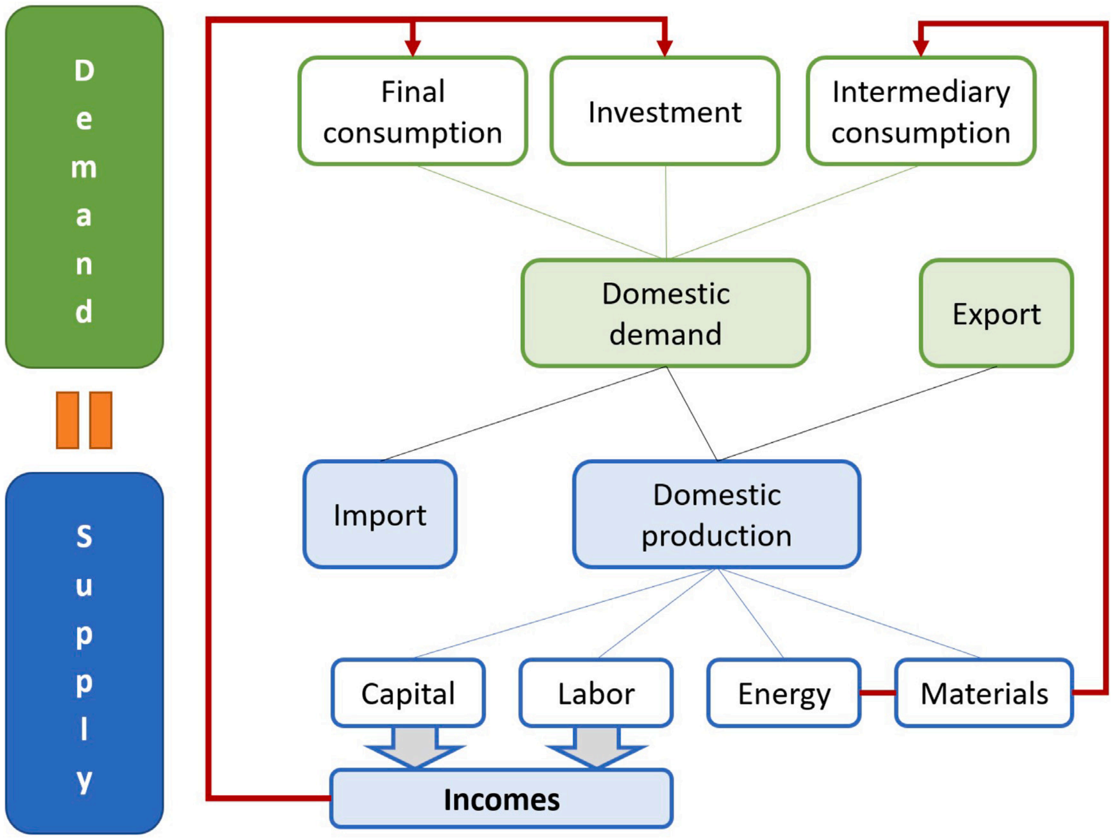


Fig. 1. Computable general equilibrium model architecture.

energy-intensive sectors, as a near-term strategy to decouple domestic economic activity from foreign gas supply.

This paper is organized into four sections, including this introduction. Section 2 describes the macroeconomic model used for the analysis, the energy system model, the procedure for linking and calibrating the baseline energy transition in the macroeconomic model, and the scenarios analyzed. Section 3 presents the results, comparing baseline outcomes with those under alternative foreign gas supply scenarios. Lastly, Section 4 provides concluding remarks, policy implications, and recommendations for future research.

2. Methodology

Our analysis examines the combined effect of foreign gas price shocks and the energy transition at the macroeconomic level. To achieve this, we use a dynamic CGE framework calibrated to represent a technoeconomically plausible energy transition path for the Netherlands as a baseline. We then introduce alternative imported gas price trajectories as separate scenarios to assess how different characteristics of a foreign gas supply shock (e.g., timing and persistence) influence the domestic economy's response. As detailed below, our framework consists of four main components as follows: a macroeconomic model, inputs for calibrating the energy transition in the baseline scenario, a calibration procedure, and imported gas price scenarios.

2.1. Macroeconomic model

Our analysis is based on the ThreeME CGE model, an open-source macroeconomic model developed by Reynès et al. (2021). The general structure of a CGE model is illustrated in Fig. 1.

ThreeME represents a small open economy with a neo-Keynesian closure.[4] Under this closure, price stickiness (i.e., prices that do not adjust immediately) prevents the economy from reaching a new market-clearing equilibrium right away. As a result, shocks can temporarily push the economy into a state where market outcomes are suboptimal. During the adjustment process, gaps between supply and demand (e.g., unemployment) may emerge. The gradual economic adjustment characteristic of a Keynesian closure can be attributed to behavioral biases or adjustment costs. This feature makes ThreeME particularly suitable for analyzing the combined effects of gas price shocks and energy transition policies on the economy.

Unlike a Walrasian CGE model, which expresses all prices in real terms relative to a numéraire and does not model inflation, ThreeME does not include a numéraire. Instead, it follows a neo-Keynesian closure, where each price has its own inflationary dynamic. However, inflation is primarily driven by the interaction between nominal wages and nominal prices, a mechanism often referred to as the wage–price loop. This interaction is modeled using a wage setting–price setting (WS–PS) framework, the standard approach in neo-Keynesian models.

The model represents a small open economy and requires a national social accounting matrix (SAM) as input. For this analysis, we use a SAM of the Netherlands that includes a detailed description of energy production. In this SAM, the economy is divided into 11 nonenergy sectors and 16 energy sectors. These sectors produce 22 commodities as follows: 11 nonenergy commodities and 11 energy commodities. A complete list of sectors and commodities is provided in Table A.1 of the Appendix.[5]

[4] See Reynès et al. (2021) for a detailed description of ThreeME, and Fattahi et al. (2023) for a two-way linking assessment between top-down model ThreeME and a bottom-up energy system model. Relatedly, Boonman et al. (2024) develop a linking exercise between two macroeconomic models (EXIOMOD and REMES-EU) and an energy system model (GENeSYS-MOD).

2.1.1. Production

The total production of each of these 27 sectors is modeled using a capital–labor–energy–materials production function, where sectors utilize capital (K), labor (L), energy (E), and materials (M) as factors of production. This function determines the required inputs for each sector, and the intrasectoral production structure follows a four-layer nesting approach, as shown in Fig. 2. Each layer is characterized by an elasticity of substitution, σ, which determines whether the intervening inputs function as complements or substitutes and to what extent.[6] The inclusion of materials in the model accounts for intersectoral dependencies, which act as channels through which shocks propagate.

At the highest level, perfect complementarity is assumed between a sector's demand for materials and its expenditures on capital–energy–labor, meaning the elasticity of substitution is set to zero. The second and third levels establish that energy can be substituted with capital more easily than with labor. The fourth level (i.e., energy nest) sets the elasticity of substitution between different energy sources at a relatively low value. This indicates that shifting from one energy carrier to another is costly.[7]

The production structure of the model provides insight into the various interacting elements that determine the sectoral response to higher gas prices, and underscores the importance of a quantitative assessment to understand the effects of the shock to foreign gas prices. For example, the impact of such a shock on sectoral outcomes will depend, among other things, on: (i) how costly it is to substitute gas with electricity, which relates to the elasticity of substitution in the energy nest; (ii) the incentives to substitute gas with electricity, which depends on how much do electricity prices react to gas prices, and this is in turn determined by the production structure of the electricity producing sectors; (iii) how quickly capital accumulation can reduce the energy intensity of sectors; and, (iv) how non-energy-intensive industries respond to higher gas prices, and what this implies for the overall demand of factors of production and energy in the economy.

2.1.2. Households

The representative household in this economy consumes 11 nonenergy commodities and 11 energy commodities, including electricity and heat. We assume that households follow a linear expenditure system–constant elasticity of substitution (LES–CES) demand function. Under this framework, consumption of each commodity is divided into two components as follows: one portion remains unchanged by income fluctuations, whereas the other adjusts linearly with income changes. This structure reflects the idea that part of consumption is tied to basic needs.

Beyond distinguishing basic consumption by commodity type, the LES–CES function also determines how nonbasic consumption expenditures are optimally distributed across different goods. This assumes that households have a utility function with constant elasticity of substitution between different goods. This is implemented through a two-level nesting structure (Fig. 3). At the upper level, the household allocates expenditures between nonenergy and energy aggregates, which are not substitutable. Within each subnest (i.e., nonenergy or energy), households can adjust their demand among various goods. Shifting consumption between nonenergy commodities is less costly than adjusting demand between energy commodities, as reflected in the lower elasticities in the energy nest. The elasticity of substitution for the energy nest is taken from Labandeira et al. (2017). The two-layer structure of household consumption and the associated elasticities of substitution imply that an increase in gas prices directly influences household demand for alternative energy commodities, whereas demand for food and services remains largely unchanged.

2.1.3. Rest of the world

All goods and services can be imported. ThreeME first determines the total demand for a given commodity, including demand from final consumers and industries, and then allocates this demand between domestic and imported sources. However, production in the rest of the world — specifically, the use of foreign factors of production and energy — is not explicitly modeled.

The substitution between domestically produced goods and their imported counterparts is governed by Armington elasticities, which we take from Bajzik et al. (2019). In their estimates, the substitutability of natural gas is relatively high, with an elasticity of 1.85. This suggests that an increase in the price of imported gas could lead to a response in domestic gas supply, as imported gas can, to some extent, be substituted with domestically produced alternatives.

2.1.4. Energy sectors and commodities

A key feature of ThreeME for our analysis is its detailed representation of energy production (16 energy sectors) and energy commodities (11 commodities). This level of detail allows us to specifically identify the initial source of an energy price surge. Instead of modeling the exogenous shock as a general increase in gas or energy prices, we can directly simulate its effect on the price of imported gas.

Additionally, the model accounts for substitution possibilities between energy sources, whether they are directly consumed by nonenergy sectors or used in electricity production. The high resolution of energy commodities also enables us to capture sectoral energy transition paths, both in terms of energy production and sectoral level changes. This feature allows us to accurately represent how a shock to foreign gas prices unfolds in a market that is continuously evolving due to the energy transition.

2.2. Scenarios

Motivated by recent developments in energy markets, this paper analyzes a baseline scenario and three alternative scenarios in which a shock to the price of imported gas occurs. The baseline scenario represents the trajectory of the Dutch economy as it transitions away from fossil fuels. This includes changes in the electricity mix as well as shifts in industrial and residential energy demand. Additionally, the baseline scenario accounts for the ongoing phaseout of domestic gas production in the Netherlands.

Earthquakes caused by gas extraction in the northern province of Groningen led Dutch policymakers to halt operations there, with remaining reserves designated for use only in "critical" situations. In the baseline scenario, we assume that beginning in 2023, domestic gas supply is reduced to 10% of its 2015 level, following a gradual decline from 2015 to 2023. The three alternative scenarios build on the baseline assumptions but introduce a shock to imported gas prices in 2022 and 2040, and the duration and persistence of the shock vary across scenarios.

2.2.1. Baseline scenario

The baseline scenario incorporates changes to the energy system that align with the Netherlands' energy transition goals, using exogenous energy scenarios to inform the inputs of the macroeconomic model.[8] The objective is to ensure that the baseline scenario represents

[5] The difference in the number of energy sectors relative to energy commodities corresponds to the modeling structure of the 'electricity' commodity, which is exclusively produced by multiple sectors.

[6] Note that the nesting structure reflects our view on where substitutability between capital, labor and energy takes place. As Lecca et al. (2011) point out, the nesting structure mostly affects the short run results when different nests have different elasticity assumptions (as is the case in our model).

[7] Following Bachmann et al. (2024) we set the elasticity of substitution in this layer to 0.1.

[8] The version of the KEV used for our analysis is available in PBL (2021). For the description of OPERA see van Stralen et al. (2021). Details on the ADAPT scenario are available in Scheepers et al. (2022).

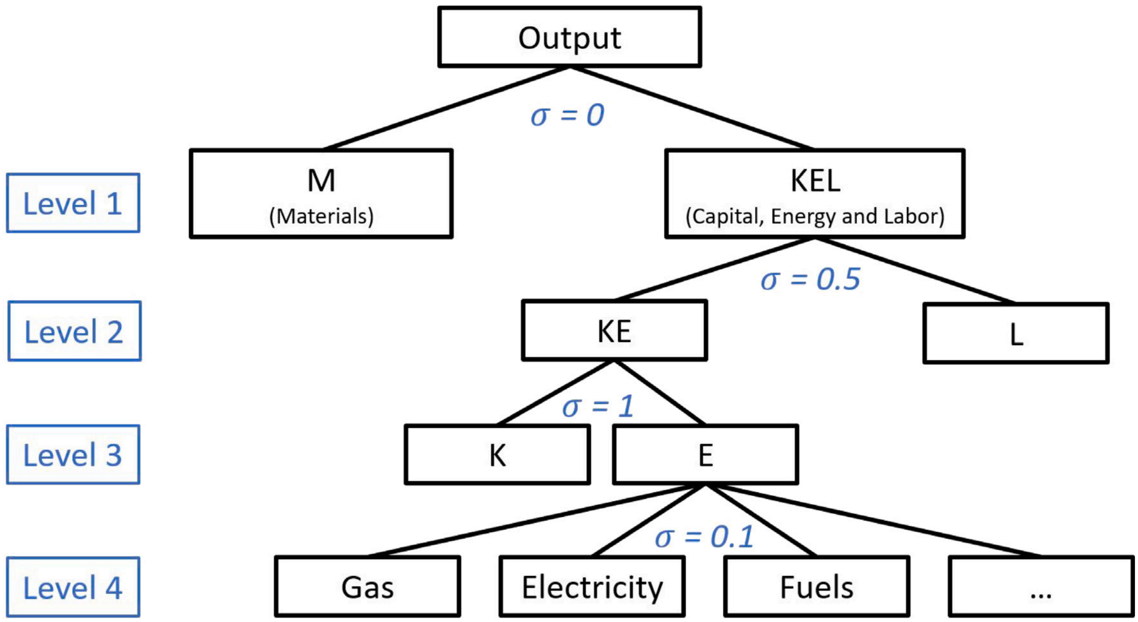


Fig. 2. Production structure.

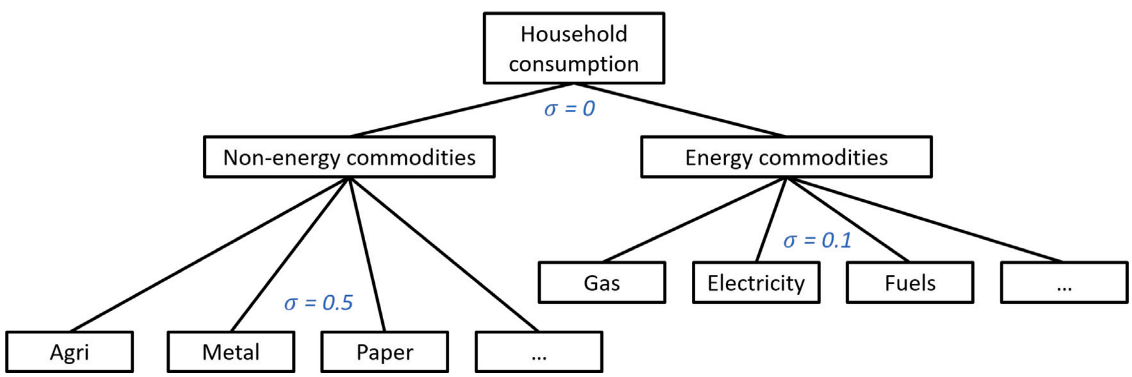


Fig. 3. Nested utility structure for households.

an energy transition path consistent with Dutch climate goals. To achieve this, we rely on two Dutch energy system scenarios as follows: The Climate and Energy Outlook of the Netherlands (KEV) and the ADAPT scenario from the OPERA energy system model.

For brevity, we refer to the KEV/OPERA ADAPT scenario as OA. Broadly, our approach involves using OA output to calibrate the parameters of ThreeME, which govern technological and behavioral change over time. These parameters ultimately determine the speed and direction of the energy transition.

The OA scenario retains some fossil-based energy carriers in 2050, making it particularly relevant for our counterfactual analysis, in which the economy faces both the energy transition and a new regime with higher imported gas prices. The OA scenario assumes that the economic structure and production of nonenergy sectors remain unchanged and takes a conservative stance on behavioral changes. As a result, energy demand continues to grow over time. To meet emission reduction targets, this necessitates a rapid expansion of carbon capture and storage (CCS) capacity.[9]

[9] CO2 storage capacity which is projected at $7.5Mt/yr$ in 2030 is assumed to increase to $50Mt/yr$ by 2050.

2.2.2. Calibration procedure for the baseline

To implement the baseline scenario in the macroeconomic model, we distinguish inputs as assumptions like those used in the energy system model that produced OA, results from OA that inform parameters in the macroeconomic model, and the gradual reduction of domestic gas supply between 2015 and 2023 (Fig. 4). Integrating OA into the ThreeME macroeconomic model requires several steps, including aligning sectoral definitions between the models. Details on this process, as well as the specific data used as input in ThreeME, are provided in Appendix A.2. Here, we present a condensed version of the integration procedure. Our objective is to ensure that the pace and direction of the energy transition in ThreeME align with the energy system scenarios, which incorporate decarbonization targets for the Netherlands.

2.2.2.1. Common assumptions.

Both OA and ThreeME require growth projections for GDP and population, sourced from KEV PBL (2021). Additionally, some of the innovative energy technologies modeled in the energy system scenario is assumed to experience cost reductions through learning in OA. To reflect this in the macroeconomic model, we assume that technological progress leads to a reduction in capital costs for energy sectors.

2.2.2.2. OA output as ThreeME input.

OA provides projections for the electricity production technology mix in 2030, 2040, and 2050. In ThreeME, electricity can be generated

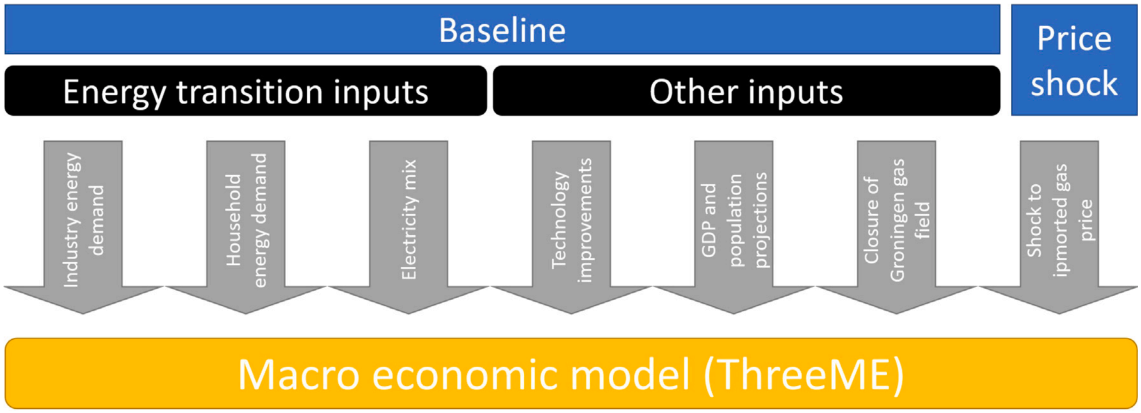


Fig. 4. Framework of inputs to macroeconomic analysis.

using seven different technologies, each linked to a primary energy carrier as follows: solid fossil fuels, gas, hydro, wind, solar, biomass and biofuels, or nuclear. In the macroeconomic model, the shares of electricity production by these technologies are exogenous. We set these shares to evolve gradually to match the OA projections for 2030, 2040, and 2050.

OA also provides projections for intrasectoral changes in the production structure of nonenergy sectors and shifts in household preferences. Specifically, it outlines the expected changes in energy demand from industries and households across various energy carriers. To ensure that industry-specific energy demand in ThreeME aligns with OA, we introduce an additional growth parameter into the gradual price-formation process within ThreeME.[10]

For households, the macroeconomic model implements a LES–CES formulation, which enforces a minimum and fixed expenditure on essential goods. The remaining budget is allocated across different commodities based on CES preferences. First, we activate an energy nest within this system, which includes all energy commodities (Fig. 3). Next, household expenditure on this energy nest is set to follow the growth rate of energy consumption from OA as an exogenous variable. Finally, demand for each energy carrier within the energy nest is determined using OA values, incorporating an additional growth parameter within the CES structure.

2.2.2.3. Phaseout of domestic gas supply.

The final component of the baseline implementation is the gradual reduction of domestic gas supply between 2015 and 2023. Data from the Central Bureau of Statistics (CBS) in the Netherlands is used to determine the appropriate reduction trajectory through 2022. By 2023, domestic gas supply is assumed to be 10% of its 2015 level.

Because domestic natural gas supply is an endogenous variable in the model, this reduction is implemented by adjusting the price of domestic gas upward, which reduces the equilibrium quantity. This is achieved by introducing an endogenous shadow price, effectively capping domestic gas supply.

2.2.3. Alternative scenarios: Shock to foreign gas supply

Building on the baseline integration of OA into ThreeME, and motivated by recent developments in fossil energy markets, we analyze alternative scenarios in which a shock to international gas markets occurs. This is modeled by introducing deviations in the price trajectory of imported natural gas relative to the baseline scenario.

The detailed structure of energy production and demand in ThreeME allows us to specifically target the price of imported natural gas—rather than energy prices in general—as the source of the economic shock. The production capabilities of the rest of the world economy are not explicitly modeled in ThreeME. Instead, the model treats the price trajectories of all imported goods and services as exogenous inputs, and the baseline calibration sets their inflation rate 2%.[11]

In the alternative price scenarios, where foreign gas supply is disrupted, we assume that the inflation path of imported gas deviates from the constant baseline level. Specifically, we model an increase in imported gas inflation that surpasses the baseline level, resembling the 2022 shock, with the possibility that the price difference persists over time. Alternatively, the inflation rate for other imported goods and services remains unchanged at the baseline level.

By comparing the baseline scenario with the alternative foreign gas price paths, our approach isolates the direct impact of rising imported gas prices on the Dutch economy, while abstracting from indirect effects that might arise from price changes in other imported goods.[12] The dynamic nature of ThreeME, combined with the calibrated energy transition trajectory assumed in the baseline, allows us to examine how an exogenous shock to imported gas prices propagates over time and to distinguish between immediate and long-term effects. To conduct this dynamic assessment, we must specify two keys aspects of the imported gas price trajectory under the alternative exogenous scenarios.

The first key aspect concerns the evolution of imported gas prices following the initial sudden increase in gas price inflation. One possibility is that the shock is short-lived, with inflation returning to the baseline trajectory immediately after the initial increase. Alternatively, the shock may persist, causing imported gas prices to continue rising faster than in the baseline for some time after the initial surge. To account for these possibilities, we define three alternative exogenous scenarios for the trajectory of imported gas prices after 2022, labeled $pgas1$, $pgas2$, and $pgas3$. These scenarios differ in the assumed duration of elevated imported gas inflation relative to the baseline level, meaning the expected time for inflation to return to the baseline trajectory.

The second key aspect for our quantitative assessment is the timing of the exogenous shock to imported gas inflation, specifically how early or late in the energy transition the shock occurs. The economy's vulnerability to rising imported gas prices depends on its fossil fuel

[10] ThreeME assumes a that prices and quantities slowly adjust to the optimal or target level. For example, the demand for gas by a certain industry in a certain year is therefore dependent on the long-run optimal level, demand in the year before, and expected demand in the year after. In the long run demand converges to the long-run optimum, but the adjustment process takes both forward looking as backward looking information into account (Reynès et al., 2021).

[11] This value ultimately pins-down inflation in the long run.

[12] As such, our results provide a conservative quantification of the overall increase in prices of imported goods and services faced by the Dutch economy in 2022.

dependence, which is expected to decline over the course of the energy transition. To assess how the energy transition mitigates fossil fuel shocks, we conduct a thought experiment in which we examine the impact of a shock to imported gas prices identical to the one implemented in 2022, but occurring later in the transition. Specifically, we assume that in 2040, at a more advanced stage of the transition, the Dutch economy experiences a second sudden and unexpected shock to imported gas prices, of the same magnitude as the 2022 shock. We then compare the economic impacts of the 2022 and 2040 shocks.

To construct the exogenous imported gas price paths used as input for our analysis, we assume that, in the three alternative price scenarios, the price trajectory follows the baseline path (2% inflation) up to 2021. We also assume that, in 2022, the economy experiences a sudden and unexpected shock that doubles the price of imported gas (100% imported gas inflation). This mirrors the magnitude and unanticipated nature of the 2022 imported gas price shock experienced by the Netherlands. To explore the potential mitigating effect of the energy transition, we further assume that, in addition to the 2022 shock, the economy is hit by a second unexpected shock of the same magnitude in 2040, when the energy transition will be at a more advanced stage. Furthermore, we assume that the inflation rate of imported gas may continue to deviate from the baseline level of 2% after the sudden and unexpected shocks in 2022 and 2040. To model this, we assume that the deviation in gas inflation relative to the baseline follows an autoregressive process of order 1 (Eq. (1) below). This means that the imported gas inflation rate in year t, π_t, is a weighted average of the previous year's imported gas inflation, π_{t-1}, and the baseline inflation rate of 2%, π^* (plus a zero-mean random term).

By using this parametric specification to model the evolution of imported gas inflation, we capture the potential persistence of shocks. For example, under high persistence, gas price inflation remains elevated in the periods following the shock, whereas, under low persistence, inflation returns to the baseline more quickly. By modeling the shock as deviations in inflation relative to the baseline, rather than as deviations in the price level itself, we ensure that the price of imported gas remains permanently higher than in the baseline. This reflects the realistic assumption that, after the shock, imported gas is likely to be sourced from more expensive suppliers.

Formally, defining the inflation of imported gas prices in year t as $\pi_{mgas,t}$, we assume that $\pi_{mgas,2022} = \pi_{mgas,2040} = 1$ to represent the sudden doubling of gas prices in 2022 and 2040. For all other years, i.e., between 2023 and 2039 and after 2040, we assume that inflation evolves according to

$$\pi_{mgas,t} = \rho\pi_{mgas,t-1} + (1-\rho)\pi^* + u_t; \tag{1}$$

where $\pi^* = 0.02$ is the long-run level of imported gas inflation, and u_t is a normally distributed random error with mean 0 and standard deviation 0.1. The parameter ρ governs the persistence of shocks to imported gas inflation and varies across scenarios. We consider three alternative values for ρ. In the $pgas1$ scenario, we assume no persistence and set $\rho = 0$. In the $pgas2$ scenario, we assume low persistence with $\rho = 0.05$, and in the $pgas3$ scenario, we assume high persistence with $\rho = 0.25$. Based on Eq. (1), and setting $\pi_{mgas,2022} = \pi_{mgas,2040} = 1$, we simulate three distinct gas inflation series, one for each value of ρ.[13] These simulated inflation series are used as exogenous input to the model.

3. Results

To understand the quantitative implications of integrating these outputs into ThreeME, we present key outcomes that characterize the energy transition in the baseline scenario. These baseline results are followed by those from alternative scenarios, which incorporate shocks to the price of imported gas.

[13] The simulated series are random as they depend on realizations of u_t. For this we assume that the realizations of u are drawn from a normal distribution with mean 0 and standard deviation 1.

3.1. Baseline scenario

Selected output from the baseline scenario is presented in Fig. 5, illustrating the energy transition and its macroeconomic implications. Notably, Panels a and b display aggregate energy use and emissions in the economy, respectively, whereas Panels c and e characterize the economy's exposure to gas price shocks and its transition away from gas, respectively.

Panel a presents total energy use in physical units of million tons of oil equivalent (Mtoe) by type of user. The results indicate that, under the baseline scenario, the energy transition requires a reduction in total energy use by households and the 11 nonenergy-producing sectors. This outcome is a direct result of integrating OA into ThreeME, where the evolution of physical energy use in productive sectors aligns with the growth rates in energy use from OA.

Panel b illustrates total CO2 and GHG emissions from 2015 to 2050. The declining trend suggests that the economy is rapidly reducing its emissions under the baseline scenario. However, because this represents gross emissions and does not account for factors such as CCS deployment, the CO2 trajectory does not reach zero by 2050.[14] OA assumes that 50 Mton of CO2 emissions will be stored annually by 2050. After subtracting these stored emissions from the values in Panel b, 52 Mton of net CO2 emissions remain in 2050. Overall, the decreasing trend in CO2 emissions is partly due to the substitution of fossil-based energy carriers with electricity, which is increasingly generated from renewable sources. Fig. 10 in the Appendix for more information.

Panel c depicts the share of gas and electricity in total energy use for households and the 11 nonenergy sectors, illustrating the transition away from gas. A key component of industrial transformation, as modeled in OA, is the electrification of productive sectors. Under this transformation, the share of gas in total energy use declines from 35% in 2015 to 5% in 2050, and the share of electricity doubles, increasing from 20% to 40% over the same period. Additionally, for households, the transition is more gradual, with gas usage declining from 40% to 35%, only partially offset by an increase in electricity consumption.

Another major component of the transition away from gas is how electricity is produced (Panel d). The share of electricity generated from gas peaks in 2020 at approximately 40%, declines to 5% by 2030, and reaches zero by 2050. Together, Panels c and d depict an economy where, under the baseline scenario, reliance on gas for energy needs diminishes over time, thereby reducing exposure to potential gas price shocks. The integration procedure we implement allows for a baseline scenario in which the energy transition varies across sectors. This is illustrated by the sectoral shares of gas and electricity use in the total energy consumption of nonenergy sectors (Panels e and f).

Panel e shows that the sectoral transition away from gas, as implied by OA, leads to a convergence in the reliance on gas as an energy carrier across sectors over time. In 2015, four sectors derived more than 50% of their energy from gas. By 2050, gas accounts for less than 10% of energy use in all but one sector (Agriculture). This convergence reflects a faster transition away from gas in sectors that were initially more dependent on it, although the transition does not occur simultaneously across all sectors. For example, the paper sector begins its transition as early as 2020, and the glass and food sectors, which are the most gas-dependent, do not begin their transition until 2030.

The results in Panel f indicate that, although sectoral gas reliance becomes more uniform over time, the same is not true for electricity use. Instead, the dispersion in the share of electricity in total energy use among productive sectors is higher in 2050 than in 2015. This divergence reflects technological differences in industrial decarbonization

[14] This difference with respect to the results in OA comes from: (i) the use of two different databases, - ThreeME assumes for example different sectoral CO2-coefficients; and, (ii) the linking procedure between OA and ThreeME via growth rates.

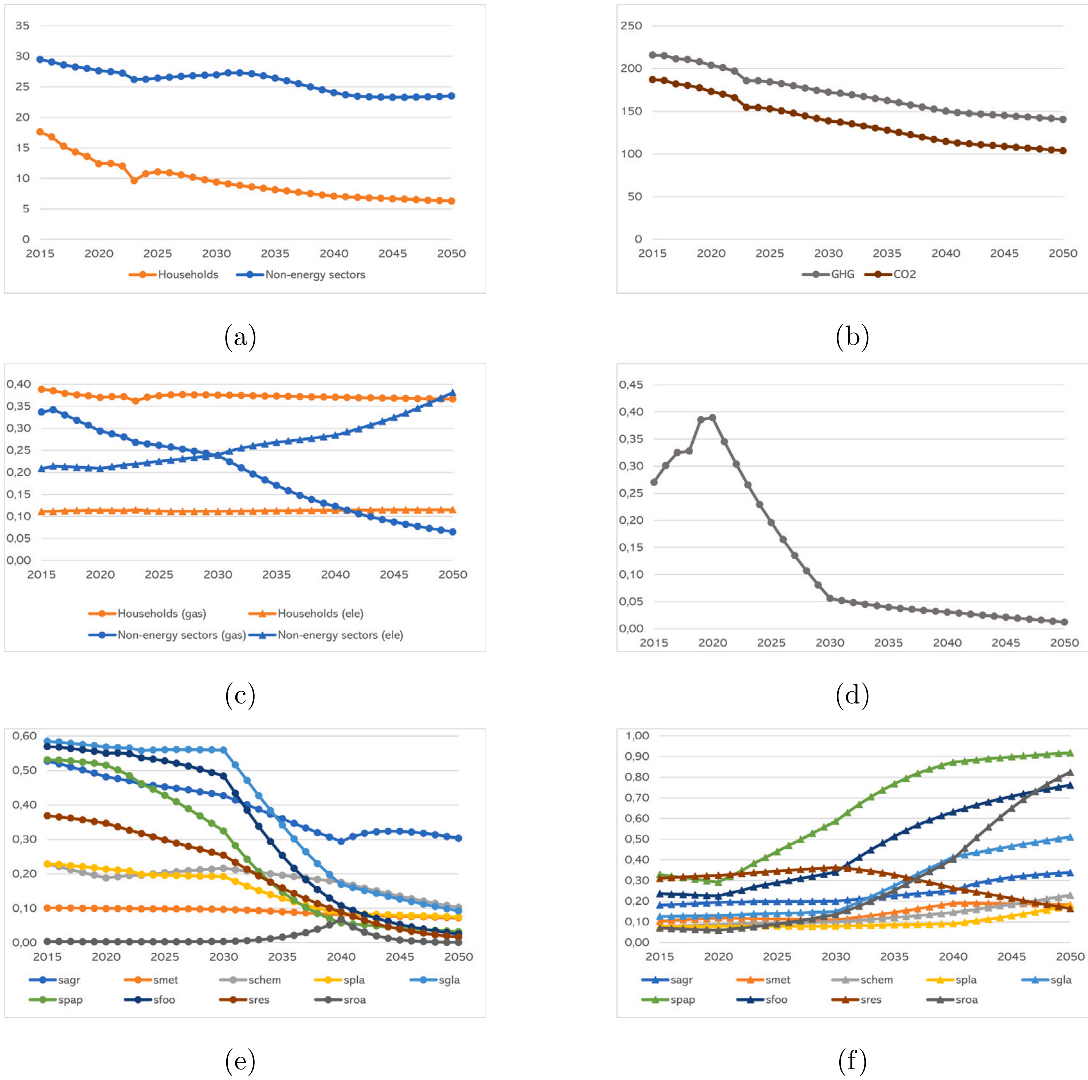


Fig. 5. Baseline scenario—Energy transition. (a) Energy use (Mtoe), (b) emissions (MtCO2eq), (c) gas and electricity use (share of energy use), (d) share of gas in electricity production, (e) gas use in nonenergy sectors (share of sectoral energy use), (f) electricity use in nonenergy sectors (share of sectoral energy use).

pathways, as modeled in OA. For example, in some sectors (e.g., paper), the transition is driven primarily by electrification. For others (e.g., plastics and chemicals), electrification plays a less dominant role in their transition.

3.2. Alternative scenarios

3.2.1. Domestic energy market

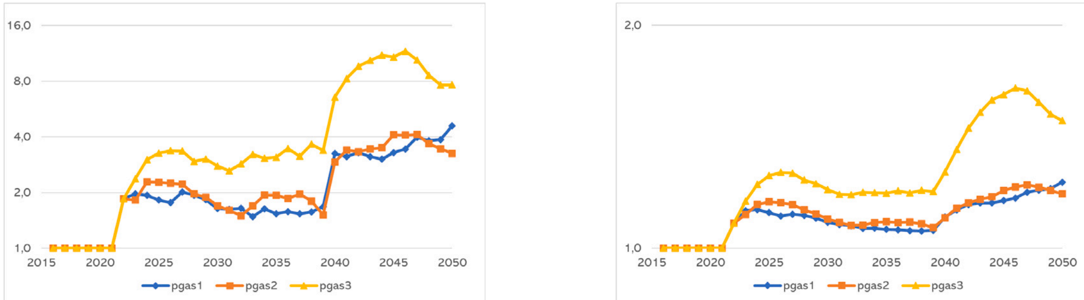
Figs. 6 and 7 illustrate the reaction of the domestic energy market to imported gas price shocks under the three alternative price scenarios: no persistence ($pgas1$), low persistence ($pgas2$), and high persistence ($pgas3$). Panels (a) and (b) in Fig. 6 focus on the domestic price indices for gas and electricity, respectively.[15] Prices follow the baseline until 2022, when the first shock to the price of imported gas affects the economy.

The size of the 2022 shock is the same across all three gas price scenarios, leading to an identical immediate response in the domestic price of gas, which roughly doubles relative to the baseline in 2022. After 2022, distinct patterns emerge across the price scenarios. Under higher persistence, the effect of the shock builds up more gradually. As shown in the figure, in the high-persistence scenario ($pgas3$), where the inflation of imported gas remains high after the shock, the price of gas relative to the baseline continues to rise beyond 2025. In contrast, without persistence ($pgas1$), the price index immediately begins to converge to the baseline level after the shock. This pattern is also evident following the 2040 shock, where relative to the baseline the price of gas continues to increase after the shock in the high-persistence scenario.[16]

The electricity price index, relative to the baseline, follows a similar pattern to gas, but with a smaller increase. This occurs because gas is not the only energy carrier used to produce electricity. Furthermore, the less pronounced response of electricity prices to the 2040 shock, compared with the 2022 shock, demonstrates the diminishing role of gas in electricity production. This trend confirms that electrification reduces the economy's exposure to future foreign fossil fuel supply

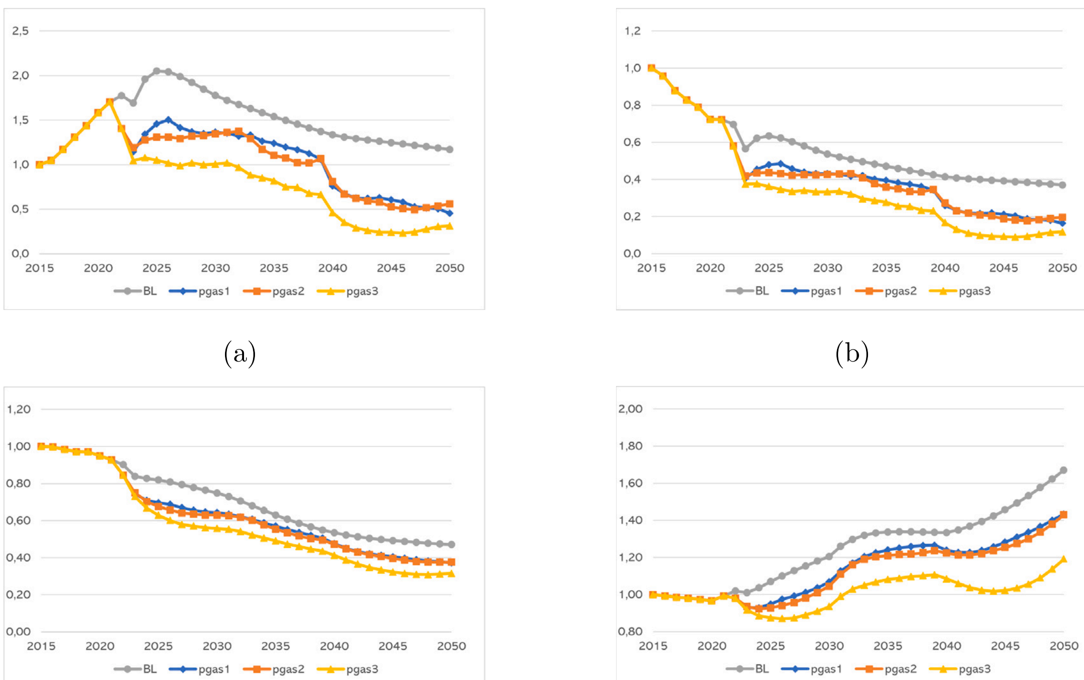
[15] These indices illustrate the endogenous response of domestic prices to the exogenous shock to imported prices (see Eq. (1)).

[16] Under a given scenario the expected time it takes for imported gas inflation to return to the baseline is the same after the 2022 and the 2040 shock, and this is fully determined by ρ. Yet, because of the random nature of the simulated imported gas inflation series after the 2022 and the 2040 shock, we obtain a realization of the gas inflation series that exhibits a slower decline after the 2040 shock.



(a) (b)

Fig. 6. Domestic energy price indices—Relative to Baseline [log scale]. (a) Gas, (b) electricity.



(a) (b)

(c) (d)

Fig. 7. Energy demand (2015 = 1). (a) Households–imported gas, (b) households–electricity, (c) nonenergy sectors–gas, (d) nonenergy sectors–electricity.

shocks. Given the logarithmic scale of the vertical axis in Fig. 6 the slope of each curve is equivalent to the difference between inflation under the corresponding scenario and inflation under the baseline.

Next, we examine how different gas price scenarios affect the evolution of gas and electricity demand in households and nonenergy-producing sectors (Fig. 7). All scenarios assume a reduction in domestic gas availability, reflecting the phaseout of gas production in the Netherlands. By 2023, household use of domestic gas falls to less than 10% of its 2015 level across all scenarios. This drastic reduction initially leads to higher demand for imported gas. However, the shock to imported gas prices in 2022 disrupts this trend.

Interestingly, under the high persistence scenario ($pgas3$), the break in the demand trend is permanent, initiating a transition away from both domestic and imported gas. When the economy is hit again in 2040, the shock to imported gas prices accelerates the shift away from gas even further. Similarly, the increase in electricity prices, caused by the imported gas price shock, reinforces the shift toward energy-efficient consumption patterns already present in the baseline scenario (Panel b).

Following OA, in the baseline scenario, gas demand by nonenergy-producing sectors decreases over time. The shock to imported gas prices accelerates this reduction, particularly in cases of higher persistence. This acceleration is more pronounced earlier in the energy transition, when sectoral production structures are more exposed to gas prices.

Panel (d) shows that under all three gas price scenarios, electricity demand is lower than in the baseline. This is due to a slower increase in electricity consumption by nonenergy-producing sectors, whereas in the baseline scenario, demand growth is largely driven by the electrification of industry. Higher electricity prices, caused by the increase in gas prices, slow the growth of domestic electricity demand across scenarios. Because productive sectors have a very low elasticity of substitution between gas and electricity (Fig. 2), the short-term response to the gas price shock does not lead to a significant increase in electricity demand.

3.2.2. Sectoral production structure

Through its effect on energy costs, the shock to imported gas prices triggers changes in the production structure of different sectors. Industries have three primary ways to cope with higher energy costs, such as reducing energy use and substitute energy with other factors of production, switching to alternative energy carriers with lower prices or absorbing the cost through higher prices and lower output. The extent to which each industry can adapt depends on the substitution possibilities allowed by production technologies and the availability of production factors. For instance, in the short run, the ability to substitute energy with other factors of production is limited, as energy is more easily replaced with capital than with labor.

To examine these sectoral responses, we analyze changes in the demand for production factors (i.e., capital and labor) and output adjustments in the most energy-intensive, nonenergy, and nontransport sectors, relative to the baseline. This analysis focuses on the low persistence scenario ($pgas2$), with results presented in Fig. 8.

Fig. 8 indicates similar patterns of factor and energy use across nonenergy sectors, relative to the baseline. The immediate response to the gas price shock is a reduction in energy use, with firms substituting energy with labor. However, these short run adjustments overshoot longer-term responses, as seen in the inverted U-shaped pattern for labor demand and the U-shaped pattern for energy use.

The neo-Keynesian closure of the model results in a persistent excess supply in the labor market (i.e., unemployment). This allows for some short-term substitution of energy with labor, although the elasticity of substitution between labor and energy is lower than that between energy and capital. The increase in labor demand, relative to the baseline, leads to a decline in the unemployment rate. Through the wage setting framework of the model, this lower unemployment rate creates upward pressure on nominal wages, further amplifying the initial increase in domestic prices triggered by rising energy costs.

The increase in nominal wages slightly outpaces the rise in domestic price levels, resulting in a moderate increase in real wages following the imported gas price shocks.[17] Owing to the shock and the subsequent increase in production costs, imported gas inflation ultimately reduces the output of domestic energy-intensive sectors relative to the baseline.[18] As energy becomes permanently more expensive after the shock, productive sectors gradually accumulate capital to substitute energy use and reduce their energy intensity. This capital accumulation occurs over time, leading to higher capital stocks and lower energy consumption in the long run, relative to the baseline.

However, because of the partial phaseout of gas as an energy source and the imperfect substitutability between energy and production factors, the surge in gas prices inevitably results in higher sectoral production costs and a decline in sectoral output, relative to the baseline. As a result, in the long run, compared to the baseline, productive sectors experience an increase in capital stocks but a contraction in output. Nevertheless, this output contraction is less severe than it would be if sectors were entirely unable to substitute energy with other production factors.

As sectors reduce their energy intensity through the accumulation of physical capital, gas becomes a less significant energy source, both directly and indirectly, due to its declining role in electricity production (Fig. 5). These combined developments mean that when the unexpected 2040 shock occurs, sectors are less exposed than in 2022. Among the sectors in Fig. 8, metals (Panel b) and food and beverages (Panel f) stand out for being at opposite ends of the energy intensity spectrum. Metals is the most energy-intensive sector before the imported gas shocks . Compared with the baseline, this sector reduces energy use less than other sectors in response to the foreign gas price shock.

This reflects the high energy dependence of the metals sector and its limited ability to mitigate rising production costs through factor substitution. Hence, the output reduction in the metals sector is more pronounced than in other sectors relative to the baseline scenario. Food and beverages, by contrast, is the least energy-intensive sector in Fig. 8.

Its lower reliance on energy makes it more resilient to gas price shocks, and the sector can reduce energy use with only a moderate negative impact on output. In the long run, this means that food and beverages have a relatively lower need to increase capital use over time.

Relative to the baseline, all sectors in Fig. 8 experience a permanent reduction in output due to the shock to imported gas prices. The immediate decline in output, driven by limited substitution possibilities, gradually diminishes as sectors accumulate physical capital and reduce their energy needs. Although the output response follows a similar pattern across energy-intensive sectors, the intensity of the response varies depending on sectoral substitution possibilities.

Compared with the baseline, the more capital-intensive sectors (e.g., metals and chemicals), experience the largest contraction in output due to their more limited short-term ability to substitute energy with other inputs, as substitution primarily occurs through labor. Over time, the buildup of capital makes these sectors even more capital-intensive in the long run, relative to the baseline.

Unlike other sectors in ThreeME, the rest sector (not depicted in Fig. 8) exhibits a positive output response. This aggregate sector, composed primarily of services, has the lowest energy intensity in the economy. As a result, it is less exposed to the shock to imported gas prices and gains a cost advantage relative to other sectors after the shock. Through substitution among the 11 nonenergy commodities in household consumption, the rest sector expands its share of the economy relative to the other 10 nonenergy sectors. The combined sectoral responses lead to only negligible changes in aggregate GDP relative to the baseline.

3.3. Discussion

Our results illustrate the interplay between shocks to foreign fossil fuel supply and the forces of the energy transition, demonstrating how these effects vary across productive sectors. The analysis suggests that focusing solely on the immediate sectoral response risks overlooking important aspects of the shock's long-term aftermath. A broader time perspective offers valuable insights into short- versus long-term effects and helps identify policy intervention opportunities across different time horizons. Taken together, our findings support a sector-specific policy approach that considers interventions with differentiated impacts over time. Two main implications emerge from this analysis.

First, our results align with the long-term policy perspective that accelerating investments in renewable capacity can reduce exposure to foreign fossil fuel supply shocks. Apart from the environmental benefits

[17] Labor market responses are relatively larger in 2040 than in 2022, with real wages increasing by around 2%, relative to the baseline after the 2040 shock. This is explained by the simulated price path of imported gas under the pgas2 scenario which exhibits a slower return to the mean after the 2040 shock.

[18] In addition to capital energy and labor, sectors also use materials. Given that materials are a perfect complement to the KEL composite, the sectoral use of materials relative to the baseline follows exactly the same path as output relative to the baseline.

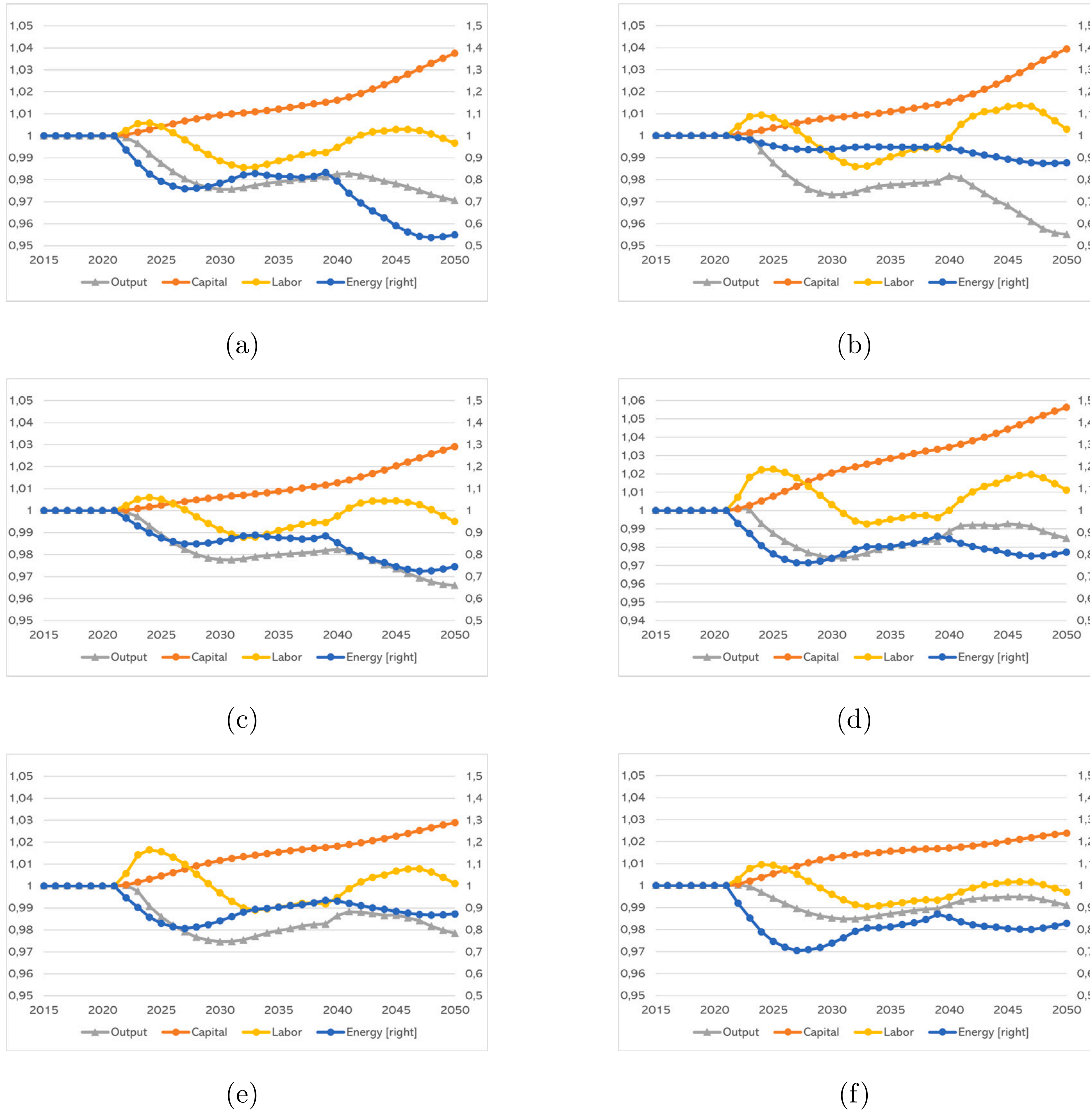


Fig. 8. Output, energy use, and factor use for nontransport sectors with the highest energy intensity in 2015 (*pgas*2 scenario relative to Baseline): (a) Agriculture, (b) metals, (c) chemicals, (d) glass, (e) paper, (f) food and beverages.

associated with lower emissions, expanding renewable energy capacity and electrifying industry can help decouple domestic economic activity from imported fossil fuels, strengthening the economy's resilience to external energy supply disruptions.

Second, investments in renewable capacity and electrification can be complemented by policies that promote physical capital investments to lower the energy intensity of production. Accelerating capital renewal can mitigate production contractions resulting from higher imported gas and fossil fuel prices. The impact of foreign fossil supply shocks on sectoral activity depends on industries' substitution possibilities, which evolve over time. In the short-term, electrification cannot fully buffer fossil fuel price shocks, as industrial processes cannot be rapidly adjusted to substitute between energy carriers. Consequently, an external fossil fuel supply shock is expected to lead to higher energy costs, lower energy use, and declining sectoral output. Therefore, facilitating investments in physical capital to reduce energy intensity emerges as an effective strategy. Reducing energy dependence for sectoral output would help offset production losses associated with higher imported fossil fuel prices. Moreover, achieving permanently lower sectoral energy intensity through faster capital accumulation serves a dual purpose: advancing energy transition goals while reducing sectoral exposure to future energy supply shocks.

The use of a macroeconomic model is instrumental in supporting these findings. Although it is intuitive that higher imported gas prices lead to higher domestic gas prices in the short-term, the model provides critical insights into the distinctions between short- and long-term impacts, how domestic sectors adjust their production structures after a shock, and the potential role of policy in mitigating these effects through capital renewal. Notably, the role of empirically estimated elasticities at a detailed sectoral level as inputs for the model (e.g., Antimiani et al. 2015). The results would differ significantly if we had assumed an excessively high elasticity of substitution between energy carriers in nonenergy sectors. In such a case, electrification would appear as a relatively inexpensive solution for offsetting rising gas costs, and energy-intensive sectors, such as the metal industry, would experience less severe output reductions.

The model closure is another key assumption influencing the results and their policy implications. ThreeME adopts a neo-Keynesian closure in which wages and prices do not adjust instantaneously to changes in demand or supply. Compared with a Walrasian closure, which assumes that markets always clear instantly, our approach is better suited for distinguishing short-term from long-term impacts and assessing policy options across different time horizons.

4. Conclusion

This paper examines the macroeconomic interplay between the transition away from fossil fuels and a shock to foreign gas supply. The analysis is motivated by recent developments in gas markets and their impact on European economies, particularly those undergoing an energy transition. We focus on the Netherlands, an economy with ambitious GHG emission reduction targets, which has recently experienced a shock to foreign gas supply.

As a starting point, we model a baseline scenario that simulates the Dutch economy following a GHG emission reduction path aligned with 2050 targets. Building on this baseline, we propose three alternative scenarios, each involving a shock to the price of imported gas in 2022 and 2040. These scenarios differ in terms of the persistence of the shock, meaning how long imported gas price inflation remains elevated.

Three key results from this analysis are particularly relevant from a policy perspective. First, we address the question: How sensitive is the Netherlands to foreign fossil fuel supply? Our results show that higher persistence of the shock to imported gas prices leads to greater deviations in domestic gas and electricity prices from their baseline levels. Additionally, the shock accelerates the transition away from both domestic and imported gas use, with the effect being more pronounced in the case of a highly persistent shock.

Second, we demonstrate that a shock in 2022 has notably different implications compared with a shock in 2040, when the Dutch energy transition is at a more advanced stage. For example, the increase in electricity prices following the 2040 shock is more moderate than after the 2022 shock, as investments in the energy transition have significantly reduced the role of gas in the electricity mix. Similarly, the electrification of nonenergy sectors reduces their reliance on gas as a primary energy source, which dampens the magnitude of the sectoral response to the shock. This shows that policies aimed at accelerating the energy transition not only lower GHG emissions but also reduce the domestic economy's exposure to foreign fossil fuel supply shocks.

Third, our results promote heterogeneous responses of nonenergy sectors to energy shocks. In the short-term, sectors face significant challenges in mitigating the impact of rising gas prices on their energy costs. Replacing gas with electricity is expensive due to low substitution opportunities, whereas substituting energy with capital takes time, as capital accumulation is a gradual process. However, in the long-term, capital plays a larger role as a factor of production, allowing sectors to reduce their energy use. For the metal industry, the most energy-intensive sector in the Netherlands, the shock to imported gas prices not only drives substantial capital accumulation but also leads to a reduction in sectoral output relative to a baseline without the shock. This reflects the importance of facilitating energy-saving investments, particularly for energy-intensive sectors, as a near-term policy intervention against shocks that create lasting increases in energy prices.

This paper examines the impact of rising international gas prices following Russia's invasion of Ukraine and the disruption of Russian gas supply to Europe. However, our approach and findings are also relevant for understanding the Dutch economy's potential responses and vulnerabilities to future energy price increases. Other factors that could drive higher energy prices include changes in the EU Emissions Trading System, which could raise the cost of fossil fuels or structural increases in electricity demand, such as those resulting from stricter electrification requirements for industry, leading to higher electricity prices. Future applications of our framework can assess whether these events might have similar sectoral and aggregate impacts on the Dutch economy.

During the preparation of this work the authors used ChatGPT to obtain suggestions on how to enhance the readability of certain sentences in this manuscript. Following the use of this tool, the authors thoroughly reviewed and edited the suggested content and take full responsibility for the published version of the manuscript.

Declaration of competing interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Appendix A. Methodological details

A.1. Sectoral detail ThreeME

The production structure of this economy consists of 27 sectors, including 11 nonenergy sectors and 16 energy sectors. Among the 16 energy sectors, eight produce energy commodities other than electricity, seven exclusively produce electricity, and one (i.e., heat) produces electricity and other energy commodities.

The sector abbreviations used throughout this paper is defined in Table A.1 and begin with the letter "s". Notably, there are fewer commodities than sectors. When a commodity and a sector shares the same name, it indicates that the commodity is the primary product of that sector. However, the commodity may also be produced by other sectors. For example, the rubber and plastic (cpla) commodity is primarily produced by the rubber and plastic (spla) sector but can also be produced as a byproduct by the chemical industry (schem) sector.

A.2. Linking of ADAPT results to ThreeME input

The integration of the ADAPT energy scenario into the ThreeME macroeconomic model requires several steps, including aligning sectoral definitions between models. Here we outline this integration process. Our objective with this process is to align the pace and direction of the energy transition modeled in ThreeME with the energy system scenarios developed for the Netherlands. To achieve this, we calibrate ThreeME to reflect sector-specific trends in energy use from different sources for the period 2015–2050.

To ensure consistency when initializing ThreeME, we use the ThreeME database version for energy use in 2015, denoted as $E_{s,e,15}$ using data primarily sourced from the IEA Energy Balances.[19] However, because the ADAPT scenarios are only available starting in 2030, we must bridge the informational gap for $E_{s,e,t}$ between 2015 and 2030. To do this, we rely on the 2020 version of the Climate Energy Outlook of the Netherlands (KEV) (PBL, 2021), which provides information on $E_{s,e,t}$ for 2015, 2020, and 2030. Using this data, we calculate the average yearly growth rate of energy use, $\Delta\% E_{S,E}$, between 2015–2020 and 2020–2030. Starting from the base year $E_{s,e,15}$, we apply these growth rates to extrapolate $E_{s,e,t}$ up to 2030.

For the period 2030–2050, we obtain growth rates $\Delta\% E_{S,E}$ from the ADAPT scenario, which we use to extrapolate $E_{s,e,t}$ until 2050. In cases where the calculated growth rate is excessively high (above 1,000%), we set the growth rate to one, as such extreme values typically occur when energy demand in the reference year is negligible. Similarly, when the net energy demand in ADAPT is negative, which indicates energy production rather than consumption, we also set the growth rate to one to avoid unrealistic projections.

Once the full time series of $E_{s,e,t}$ is constructed, it is used as an input to guide the energy transition in ThreeME. This is accomplished by introducing sector-energy-source-specific trend parameters into sectoral energy demand. These parameters are calibrated to ensure that the energy demand per source by each sector in ThreeME matches the levels of $E_{s,e,t}$ estimated using the procedure described above. These trend parameters function similarly to exogenous, energy-source-specific technological change, as they modify the demand for specific energy types relative to others, given the prevailing relative energy and

[19] See Reynès et al. (2021, p. 45–46) for details on how the IEA energy balances are adapted as a data source for ThreeME.

Table A.1
ThreeME sectoral details.

Description	Sector abbreviation	Commodity abbreviation
Products of agriculture, hunting, forestry, and fishing	sagr	cagr
Basic metals (steel, aluminum, zinc)	smet	cmet
Chemical products (nitric acid, urea, chlorine, other)	schem	cchem
Rubber and plastic (ethylene, propylene, other HVC)	spla	cpla
Non-metallic mineral products (glass, ceramic)	sgla	cgla
Paper and paperboard	spap	cpap
Food products and beverages	sfoo	cfoo
Rest of economy	sres	cres
Land transport	sroa	croa
Water transport (navigation)	swat	cwat
Air transport (aviation)	sair	cair
Coal and coal products	scoa	ccoa
Crude oil	soil	coil
Gasoline and other fuels		cfue
Petroleum refining for production fuels	spen	
Petroleum products	spch	cpch
Natural gas	sgas	cgas
Manufactured gas		cmga
Biogas	sbiog	cbiog
Biomass	sbiom	cbiom
Biofuel	sbiof	cbiof
Heat	shea	chea
Electricity		cele
Electricity by solid fossil fuels	sesf	
Electricity by gas	sega	
Electricity by hydro	sehy	
Electricity by wind	sewi	
Electricity by solar (PV and thermal)	seso	
Electricity by biomass and biofuels	sebi	
Electricity by nuclear	senu	

factor prices. By design, this procedure does not yield identical levels of $E_{s,e,t}$ as those found in KEV and ADAPT. The discrepancy arises primarily because we start from ThreeME levels and then apply the growth rates from KEV and OPERA. In addition to the procedure used to match the evolution of $E_{e,t}$, additional inputs from KEV, ADAPT, and CBS inform the parameters in ThreeME.

For total energy use by households, $E_{h,t}$, we take the ThreeME data for 2015 and extrapolate it to align with KEV levels in 2020 and ADAPT levels for 2030, 2040, and 2050, constructing a complete series. Unlike energy demand in productive sectors, which requires reconciling differences between ADAPT, KEV, and ThreeME sectoral classifications, household energy demand follows a single definition. This consistency allows us to match absolute values rather than relying on growth rates.

Additionally, in contrast to industry demand for energy, total household energy demand is explicitly matched in ThreeME. Although it is essential to reflect the energy demand by carrier from ADAPT, it is equally important to preserve ThreeME's strengths, especially its ability to model household demand responses to prices. To achieve this balance, we introduce a trend parameter that ensures total energy demand matches the levels from KEV and ADAPT. A negative value for this parameter reflects energy-saving behavioral changes, meaning household energy consumption declines even if relative prices remain constant. However, household demand for specific energy carriers remains flexible within the model. This flexibility is necessary because, under a high-gas-price scenario, households must be able to respond by shifting to alternative energy sources.

For the technology mix in electricity production, we use ThreeME data for 2015 to establish the level of electricity generated by each of the nine electricity-producing sectors, categorized by technology (e.g., wind, solar, and gas). This is supplemented with CBS data to obtain electricity production levels for 2020. The 2015 levels are linearly extrapolated to match the CBS levels in 2020, and these 2020 levels are further extrapolated to align with ADAPT projections for 2030, 2040, and 2050. From this constructed time series, we derive the electricity mix for each year, replacing the base year shares for 2016–2050. Because electricity is modeled as a single commodity,

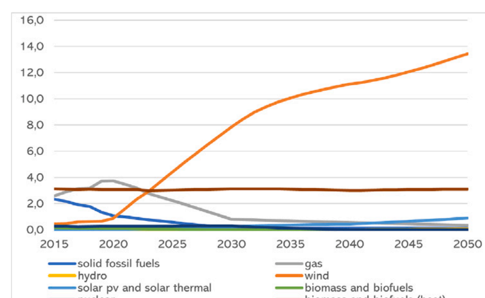


Fig. 9. Electricity and heat production by source (Mtoe).

produced by nine different sectors using distinct technologies, these shares determine how clean the electricity production process is.

For technological progress in energy production, ADAPT assumes cost reductions in energy production driven by technological advancements. We incorporate this assumption into ThreeME by allowing for improvements in capital efficiency, effectively reducing the cost of capital in energy-producing sectors. The technological improvements are sourced from technological factsheets.[20] When no specific data are available for a given sector or technology, we adopt the same assumption used in the ADAPT scenario. A 20% improvement in efficiency between 2030 and 2050.

Appendix B. Electricity and heat mix

B.1. Electricity mix

See Figs. 9 and 10.

[20] Technology factsheets can be extracted from energy.nl.

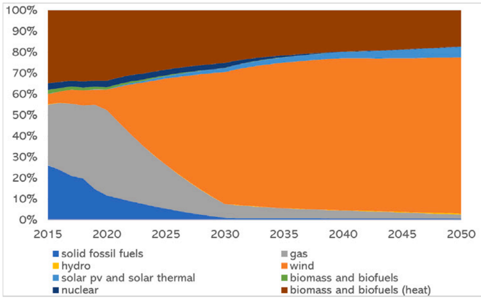


Fig. 10. Electricity and heat production by source (%).

Data availability

Replication files (data and code) are available at:

Mitigating Foreign Fossil Fuel Shocks: The Role of Renewable Energy and Industrial Electrification in The Netherlands (Mendeley Data)

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