



Soft-linking a general equilibrium model and an energy system model: towards a carbon-neutral economy by 2050

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ABSTRACT

This study examines the macroeconomic impacts of the energy transition in the Netherlands. To capture key energy transition dynamics and improve the assessment of alternative fuels adoption, particularly in hard-to-abate sectors such as steel and chemical production, we incorporate hydrogen-related activities into a Computable General Equilibrium (CGE) model and soft-link it to an Energy System Model (ESM). We evaluate two main scenarios: a business-as-usual (BAU) trajectory and an Energy Transition (ET) pathway aligned with a carbon neutrality target. A variant of the ET scenario with limited capital inflows (ET-CA) is considered to assess the role of financing in the energy transition. Our results show that replacing fossil fuels with renewable alternatives drives GDP growth in the long term, with GDP 1.7% higher in 2050 under the ET scenario compared to BAU. Cumulative GDP over 2025–2050 increases in ET compared to BAU, while it declines by €70 billion in ET-CA. Unemployment peaks around the mid-transition period in ET and declines thereafter, converging to about 0.2% above BAU by 2050. In ET, welfare losses are initially severe but moderate over time, whereas they remain consistently higher under ET-CA. We argue that the negative impacts observed under the ET scenarios should be weighed against the potential climate-related economic damages omitted in BAU, which could otherwise reduce its apparent macroeconomic advantage. Our analysis underscores the necessity of policy frameworks that balance the socio-economic impacts of the energy transition with its environmental benefits, especially under constrained financing conditions.

1. Introduction

Achieving carbon neutrality by 2050 is currently at the forefront of the European agenda. This requires transformations across multiple sectors of the economy, particularly in industries such as steel and chemicals, which rely heavily on fossil fuels. However, this shift in energy sources can lead to ripple effects across the broader macroeconomy, influencing employment, trade, and economic output. In this study, we employ the GEM-E3 model, a Computable General Equilibrium (CGE) model, to analyse the broader economic shifts that occur as a result of the energy transition in the Netherlands. However, CGE models lack the level of detail needed to capture relevant technological complexities and sector-specific developments [1]. Recognising this limitation, in our

study, we soft-link an energy system model (ESM) to the CGE model. This linking ensures that critical details regarding energy production, consumption, and transition pathways are incorporated into the broader economic context. For example, decarbonising the steel industry through direct reduced iron (DRI) processes would not simply replace natural gas with an equivalent amount of hydrogen. Such a shift would alter the entire energy mix and require additional infrastructure investments. Without the linking, the CGE model would overlook these implications and misrepresent key technological and energy system details. Refs. [2–6] provide detailed discussions on the linking between CGE models and ESMs as a methodological approach for improving the analysis of the energy transition.

The literature includes fully integrated hard-linked models and

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hybrid energy–economy frameworks. In hard-linking, models jointly solve energy system and macroeconomic decisions within a single optimisation framework, as in MARKAL-MACRO and MESSAGE-MACRO [7,8]. Other contributions adopt hybrid modelling approaches, which combine detailed bottom-up representations of the energy system with macroeconomic consistency without full joint optimisation, such as IMACLIM-S and related applications [9], or CGE models with embedded power dispatch and capacity expansion modules [10]. Other work proposes algorithmic coordination approaches, which introduce iterative, bidirectional feedback between top-down and bottom-up models until convergence is achieved, representing an advanced form of soft-linking that avoids hard-linking the two models [11]. In soft-linking methodology, the models remain separate entities where they communicate through the exchange of output and input data while retaining their original structures and functionalities. While there are different types of linking Bottom-Up (BU) models with Top-Down (TD) models [12], soft-linking is favourable when established stand-alone models are available [4,13], as is the case in this study.

There are various studies that analyse the macroeconomic implications of the energy transition at different geographical levels, both with and without linking to an ESM [14–16]. For example, Boonman et al. soft-link an ESM to two different CGE models to examine decarbonisation scenarios for the European Union [15]. Fortes et al. soft-link the TIMES ESM to GEM-E3 in the context of climate policy scenarios for Portugal [17]. Similarly, Krook-Riekkola et al. soft-link TIMES to the Environmental Medium-term Economic model (EMEC) for analysing the climate policies of Sweden [3]. Fragkiadakis et al. soft-link GEM-E3-ITA with TIMES-RSE to assess the Italian energy transition [18]. Arndt et al. apply a sequential linking approach between the South African TIMES model (SATIM) and the South African General Equilibrium (SAGE) model to investigate the macroeconomic implications of different energy strategies (e.g. carbon taxes) in South Africa [19]. Many studies concentrate on soft-linking TD and BU models for specific sectors such as the residential sector [20], the transport sector [21,22], and the power sector [23]. In this study, we adopt a more comprehensive linking approach that spans economic activities across power, energy, industrial, and transport sectors. Notable examples that have also involved a comprehensive linking between BU and TD models are [12,17,24]. These comprehensive approaches enable us to provide a more holistic analysis of the interplay between technological and economic dimensions across multiple sectors.

Low-carbon and renewable energy are regarded as key enablers for the energy transition, with hydrogen attracting particular interest thanks to its dual utility as both a fuel and a feedstock across a spectrum of industries. In hard-to-abate sectors such as steel production, hydrogen holds promise as a reducing agent in the direct iron reduction process. The use of hydrogen further extends beyond industry to agriculture, residential, and power sectors, where it contributes to reducing emissions and supporting renewable energy integration. To facilitate the transition, blue hydrogen will be produced as both a pragmatic and transitory solution while the technologies and systems for green hydrogen production continue to evolve. Despite the promising potential of green hydrogen, its production essentially relies on intermittent renewable energy sources. This introduces the need for large-scale hydrogen storage solutions as well as pipeline networks to distribute hydrogen efficiently across sectors, both of which are currently being developed under Dutch government initiatives. In the context of hydrogen modelling in CGE frameworks, Mueller and Gronau review the hydrogen representation in CGE models [25]. They highlight the underrepresentation of green hydrogen in CGE models compared to fossil-based hydrogen production pathways [26–28], which are incompatible with sustainability goals [29].

While the set of literature reviewed above provides a broad overview of several themes specific to energy transition economics, it does not focus on the Netherlands. There are, however, existing CGE studies that analyse the energy transition for the Netherlands. For example,

Hoefnagels et al. investigate the impacts of substituting fossil fuels with biomass in the electricity, transport, and chemical sectors of the Netherlands. Their analysis spans up to 2030, using the LEITAP model, a global CGE model, without considering linking to an ESM [30]. Bulavskaya and Reynès evaluate the impacts of transitioning the Dutch power sector to be 75% renewable by 2030. They use the ThreeME national CGE model, combined with the Energy Transition Model (ETM), an ESM, through soft-linking. Similarly, Fattahi et al. apply the ThreeME model, soft-linked with an ESM, to explore a scenario where the Netherlands achieves greenhouse gas neutrality by 2050. However, their analysis primarily focuses on changes in GDP and exports as the key economic indicators. The primary objective of their study is to illustrate the impact of employing soft-linking as a methodology on the outcomes of both models, with particular emphasis on the changes relevant to the ESM [31].

Our contributions in this study are centred on three aspects. First, we incorporate four hydrogen-related activities into the CGE framework: blue hydrogen, green hydrogen, hydrogen storage, and hydrogen pipelines. Although green hydrogen is included in some models [32], critical considerations such as its transport network, storage, and diverse end-use applications remain largely unexplored. The GEM-E3 model already incorporates biofuels, synthetic fuels, and biomass, reflecting a broader spectrum of alternative fuels essential for the energy transition. This integration of hydrogen-related activities, therefore, further broadens the model's capacity to assess the energy transition in a more complete manner. Second, we create a version of the GEM-E3 model specifically tailored to the Netherlands, which we name GEM-E3-NLD. While GEM-E3-NLD focuses on the Netherlands, we retain the global scope of the original model by aggregating the other countries into two regions: the rest of the EU and the rest of the world. Third, we soft-link the OPERA ESM to the GEM-E3-NLD to analyse the effect of the transition of the Netherlands to a low-carbon economy on the GDP, employment, prices, and welfare. Additionally, we define two different macro closures with respect to the foreign capital inflows, which enables us to examine how assumptions about capital mobility can impact the macroeconomy of the Netherlands.

For policymakers, comprehending these impacts is crucial for designing effective industrial strategies and environmental regulations that can navigate the challenges and capitalise on the opportunities presented by the ongoing transformation. Section 2 outlines the methods, tools, and scenarios used. Sections 3 and 4 present and discuss the outcomes of the decarbonisation scenarios, respectively. Section 5 concludes with key findings and recommendations for future research.

2. Methodology

In the following subsections, we elaborate on the characteristics of the GEM-E3 model, and the ESM employed in this study; we shed light on their structures, assumptions, and the methodological approach used in linking them. We also outline how the GEM-E3 model has been extended to include activities that represent a comprehensive hydrogen supply chain.

2.1. The CGE model: GEM-E3

The GEM-E3 model is a multisectoral recursive dynamic model capable of running projections up to the year 2100. It is noted for its comprehensive approach in capturing the interactions between the economy, environment, and energy domains. The model uses a combination of Leontief and CES production functions to reflect sector-specific characteristics. We discuss the rationale for employing these functions across different sectors, as well as the broader model framework, in Appendix A: GEM-E3 structure.

The database of GEM-E3 comprises input–output tables, trade flows, and energy balances, which together enable the representation of a wide range of economic sectors, agents, and regions. It is primarily based on

the Global Trade Analysis Project (GTAP) database but is extended with data from EUROSTAT, the World Bank, the International Energy Agency (IEA), and academic literature.

2.1.1. Sectoral coverage

The current version of GEM-E3 outlines 100 distinct economic activities, which are mapped across a spectrum of diverse economic sectors. This categorisation is particularly evident in the energy generation sector, where it covers various types of energy generation, as well as related activities such as photovoltaic (PV) manufacturing. A detailed breakdown of these activities is provided in Table 1B, Appendix B.

2.1.2. Learning by doing

Learning-by-doing curves describe the quantitative relationship between cumulative production and the resulting cost decrease of a technology. In our model, we specify learning-by-doing rates for: (i) battery manufacturing at 12% [33,34]; (ii) wind turbine manufacturing at 12.5% [35,36]; (iii) solar PV manufacturing at 20% [37]; and (iv) green hydrogen production at ~4% [38]. For wind turbines, the value of 12.5% corresponds to the midpoint of the range reported in the two respective sources.

For green hydrogen, the lower learning rate is applied at the system level, which means it concerns the overall hydrogen production process per se rather than the manufacturing of individual components such as electrolyzers. All specified learning rates are global average estimates and are applied uniformly across the three regions of GEM-E3-NLD. The details of how learning curves are modelled in GEM-E3 can be found in [39].

2.2. Integration of hydrogen supply chain activities in the GEM-E3 model

2.2.1. Selection of activities

We disaggregate the hydrogen sector into four categories: blue hydrogen, green hydrogen, hydrogen pipeline network, and underground hydrogen storage. In aligning with the European Commission and Dutch policy frameworks for a carbon-neutral energy system, we

assume the following:

- **Production:** our analysis is limited to zero-emission hydrogen production methods—Steam Methane Reforming with Carbon Capture and Storage (SMR + CCS) for blue hydrogen, and water electrolyzers powered by Renewable Energy (RE) sources for green hydrogen.
- **Transport:** the study exclusively focuses on gaseous hydrogen transport via pipelines, excluding liquid and chemically bound forms due to their higher energy intensity or lower Technology Readiness Levels (TRLs).
- **Storage:** given its high capacity and long-term storage capabilities, underground storage is assumed to be the primary storage method for hydrogen (this type of storage can contain substantially larger volumes of hydrogen in comparison to surface-level storage facilities such as tanks).

Fig. 1 depicts the hydrogen flow dynamics, beginning with the production of both green and blue hydrogen. These are then distributed to end-users via the pipeline network, after which end-users are invoiced for both production and transport costs. During periods of renewable energy surplus and low hydrogen demand, green hydrogen is channelled to storage facilities. The stored hydrogen can then be retailed during low RE generation/high-demand periods.

2.2.2. Model modification

This section describes the approach that we employ to incorporate the new hydrogen activities into the GEM-E3 model. The process began with an initial phase of extensive data collection, progressing through the creation of an investment matrix and an expansion of the input–output table. This was followed by a series of calibration and balance checks to validate the model's state of equilibrium, representing a balanced economic condition with supply and demand within each sector of the economy, and ensuring that the model's projections align with observed economic data. The final step of the process is the regional aggregation, which results in a customised version of the model for the Netherlands, denoted as GEM-E3-NLD. The process flow of our

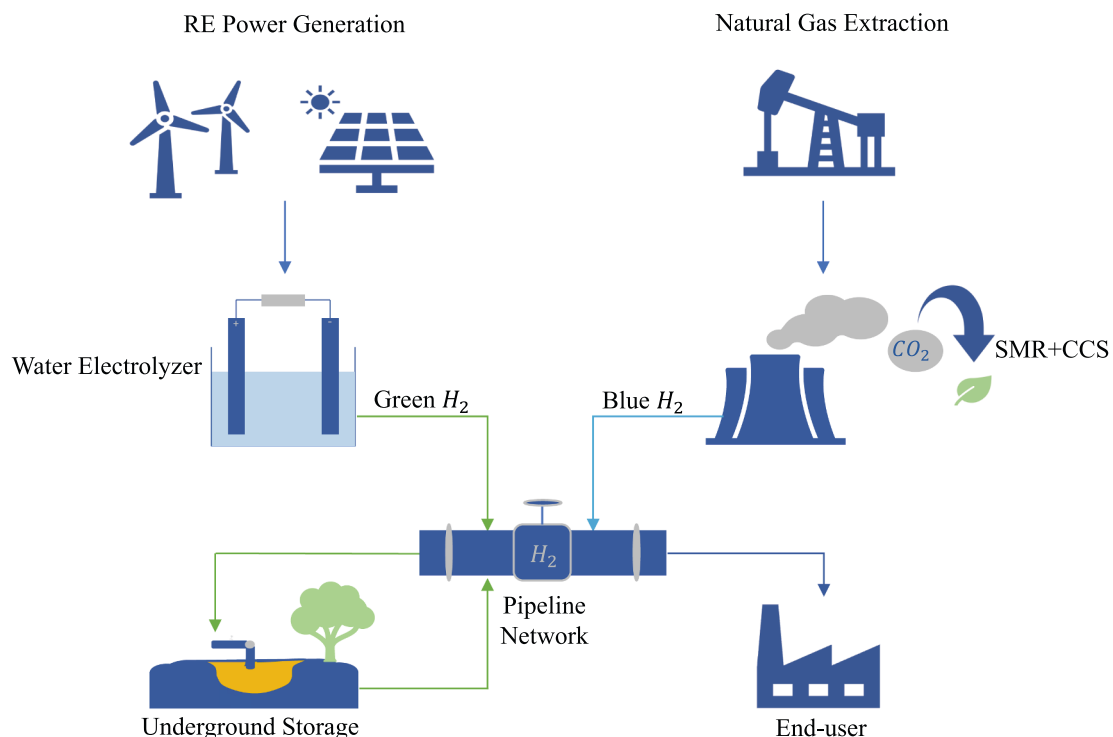


Fig. 1. Schematic representation of the hydrogen flow with respect to our methodological approach.

framework is visually summarised in Fig. 2, and all the steps are explained in detail in Appendix A.

2.3. The ESM: OPERA

The OPERA model is a Linear Programming (LP) optimisation model, designed to provide detailed insights into sector integration within the energy system [40]. While OPERA can be applied globally, its primary focus currently lies in representing the energy system of the Netherlands.

2.3.1. Database and scope

The model’s database comprises around 500 technologies from production to end-use demand services. It integrates extensive and diverse energy carriers that offer a comprehensive representation of the entire energy system, including bunker fuels, feedstocks, and all domestic GHG emissions.

2.3.2. Optimisation approach

OPERA employs a myopic optimisation approach, with time-steps of five years, meaning the optimisation is done for individual years, but the installed capacity is transferred to the subsequent period. The model incorporates high-resolution time-slice data, such as hourly wind speeds and electricity demand profiles, to enhance its accuracy and reliability.

2.4. Linking OPERA to GEM-E3-NLD

We implement a unidirectional soft-linking approach to link OPERA to GEM-E3-NLD. In this method, the output from OPERA feeds into GEM-E3-NLD, but not vice versa (see Fig. 3). Studies have shown that while a bidirectional loop can offer more insights (particularly when the ESM uses the CGE outputs to improve its results), the added complexity does not always yield proportionally greater benefits in understanding the interactions between the energy system and the broader economy [12,31]. In that regard, Delzeit et al. also emphasise that the choice between unidirectional and bidirectional soft-linking depends on the

research objective and the trade-off between analytical gains and model complexity [2]. In certain contexts, particularly where the focus is on the macroeconomic implications of changes within the energy sector, a one-way flow from the ESM to the CGE model can provide sufficient insights [2,15]. We adopt the following steps in linking the two models:

2.4.1. Transferred data points from OPERA to GEM-E3-NLD

When linking two models, specific points of contact are established through which data is transferred. The key data points considered in our study are outlined in Fig. 4. The choice of these variables varies across sectors based on their unique characteristics and energy needs. For example, in some sectors, expenditures related to consumer-level decisions, like personal vehicles, are relevant, while in others, such expenditures are not applicable. Similarly, sectors may focus on investments in specific energy technologies, such as geothermal energy in agriculture.

In the energy system model, investments are typically represented as a single value. However, when CCS is involved, this investment must be broken down into components, as the GEM-E3-NLD model includes a dedicated sector for CCS equipment. This disaggregation ensures accurate allocation of expenditures across both the primary technology and its associated emissions-reduction

2.4.2. Aggregation and alignment of sectors

OPERA provides a highly detailed representation of various technologies that are not mirrored in GEM-E3-NLD. In this case, we aggregate the outputs of the ESM to fit the broader and less technologically detailed structure of the CGE model. For example, instead of separate technologies for ‘off-shore wind energy’ and ‘on-shore wind energy’, we aggregate these into a single ‘wind energy’ category to align with the structure of GEM-E3-NLD. A detailed overview of the linked industry and energy generation sectors mapping is provided in Table 2B in Appendix B.

With respect to households, in OPERA, personal vehicles are categorised into several detailed types, including hydrogen cars, different electric car types, hybrid cars, and internal combustion engine (ICE)

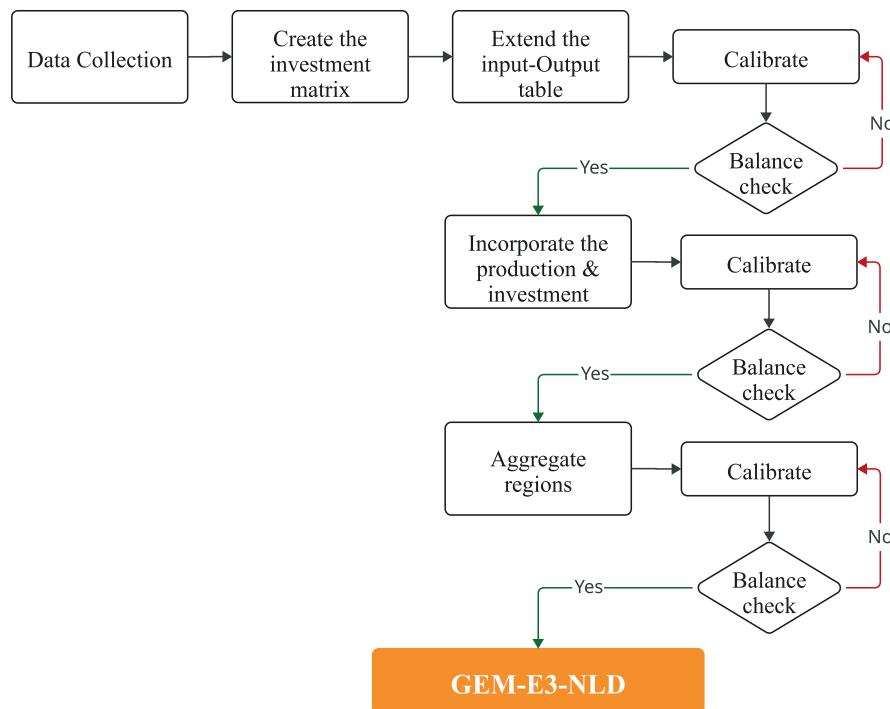


Fig. 2. Process Flow Diagram for the Integration of Hydrogen Activities into the GEM-E3 Model.

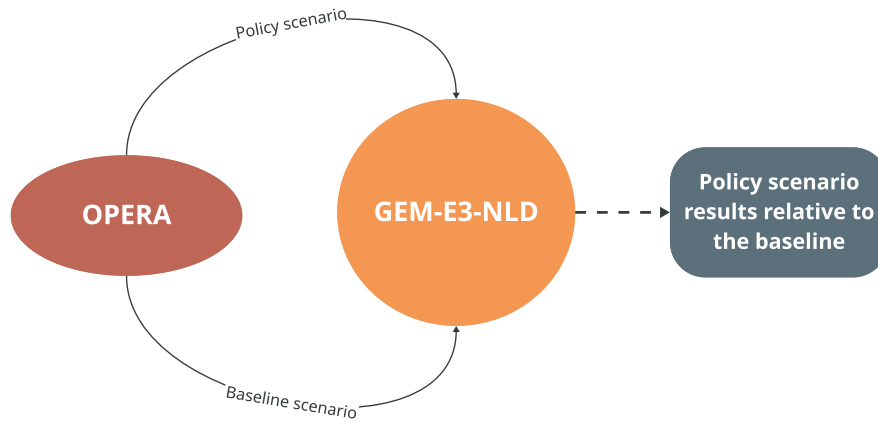


Fig. 3. Unidirectional soft-linking between OPERA and GEM-E3-NLD. Policy and baseline scenarios are generated in OPERA and used as exogenous inputs in GEM-E3-NLD. The linked sectors and variables are presented in Fig. 4. Model results are reported relative to the baseline scenario; details on the scenario setup are provided in Section 2.6.

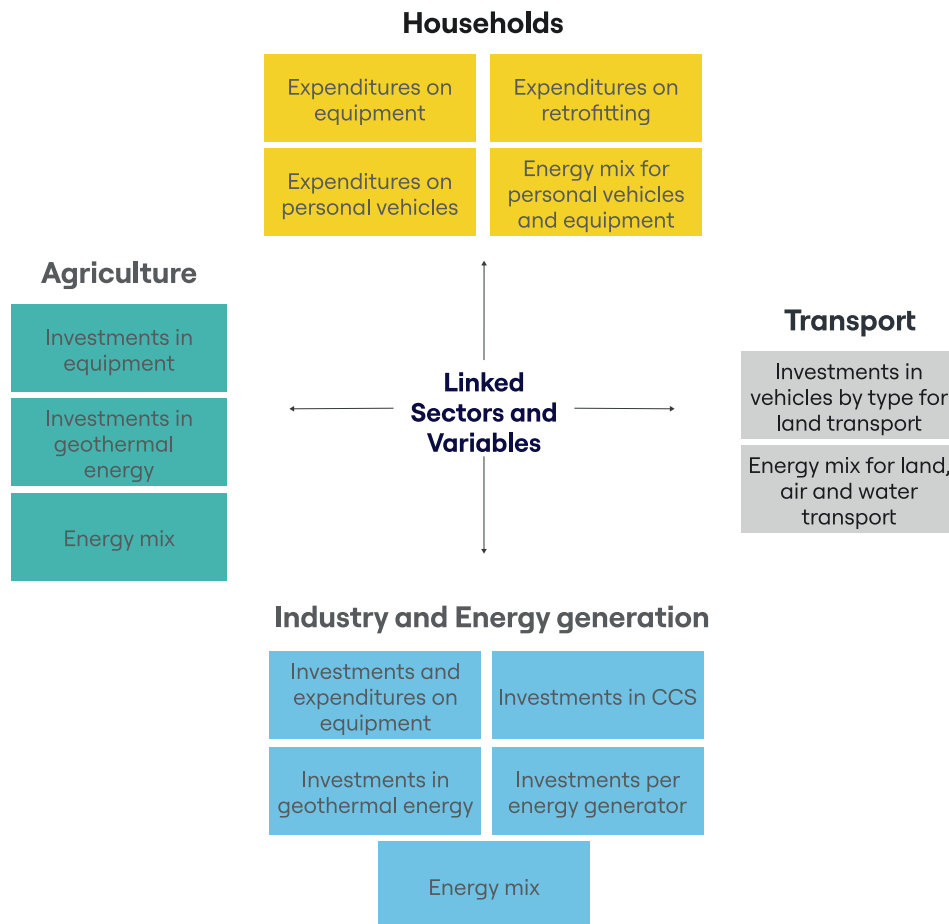


Fig. 4. An illustration of the sectors (households, transport, agriculture, and industry and energy generation) and variables (investments, expenditures, and energy mix by fuel and/or technology) considered when linking OPERA to GEM-E3-NLD.

cars. However, in GEM-E3-NLD, the categories are simplified to ICE and electric cars. To reconcile this difference, we split the expenditures for hybrid cars evenly: 50% is allocated to ICE cars, reflecting the fuel-based component of hybrids, and the other 50% is assigned to electric cars, representing the electric drive component. This assumption is consistent with the hybrid vehicle cost structure literature, which characterises hybrids as combining substantial conventional and electric drivetrain components [41,42].

2.4.3. Reconstructing the investment structure in GEM-E3-NLD

In CGE models, investments follow a general sectoral structure that includes categories such as equipment, construction, and other sectors. When an exogenous investment is introduced, it is distributed according to this structure. Within the equipment category, there are more specific sectors, such as ‘Advanced Electric Appliances’ and ‘Advanced Heating and Cooking Appliances’. This, in turn, requires additional specifications to direct the funds to the relevant and correct equipment sectors

that better align with the technology shifts associated with the energy transition. We categorise the investment outputs from OPERA, based on their input energy carrier. Given the complexity of OPERA with such a large number of technologies, we first aggregate the investments across technologies for each sector and then reorganise them by energy carrier. This allows us to allocate investments more accurately in GEM-E3-NLD. For example, if 30% of the investments are in technologies that use electricity as their input energy carrier, then this 30% will be allocated to the economic sector responsible for manufacturing electric equipment (see Eqs. (1) and (2)).

$$TotalI_{br_k,t}^{ESM} = \sum_{pr_{en} \in Pr_{en}} I_{br_k,pr_{en},t}^{ESM} \quad (1)$$

$$I_{br_k,pr_{en},t}^{ESM-\%S} = I_{br_k,pr_{en},t}^{ESM} / TotalI_{br_k,t}^{ESM} \quad (2)$$

where:

Br_k is a set that we define to represent the sectors/activities that are directly linked to the ESM; br_k denotes a sector/activity belonging to this set; $TotalI_{br_k,t}^{ESM}$ is the total investment drawn from the ESM for a specific sector (br_k) and time period (t). This excludes investments of br_k in CCS and geothermal technologies; Pr_{en} is a set of primary energy carriers used in GEM-E3-NLD, such as electricity, gas, or oil; pr_{en} denotes a specific carrier within this set; $I_{br_k,pr_{en},t}^{ESM}$ is investment per energy carrier for a specific sector at time period (t); $I^{ESM-\%S}$ is the share of investments in the ESM for a specific industrial sector (br_k and primary energy carrier (pr_{en}) at time period (t), expressed as a percentage of total investments for the sector.

It is also important to note that CGE models typically interpret investments as capital accumulation, which does not align with the nature of the energy transition. The core objective of an energy transition is to substitute existing technologies with cleaner alternatives rather than increasing overall capacity. To accurately capture this, we treat a proportion of the exogenous investments as expenditures on equipment (see Eqs. (3) and (4)).

$$I_{br,reg,t}^{exo} = \alpha_{br-I} \cdot \sum_{br_k \in Br_k: M(br_k, br)} \sum_{pr_{en} \in Pr_{en}} I_{br_k,pr_{en},t}^{ESM}, \forall_t > 2020 \quad (3)$$

$$E_{br,reg,t}^{exo} = \alpha_{br-E} \cdot \sum_{br_k \in Br_k: M(br_k, br)} \sum_{pr_{en} \in Pr_{en}} I_{br_k,pr_{en},t}^{ESM}, \forall_t > 2020 \quad (4)$$

where:

Br is a set of all the sectors/activities in the GEM-E3-NLD; br denotes a sector/activity belonging to this set; $I_{br,reg,t}^{exo}$ is the exogenous investments allocated to a specific br and region (reg) at a time period (t); α_{br-I} is the allocation factor used to multiply the total investments for a specific br_k , drawn from the ESM, in order to allocate part of it to capital investments in GEM-E3-NLD; $E_{br,reg,t}^{exo}$ is the exogenous expenditures allocated to a specific br and region (reg) at time period (t); α_{br-E} is the allocation factor used to multiply the total investments for a specific br_k , drawn from the ESM, in order to allocate part of it to expenditures in GEM-E3-NLD; $M(br_k, br)$ is a binary mapping parameter equal to one if ESM sector/activity br_k is mapped to GEM-E3-NLD sector/activity and zero otherwise.

2.4.4. Accounting treatment of exogenous investments and expenditures in GEM-E3-NLD and macro closure

The exogenous investments and expenditures defined above (and introduced from the energy system model) are incorporated into the model accounts in line with the social accounting matrix convention, whereby all expenditures are matched by corresponding sources of financing. This is orchestrated by the macro closure of GEM-E3-NLD, which ensures that global savings equal global investments, with global savings adjusting endogenously to match investments; these adjustments reflect the combined response of household and foreign

savings.

Exogenous investments (I^{exo}) are treated as sector-specific capital accumulation and therefore contribute to the evolution of the capital stock by sector. By contrast, exogenous expenditures (E^{exo}) enter the model as additional demand for equipment and machinery related to energy-saving and technology replacement. These expenditures increase demand for capital goods but do not translate into additions to the productive capital stock.

2.5. Using GEM-E3-NLD

The process of using CGE models in policy analysis involves several key steps, which we summarised in Fig. 1A (see Appendix A: Using GEM-E3-NLD). These steps follow the principles set out by Shoven and Whalley [43]. The first step is to provide the model with the basic data, such as I/O tables and trade data, which is primarily based on the existing database (refer to Sections 2.1.4 and 2.2). Once the link between the two models is concluded, we calibrate and test GEM-E3-NLD, to see if it can replicate historical trends and the base year data. This is a crucial step in verifying the accuracy of the model and identifying any potential errors. Upon successful replication check, where the model is correctly processing the input data to produce plausible results, the benchmark equilibrium is obtained. This benchmark represents the economy in a state of equilibrium without any external shocks or policy interventions. It serves as a critical reference point against which the impacts of various scenarios can be measured and compared. We then use the model to run the scenarios and conduct our comparative analyses.

2.6. Scenarios

I. Business-As-Usual (BAU) scenario:

This scenario reflects the present status of the Dutch energy sector. It focuses on current trends in energy consumption with moderate advancements in renewable energy and greenhouse gas reduction. The BAU CO₂ price trajectory, which follows the Dutch Climate and Energy Outlook (KEV), and the corresponding greenhouse gas emission reduction pathway are presented in Tables 3 and 4, respectively, both in Appendix A.

II. Energy Transition (ET) scenario:

This scenario is based on the well-established Dutch decarbonisation scenario, TRANSFORM [44,45], developed at TNO. TRANSFORM aims for climate neutrality by 2050; it involves extensive use of renewable energy, significant infrastructure overhaul, and major shifts in energy consumption patterns. In the ET scenario, we extend the role of wind and solar energy, based on the maximum possible socio-economic and environmental potential of these sources in the Netherlands, as calculated in Refs. [46,47]. The techno-economic parameters of the technologies used in OPERA are available in Ref. [48]. The CO₂ price trajectory in ET is calculated endogenously within OPERA and corresponds to the abatement cost pathway consistent with achieving climate neutrality by 2050 (see Tables 3 and 4, Appendix A). We present the energy mix and the net GHG emissions generated by OPERA for the BAU and ET scenarios over the analysis period (2025–2050) in Appendix A: OPERA results. In these scenarios, we employ the default macro closure of GEM-E3, assuming a savings-investment balance at the global level.

III. Energy Transition-Capital Availability (ET-CA) scenario:

In this scenario, we run the ET scenario but with a different macro closure where we fix the foreign capital inflows at the levels observed in the reference scenario for each region. This implies that any additional investment demand beyond the fixed inflow must be financed

domestically, i.e. national investment equals national savings.

2.7. Indicators

We employ the following key economic indicators for assessing our modelling results:

- Gross Domestic Product (GDP):** computed as the sum of household consumption, government spending, investments, and net exports (exports minus imports). Real GDP is derived by deflating nominal values using the base year prices.
- Unemployment rate:** percentage of the labour force actively seeking employment but unable to find jobs. GEM-E3 differentiates between potential labour supply (exogenous; based on demographic projections) and effective labour supply (endogenous, driven by a wage curve). The wage curve links wages to unemployment: as labour demand rises, wages increase, which draws more workers into the labour market. GEM-E3 divides the labour market into five segments: low-skilled, shop service, technicians, clerks, and managers, each with its own wage rate and set of constraints. This segmentation often leads to involuntary unemployment, where individuals are willing to work but cannot due to structural factors such as a lack of necessary skills. Even though some workers may be unemployed due to these constraints, the labour market is still considered to be in equilibrium because no individual can unilaterally improve their situation, hence referred to as the natural rate of unemployment or imperfect equilibrium.
- Consumer Price Index (CPI):** a measure of average price changes for a basket of consumer goods and services. In GEM-E3, CPI is based on the Paasche price index [49], tracking price changes of household consumption goods relative to a base year. It is calculated as the ratio of the current cost of the current basket to the base year cost of the current basket, multiplied by 100. Following this definition, if the CPI is reported as 116 in 2030, it indicates a 16% higher price level than it would have been if priced at base-year prices. Prices are endogenous, driven by production costs (e.g. energy costs or wages), import tariffs, and taxes.
- Compensating Variation (CV):** income adjustment required to maintain pre-policy household utility levels after economic shocks [50]. In GEM-E3, CV is calculated based on household utility functions, which depend on consumption levels and prices [51,52].

3. Results

The Dutch energy system is to be reshaped by hydrogen and other alternative fuels. Fig. 2A (see Appendix A) shows the energy mix by source, expressed as a percentage of the total final energy supply in the Netherlands for the BAU and ET scenarios. In the BAU scenario, fossil fuels dominate throughout the analysis period, decreasing from 81% of the energy mix in 2025 to 55% by 2050. While alternative fuels show limited growth, with their combined share rising from 6% in 2025 to 15% in 2050.

The ET scenario shows a significant shift in the energy mix, with fossil fuels declining to 11%, replaced by alternative fuels, including hydrogen, synthetic fuels, and bio-based energy, which considerably rise to 85% by 2050. The hydrogen share reflects only direct consumption and excludes its use in producing synthetic fuels and certain biofuels. Similarly, the electricity share does not account for its use in hydrogen production and synthetic fuel processes. This means that the actual contribution of both hydrogen and electricity to the system is higher than indicated in Fig. 2A. This overview is essential as it provides context for interpreting the detailed macroeconomic indicators presented in the following sections.

3.1. GDP

Fig. 5 illustrates GDP growth across the three scenarios, with changes in its components as shown in Fig. 6. In 2025, GDP in ET is slightly higher than in BAU. This early gain reflects higher investment levels coinciding with an unchanged energy mix compared to BAU, which allows investment to temporarily boost economic activity without immediate disruption. From 2030 to 2040, as the energy mix shifts towards renewables and energy prices rise, transitional disruptions occur: production slows, exports decline, and short-term growth is limited. These disruptions are driven by higher energy prices and the costs associated with replacing existing technologies, which increase production costs. However, as the transition matures, these effects moderate and GDP in ET begins to outpace BAU from 2045, reaching more than €1.2 trillion in 2050 (1.7% higher than BAU in that year).

In the ET-CA scenario, GDP initially declines compared to BAU, with the gap widening and reaching its largest point around 2035. While GDP begins to recover thereafter, it remains below BAU levels through 2040 and only shows a modest improvement by 2045, reaching +0.6% relative to BAU in 2050. The constraint on the current account limits the ability to rely on foreign financing, reducing domestic consumption and investments. Consequently, there is less demand for imported goods and services.

The reduction in exports is less pronounced in ET-CA compared to ET. Since the economy cannot rely on external financing, it prioritizes exports to generate the foreign currency needed to sustain import demands. The observed peak in investments in 2035 in ET-CA (see Fig. 6b) coincides with a dip in private consumption. This relationship reflects the crowding-out effect, where increased national investments draw resources away from household consumption who are incentivized to save more to compensate for constrained external financing.

To assess the macroeconomic cost-effectiveness of emissions reduction, we have calculated the change in GDP per tonne of CO₂-equivalent avoided ($\Delta\text{GDP}/\Delta\text{GHG}$) between the ET and BAU scenarios (see Table 1). This indicator reflects the broader economic costs-benefits of climate action in absolute terms. While it is negative in the earlier periods (e.g., -396 €/tCO₂ in 2030), it turns positive by 2040 and reaches +349 €/tCO₂, indicating that in the long run the transition delivers both

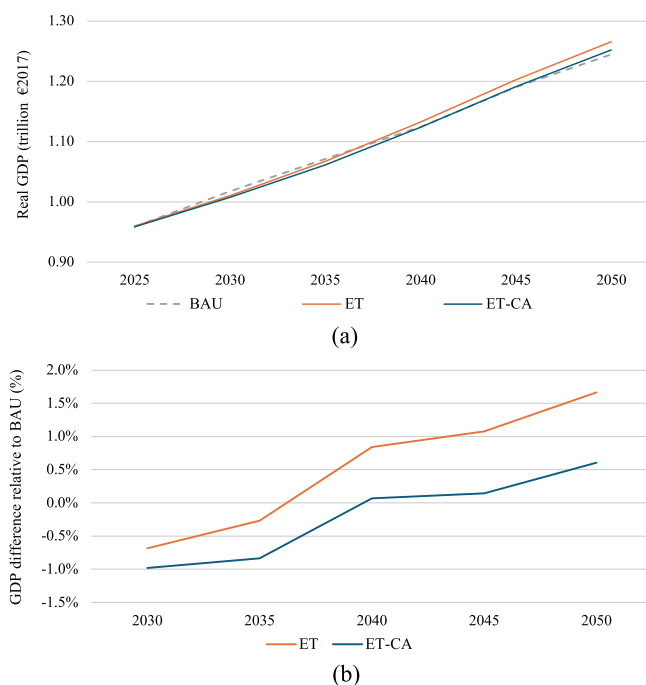


Fig. 5. Real GDP (€2017) for the three scenarios over the analysis period (a), and the GDP difference in % from BAU for the ET and ET-CA scenarios (b).

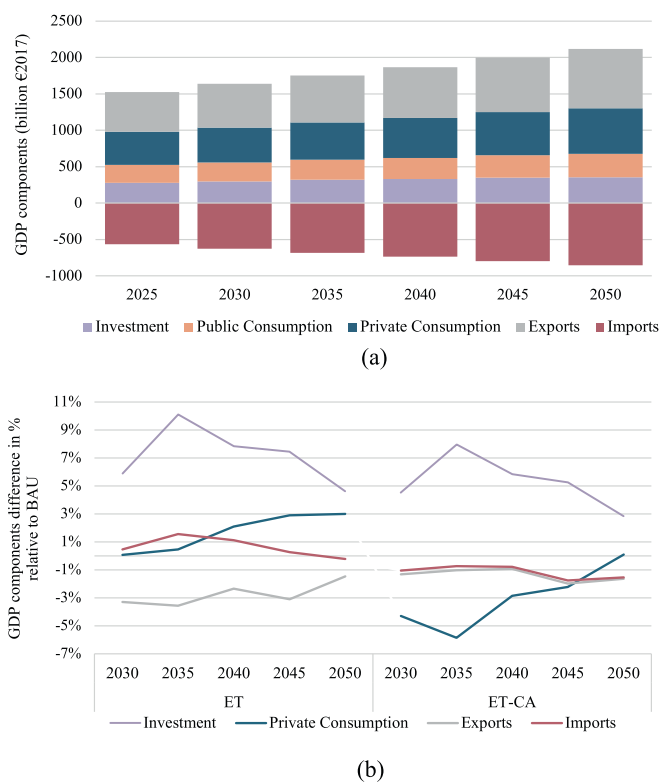


Fig. 6. The GDP components of the baseline in base year prices (a), and the difference in % for the investment, private consumption, exports, and imports components of the GDP from BAU for the ET and ET-CA scenarios (b).

Table 1
Macroeconomic cost-effectiveness of GHG emission reduction, 2030–2050.

Indicator	Unit	2030	2035	2040	2045	2050
ΔGHG (BAU-ET)	MtCO ₂	18.8	19.8	29.9	47.5	61.9
ΔGDP (BAU-ET)	bn €2017	-7	-3	10	14	24
ΔGDP/ΔGHG	€/tCO ₂	-396	-157	349	304	385

environmental and economic gains. This shift around 2040 coincides with easing transition-related expenditure pressures and continued cost reductions from learning effects in ET, along with a diminishing relative impact of the carbon price as the energy mix becomes largely fossil-free; by contrast, in BAU (to which the ET results are relative), the carbon price remains more binding as fossil fuels continue to dominate the energy mix.

Table 2 shows that the cumulative GDP slightly declines under both transition scenarios compared to BAU. In the ET scenario, cumulative GDP increases by €132.6 billion, while under ET-CA it declines by €70.2 billion. Although these differences are modest relative to the overall economy size, they indicate that the Netherlands would experience stronger economic growth under ET, whereas the current account constraint in ET-CA results in a slower growth path, leaving the country slightly less wealthy by 2050 than under BAU.

Table 2
Cumulative GDP in the Netherlands under the three scenarios over the period 2025–2050.

Scenario	Cumulative GDP (bn €2017)	Difference from BAU (bn €2017)
BAU	30,258	0
ET	30,390	133
ET-CA	30,187	-70

3.2. Unemployment rate

The shift to renewable and low-carbon fuels is expected to drive significant changes in employment across different sectors. Under the ET scenario, employment declines in traditional sectors such as refineries, gas-fired power, and blue hydrogen, as lower output directly reduces labour demand. This contraction spills over into related services such as oil-services firms, agents in fuels and chemicals, and wholesale trade of motor-vehicle parts and maintenance. However, after 2030, as the penetration of renewables and low-carbon fuels increases in the energy mix, employment expands in green sectors such as biofuels, synthetic fuels, hydrogen production, and renewable power, partially offsetting the job losses in fossil-based industries. Production costs also decline over time as the major transformation expenditures are done, which further reduces the pressure on firms. Manufacturing shows a mixed outcome, with increased employment in metals and equipment production, mainly driven by increased demand for wind turbine and solar panel components. However, the number of jobs in the chemical and other manufactured goods goes down as traditional industries shrink (for an overview, see Table 1C, Appendix C).

As shown in Fig. 7, both ET and ET-CA result in a higher unemployment rate compared to BAU due to the transition away from high-carbon industries. In the ET scenario, the unemployment rate reaches 4.5% in 2035. After that, unemployment in ET declines steadily and gradually converges towards the BAU level by 2050, with a difference of about 0.2%. This indicates that as transformation costs stabilise, the economy recovers and unemployment returns close to baseline levels. In contrast, unemployment in ET-CA remains slightly higher throughout the period, reflecting the combined effects of higher financing costs and slower investment recovery. The BAU scenario, on the other hand, maintains a lower unemployment rate of approximately 4% throughout the period with moderate variation, which reflects less disruption to existing industries.

3.3. CPI

The changes in the energy system are reflected in the CGE primarily through shifts in the energy mix across sectors. In both ET and ET-CA, these shifts introduce structural shifts in production, consumption, and costs, which propagate along value chains and raise prices for goods and services. Consequently, the CPI is higher under these two scenarios when compared to BAU (see Fig. 8), a pattern documented in the literature [53,54].

ET shows a higher CPI than ET-CA till 2040, which coincides with the higher investment and expenditures activities in the early stages of the transition (before 2045). This raises demand for construction, equipment, and labour, driving up prices in these sectors and spilling over into the broader CPI basket. However, declining investment demand post-2040 reduces CPI pressure in ET. In ET-CA, private consumption has

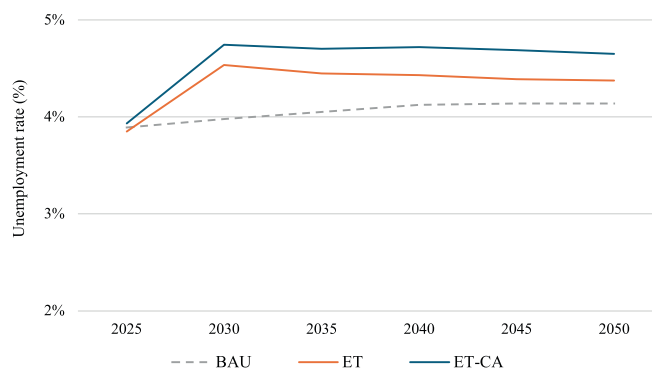


Fig. 7. Unemployment rate for the BAU, ET, and ET-CA scenarios. Values are normalised to CBS (2019).

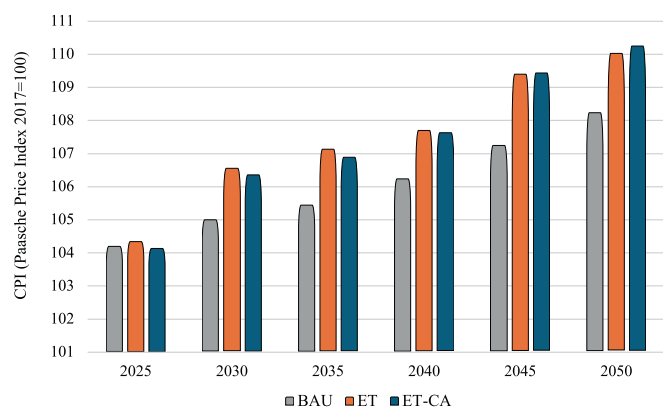


Fig. 8. Percentage change in the CPI relative to the BAU scenario for the ET and ET-CA scenarios.

consistently been lower than in ET due to tighter economic conditions and limited growth in household incomes. While this might suggest lower demand-driven price pressures, the persistent supply-side constraints (e.g. higher import costs) keep production costs high and prevent broader price relief in ET-CA.

3.4. Compensating variation

To evaluate the welfare impacts of the policy changes, the CV for ET and ET-CA is presented in Fig. 9. Both scenarios experience welfare losses in the early years of the transition, though their magnitude differ. Under ET, welfare losses peak around 2030 and gradually decline thereafter. As the transition progresses, welfare losses decrease considerably under the ET, turning positive by 2040 and continues to rise through 2045 and 2050. In contrast, welfare in the ET-CA scenario remains negative throughout the entire period.

The early welfare decline in ET stems from the high production costs and substantial investments required to transform the energy system. After 2040, when a large share of renewable and hydrogen capacities is already in place, the CV improves. This welfare improvement is not driven by higher wage rates, since unemployment remains relatively high in ET, but by an increase in disposable income. This subsequent increase results from higher returns on capital, reflected in the larger dividend payments households receive from firms, which result from the capital-intensive nature of low-carbon technologies.

Even with the same energy mix, the CV in ET-CA remains considerably higher. This can be attributed to higher energy prices resulting from costlier financing (e.g. higher interest rates) and increased import costs

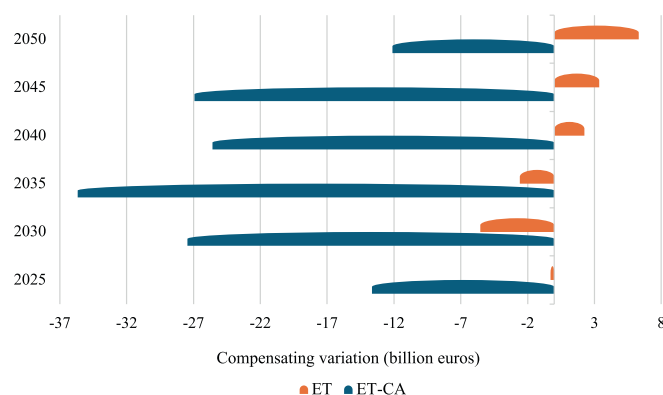


Fig. 9. The annual compensating variation for the ET and ET-CA scenarios. Note that although our CV values are negative—signifying welfare losses—we plot their absolute magnitudes as positive bars in the figure to focus on the size of the loss.

(e.g. machinery and equipment), as well as households allocating a larger share of their disposable income to savings, which further delays welfare recovery.

4. Discussion

The ET scenario has potential long-term benefits, with gains in GDP after 2040. These gains are mainly attributed to: (1) carbon prices no longer having a pronounced effect, as the energy mix becomes largely fossil-free; and (2) learning rates reducing the costs of green fuels and electricity. These results are in line with the macroeconomic modelling literature, which finds that the marginal GDP impact of carbon pricing declines over time as the economy becomes increasingly decarbonised [55,56], while learning-by-doing and technological progress reduce energy system costs and mitigate the GDP burden of climate policy in the long run [57]. This shift in the balance between transition costs and benefits also explains the evolution of the $\Delta\text{GDP}/\Delta\text{GHG}$ indicator in Table 1, which turns positive after 2040. Over the entire 25-year period, cumulative GDP is positive in ET but negative in ET-CA, which underscores that only ET manages to offset early losses through late-stage gains, whereas ET-CA leaves the Dutch economy worse off overall. In ET, however, these gains reflect investment-led growth where higher capital formation raises measured GDP.

The transition to renewables creates more jobs in the power sector than it eliminates, which aligns with other studies [58,59]. However, the new jobs created do not fully compensate for job losses in other parts of the economy, which stem primarily from structural unemployment driven by two main factors. First, production shifts that increase input costs (driven by green energy adoption and carbon pricing) disrupt competitiveness for some industrial sectors. Second, job losses occur in service sectors tied to fossil fuel value chains. This is also consistent with findings in the existing literature [60–62]. For example, a recent CGE study examining Scotland's oil and gas sector demonstrates that transition-related unemployment extends beyond direct fossil fuel industries and affects other related sectors, such as manufacturing, financial services, insurance, and retail trade [62].

Citizens' welfare, as measured by CV, suffers its largest annual loss at the beginning of the transition, before tapering off in later years. This outcome is in line with the findings of Vandyck et al. [63] and Maier et al. [64], who also report negative compensating variation under decarbonisation policies (e.g. carbon taxation). The CV, however, only reflects changes in household utility and the income needed to restore it. It excludes external costs, such as health impacts from air pollution (which lead to additional healthcare spending). Ignoring these effects means that we are underestimating total welfare losses in the BAU. The ET and ET-CA scenarios represent two extreme assumptions regarding access to foreign financing. In principle, the actual macroeconomic outcomes would fall between these two cases. The ET-CA scenario further highlights how restricting external financing can significantly increase the economic costs of decarbonisation. These findings reinforce the need for financial support mechanisms during the transition. Initiatives such as the Just Transition Fund (JTF) and the EU Innovation Fund will be critical in supporting a smoother transition, easing domestic adjustment costs, and maintaining economic stability. Our version of the GEM-E3 model introduces financing through a "World Bank" (a national bank in the case of ET-CA) that collects savings from surplus agents and provides financing to agents in deficit—a standard method for modelling financial flows in CGE models. However, the lack of explicit loan repayment mechanisms and debt accumulation in our framework may overlook how growing debt burdens influence long-term economic outcomes. Incorporating such financial details would align the model's outcomes more closely with real-world economic behaviour, as demonstrated by Paroussos et al. [57].

Building on GEM-E3's existing disaggregation of synthetic fuels, biofuels, biomass, and natural gas, we further enrich the model by adding four hydrogen activities: green H_2 production, blue H_2

production, H₂ storage, and pipeline transport. Such disaggregation for alternative fuels is essential in CGE modelling when analysing the energy transition because each pathway follows a different cost curve, energy mix, learning-rate trajectory, and labour intensity. Without this level of detail, the model misrepresents these structural differences, thus producing inaccurate macroeconomic projections.

Another important aspect we account for in our study when linking OPERA to GEM-E3-NLD is how we treat green technology investments in industry. Instead of being interpreted by the model as capacity expansion, a major portion of these investments is treated as expenditures, which reflects the replacement of existing technologies (e.g. substituting conventional blast furnaces with hydrogen-based direct reduction in steelmaking). This modelling choice has an impact on production, where costs increase not only due to rising energy prices but also due to the expenditures associated with this technological shift. This is one of the factors behind the initial GDP contraction and the slow recovery observed in our energy transition scenarios.

A limitation of our approach is that the OPERA model is linked only to the Netherlands within GEM-E3-NLD. While consistent with OPERA's national focus, this assumes that other regions (the rest of the EU and the rest of the world) do not undergo a similar energy transition. As a result, carbon pricing or sustainability-driven cost pressures are absent outside the Netherlands. This creates a structural asymmetry in trade: Dutch industrial sectors bear the full burden of decarbonisation via carbon taxes and capital expenditures, while their international competitors continue to operate under lower-cost regimes. A more balanced representation would require extending ESM integration and climate policy assumptions to the other regions. This, however, would require extensive data on energy infrastructure, policies, and market dynamics from neighbouring countries, which is not readily available or feasible to integrate within the scope of this study.

CGE models offer valuable insights into the macroeconomic and sectoral outcomes of the energy transition, but they have limitations. They assume perfect market clearing and rational expectations, which abstract from real-world complexities such as behavioural frictions and political resistance. Another limitation that stems from the OPERA model is that electricity prices are assumed to be uniform across sectors, whereas in reality, industrial and residential sectors face different prices, which would influence production costs. Moreover, fossil fuel prices are treated exogenously, which means that price volatility (driven by global supply shocks or geopolitical events) is not captured. Linking CGE models with ESMs, while improving technological resolution, introduces additional challenges—mainly around consistency in time dynamics, sectoral granularity, and assumptions about technological uptake. Addressing these limitations in both modelling frameworks often requires imposing stylised assumptions, such as full social acceptance of sustainable practices, which are far from guaranteed in practice. In reality, citizens' willingness to embrace transition policies varies widely, as discussed in [65], and our models do not yet account for this heterogeneity. Therefore, our CGE-ESM results should not be interpreted as deterministic forecasts, but as contingent scenarios highly sensitive to socio-political dynamics and market uncertainties.

5. Conclusion

This study examines the macroeconomic impacts of the energy transition in the Netherlands, towards carbon neutrality by 2050, under scenarios with and without limited capital inflows. We soft-link an ESM to a global CGE model, which allows us to better capture sector-specific energy system details, such as the adoption rates of green technologies and the energy mix required for newly deployed technologies. Additionally, we enrich the GEM-E3 model by incorporating activities that reflect a comprehensive hydrogen supply chain, ensuring that the economic dynamics of hydrogen-based energy solutions are captured in our analysis.

Our results demonstrate that:

1. Although cumulative GDP over the full period is positive in ET, this mainly reflects investment-led growth.
2. The shift to renewables creates more jobs in the power sector than it eliminates, but structural unemployment causes higher unemployment rates across the whole economy during the transition years, before gradually converging towards BAU levels by 2050.
3. Citizens' welfare declines during the early transition years, which reflects the immediate trade-offs between environmental benefits and socio-economic costs before welfare improves later in ET due to the capital-intensive nature of low-carbon technologies.
4. The ET-CA scenario amplifies unemployment and welfare losses compared to the ET scenario due to the limited foreign capital inflows. The actual macroeconomic outcome is likely to fall somewhere between these two extremes, as no economy is ever fully closed or entirely reliant on external financing.

The two employed energy transition scenarios (ET and ET-CA) are benchmarked against a baseline that reflects the Netherlands' current national plans. While this baseline already incorporates "greening" measures, it remains insufficient to achieve carbon neutrality by 2050. Our analysis thus compares incremental changes under existing policies (baseline). The BAU scenario might be overly optimistic, as it does not account for climate-related risks such as sea-level rise (which is particularly relevant for the Netherlands given its geographic vulnerabilities). It also overlooks the productivity losses and health impacts that result from environmental degradation. Accounting for these factors would likely lower GDP growth under BAU over time, which can bring its cumulative GDP substantially below that of the transition scenarios. Future research should incorporate health and environmental damage modules for a more holistic assessment of the transition impacts. Without strong policy frameworks, the socio-economic impacts in both ET and ET-CA could outweigh their environmental benefits.

These policy challenges are particularly pronounced in hard-to-abate, energy- and trade-exposed industries such as steel and chemicals, which rely heavily on hydrogen adoption in the transition scenarios. In steel production, the shift towards hydrogen-based processes (e.g. DRI) entails substantial upfront capital expenditures and infrastructure requirements, which contribute to competitiveness pressures. Targeted policy instruments, such as carbon contracts for difference (CCfDs) or expanded SDE++ support, can help bridge the cost gap during the transition phase and mitigate risks of carbon leakage and export losses. Similarly, in the chemical sector, the use of hydrogen as a feedstock requires coordinated support for pilot deployment and shared infrastructure (e.g. pipeline and storage networks) to avoid structural employment shifts and competitiveness losses in downstream manufacturing. Strengthening sector-specific transition support for these industries is therefore critical to ensuring that decarbonisation objectives are achieved without undermining the Netherlands' industry. Policy measures such as wage subsidies and social safety nets are also essential to mitigate labour market disruptions during the transition.

Although hydrogen trade is becoming increasingly relevant, it was excluded from our scenarios. This is because the energy transition is modelled only for the Netherlands, while other regions are not assumed to decarbonise. As a result, there is no implied demand for hydrogen abroad, making international trade in hydrogen irrelevant within our modelling framework. Because of the broad objectives and size limitations of this paper, we also did not provide an in-depth analysis of hydrogen as a standalone topic, which we are to explore in a future extension of this work. Additionally, the current version of the GEM-E3 model does not include dedicated sectors for materials recycling, a feature that is often missing in many CGE frameworks. This and other limitations suggest that further model refinements are needed for a more comprehensive analysis of the energy transition.

Finally, our analysis highlights the essential role of policy in pursuing goals that markets alone will not achieve, such as environmental and climate stability. Among such policy instruments, international financial

mechanisms (intra-EU in the case of the Netherlands) are especially important in mitigating socio-economic disruptions during the transition.

CRediT authorship contribution statement

Ahmed M. Elberry: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Kostas Fragkiadakis:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Leonidas Paroussos:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Joost van Stralen:** Writing – review & editing, Validation, Software, Formal analysis.

Martin Scheepers: Writing – review & editing, Investigation, Formal analysis. **Jos Sijm:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **André Faaij:** Writing – review & editing, Supervision, Resources, Project administration, Formal analysis, Conceptualization. **Bob van der Zwaan:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

1. GEM-E3 structure

A.1. Agents and behaviour

Four key economic agents – households, firms, governments, and banks – play a central role in shaping the economic equilibrium in the GEM-E3 model. The behaviour of the agents is governed by a utility function, which serves as a mathematical representation of their preferences. It reflects how agents make choices to maximise their well-being or satisfaction, subject to various constraints, such as income and prices.

A.2. Markets

In the GEM-E3 model, the economy is categorised into four essential and interconnected markets: product, capital, labour, and money. Each market has its distinctive market-clearing conditions under which prices or wages adjust to equate supply and demand. These aspects of the model are discussed thoroughly in the model's documentation [51].

A.3. Production function

Two primary types of production functions are employed in the GEM-E3 model: Constant Elasticity of Substitution (CES) and Leontief [51]. Each function is tailored to the unique characteristics of different economic sectors. These functions are rooted in the concept of elasticity of substitution, where different sectors exhibit varying levels of flexibility regarding how their inputs can be substituted for one another.

In the power production sector, a Leontief production function is applied, signifying an elasticity of substitution of zero [66]. This rigidity is crucial because the technology (capital) chosen often dictates the type of energy source in power production. A coal-fired plant, for example, cannot readily switch to using natural gas without significant modifications or complete replacement of existing infrastructure.

For non-energy and resource sectors, the CES concept is used where the production function has a hierarchical structure that reflects the potential for substituting different types of inputs across multiple levels [66]. At the first level in non-energy sectors, the substitution is between categories where capital, labour, and energy (KLE) are often combined on one side, and materials (MA) on the other. This configuration suggests that, at this level, these inputs are deemed primary and there is a limited potential to substitute between the two bundles. By way of example, a furniture manufacturing company at the first level has capital (machinery, plant, buildings) and labour (carpenters, machine operators) on one side, and materials (wood, metal, textiles) on the other. The company cannot replace a carpenter with additional wood or a sewing machine with more fabric; these inputs serve different roles in the production process.

However, at the second level, substitution takes place within categories. As such, if the cost of wood increases, the company might substitute it with a cheaper type of wood or another material like metal or plastic, depending on the product requirements and customer preferences. Likewise, if labour costs rise, the company might invest in more automated machinery to reduce reliance on manual labour. Moving down the hierarchy, the model represents alternatives for specific inputs in a more detailed manner. For instance, within the labour input, there might be a higher degree of substitution between skilled and unskilled labour, depending on the task requirements and the training costs. This hierarchical approach enables the model to simulate how an industrial activity might recalibrate its combination of inputs in reaction to market fluctuations, thereby enhancing production efficiency and ensuring economic viability.

2. Steps of the Integration of Hydrogen Activities into the GEM-E3 Model

Step 1. Data collection

We started by gathering detailed data on investment costs and the operational cost breakdown. However, achieving this detailed breakdown was not without challenges. In particular, securing accurate labour data proved to be a complex task, yet it was of utmost importance, as inaccuracies can significantly impact the reliability of the model's outputs.

Step 2. Investment matrix formulation

The investment matrix delineates the economic structure and intersectoral relationships, illustrating how investment in one sector can impact others, either directly or indirectly. We construct an investment matrix for each new activity by allocating investments across various activities in the economy. Each allocation represents the cost per unit of the investment in that specific activity or sector (e.g. €/MW).

Step 3. Expanding the input–output table

The Input-Output (I/O) table is crucial within any CGE model, including GEM-E3. It depicts the flow of goods and services between different sectors, or activities, within the economy, capturing the interdependencies and transactions that occur in the production of goods and services. In the I/O table, columns represent inputs, detailing the various sectors that provide resources or services to each specific sector, while rows represent outputs, showing where each sector's production goes. We hereby describe the process of populating the columns and rows in the I/O table for the new hydrogen activities.

a. Constructing the cash flow and determining the hydrogen price

With the fundamental assumption of an 8% interest rate, combined with the data previously collected (including capacity factors and established lifetimes for technologies in each relevant activity), we construct the discounted cash flow as per the following steps:

1. Discounted Cash Flow (DCF) calculation

We compute the DCF, encompassing all pertinent cash inflows and outflows at time t , and discounting them to their present values using Eq. (1).

$$DCF_t = \frac{R_t - C_t}{(1 + r)^t} \quad (1)$$

where:

- DCF_t : Discounted cash flow at time t .
 - R_t : cash inflow at time t .
 - C_t : cash outflow at time t .
 - r : discount rate (interest rate).
 - t : time period, with each unit corresponding to a year in the model. Thus, $t = 1$ corresponds to year 1, $t = 2$ to year 2, and so on.
2. Net Present Value (NPV)

NPV is the summation of the individual DCFs calculated for each year from the start to the end of the project's lifetime. It can be calculated as follows:

$$NPV = \sum_{t=0}^{t_f} DCF_t \quad (2)$$

where:

- t_f : time period corresponding to the end of the operational life of the plant.
3. Break-even analysis

Determining the output price at which the NPV becomes zero, which represents the minimum selling price required to cover all costs over the project's life (see Eq. (3)).

$$0 = \sum_{t=0}^{t_f} \frac{P_{break-even} \times Q_t - C_t}{(1 + r)^t} \quad (3)$$

where:

- P = The break-even price of the product or service. It is the price at which total revenue equals total cost (above which the company starts to make profits).
- Q_t = The quantity sold at time t .

In the context of the hydrogen supply chain, the P and Q parameters adapt according to the specific segment under consideration. For hydrogen production, P would represent the break-even price of the produced hydrogen, which corresponds to the Levelized Cost of Hydrogen (LCOH), distinguishing between green (LCOH_G) and blue (LCOH_B) hydrogen, while Q would represent the amount of hydrogen produced and sold. On the other hand, when focusing on transportation or storage, P and Q would denote, respectively, the prices and quantities of hydrogen being transported (Levelized Cost of Transport, LCOT) or stored (Levelized Cost of Storage, LCOS).

Using Eq. (3), the levelized costs of the four activities are calculated to be as follows: LCOH_G = 11.65 \$₂₀₁₇/kg, LCOH_B = 2.2 \$₂₀₁₇/kg, LCOT = 0.2

$\$_{2017}/\text{kg}$, and $\text{LCOS} = 2.4 \$_{2017}/\text{kg}$.¹ 2017 is the GTAP base year underlying the GEM-E3-NLD model.

4. Selling-price calculation

Built upon the break-even price, we calculate the final selling price by applying a predetermined profit margin, ensuring the financial viability of the investment.

$$P_{\text{sellingprice}} = P_{\text{break-even}} \times (1 + M) \quad (4)$$

where M represents the profit margin expressed as a decimal.

After determining the final price, we compare it with prices reported in existing literature, validating our output aligns with recognised benchmarks.

b. Coefficients

In the context of the I/O table, coefficients are fractional values that reflect the interdependencies between the economic activities. These coefficients are carefully derived from the comprehensive cost breakdown analyses and the available data.

■ Populating the I/O columns

This involves calculating and incorporating coefficients in the table to precisely depict the volume and variety of inputs required from multiple established sectors to generate one unit of output in the newly incorporated activity. For example, if we have a coefficient value of 0.2 in the I/O matrix cell intersecting the 'Batteries Manufacturing' sector row and the 'Electric Vehicles Manufacturing' sector column, it implies that to produce one unit of output in the 'Electric Vehicles Manufacturing' sector, 0.2 units of input from the 'Batteries Manufacturing' sector are required.

For every new activity, we start by determining the specific inputs required. This involves understanding the volume and type of inputs required to produce one unit of output in the new activity. Operational expenditures for each new activity are then analysed and dissected into constituent components, such as labour, materials, energy, and services, while ensuring compatibility with the granularity and specificity of the existing sectors and activities in GEM-E3. Based on this detailed breakdown, we calculate the coefficients and allocate them across the corresponding rows of the matrix in the respective column of the new activity.

■ Populating the I/O rows

When populating the rows, we first identify which sectors are likely to consume or use the new products or services within the existing economic structure of the model. We then quantify the inputs needed by each sector from the new activity based on detailed engineering calculations. Subsequently, the coefficients are computed, utilising the prices ascertained through our preceding break-even analysis.

In our study, the Netherlands serves as the reference case for computing coefficients that assess the economic impact of the newly added hydrogen activities. We then extrapolate these coefficients to the remaining regions in the GEM-E3 database in accordance with the GDP of each region as per Eqs. (5) and (6). This method assumes that the relative economic impact of the hydrogen-relevant activities in other countries would correspond to that in the Netherlands, once recalibrated for the economic scale of each region. While the robustness of this assumption might be debated, it is important to note that we presumably start with a minor hydrogen usage in the context of the Netherlands. This, on the one hand, aligns with the current, limited role of hydrogen in the global energy market. On the other hand, it is deemed a conservative approach and a safe starting point that reduces the risk of overestimating the impact of these activities on other economies.

$$TS_{i,j} = \sum_{k \in K} S_{i,k} \times \frac{GDP_j}{GDP_{ref}} \quad (5)$$

where:

- $TS_{i,j}$ is the total supply for hydrogen activity i in region j .
- $S_{i,k}$ is the supply structure value for hydrogen activity i within sector $k \in K$.
- GDP_j is the GDP of the target region.
- GDP_{ref} is the GDP of the reference region.

$$TD_{i,j} = \sum_{k \in K} D_{i,k} \frac{GDP_j}{GDP_{ref}} \quad (6)$$

where:

- $TD_{i,j}$ is the total demand for hydrogen activity i in region j .
- $D_{i,k}$ is the demand structure for hydrogen activity i within sector $k \in K$.

Step 4. Production functions for hydrogen activities

¹ Hydrogen transport refers to inland pipeline transport, while hydrogen storage refers to seasonal storage in salt caverns; see section 2.2.1 in the main text.

In the upgraded GEM-E3 model, we model the production of green and blue hydrogen using a CES (Constant Elasticity of Substitution) function. To reflect the current technological limitations, we set the elasticity of substitution between energy carriers to a value close to zero. This effectively means that the inputs for hydrogen production are used in fixed proportions, with no possibility for substitution (exclusively wind and solar power for green hydrogen, and natural gas for blue hydrogen).

Step 5. Regional aggregation

In its initial form, the GEM-E3 model encompasses 38 regions, reflecting a wide array of global economies. For the aims of this study, we aggregate these into three primary regions: the Netherlands, the rest of the European Union (EU), and the rest of the world. The reason behind including the EU as an individual region is to reflect the profound economic integration of the Netherlands within the EU's single market. Aligning the database to achieve this regional focus involved adjusting a substantial volume of data. While these steps are integral to the creation of the GEM-E3-NLD, their specific details are omitted from this discussion, as they do not contribute additional insights to this study.

2. Using GEM-E3-NLD

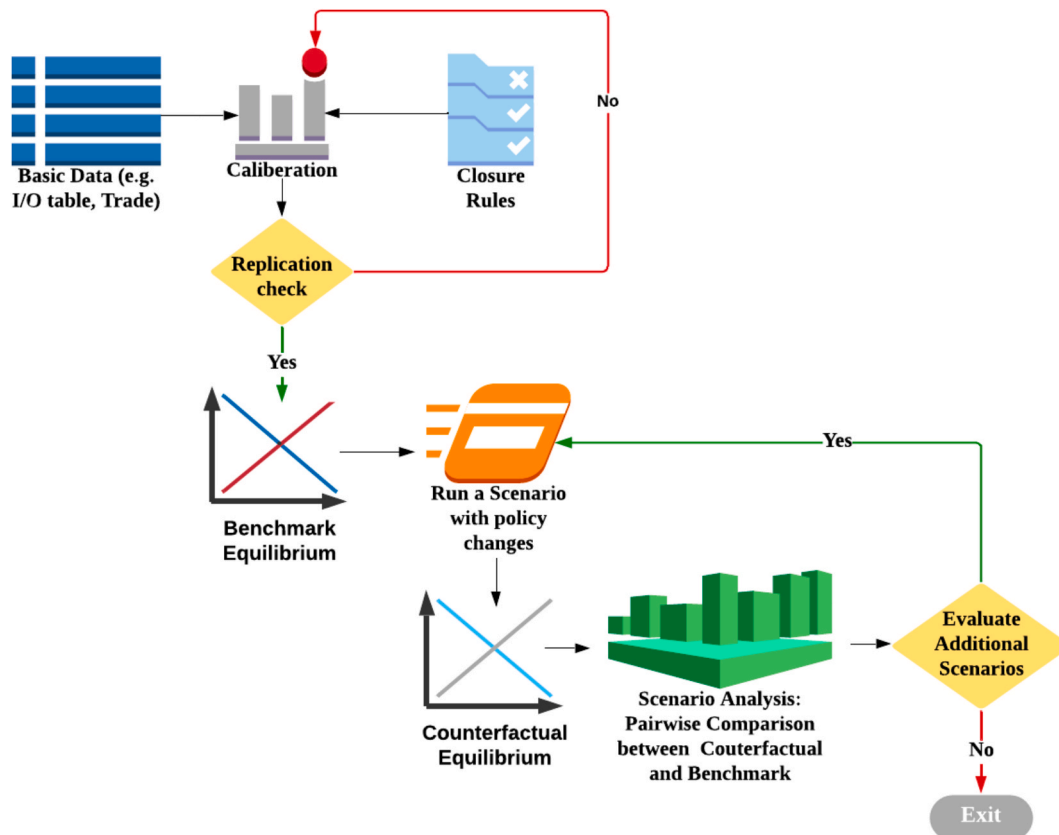


Fig. 1A. Steps of using CGE models: closure rules are the decision about which variables should be endogenous and which should be exogenous, which in turn affect how external shocks are absorbed by the model [67]. GEM-E3 closure rules can be found in [51].

3. OPERA results and key inputs

Table 3
CO₂ prices (€2017/tonCO₂) applied in the BAU and ET scenarios.

€ ₂₀₁₇ /tonCO ₂	2025	2030	2035	2040	2045	2050
BAU	80.6	103	131	168	184	203
ET	80.6	199	273	347	421	495

Table 4
Total GHG emissions (Mton CO₂eq) reduction path in BAU and ET scenarios.

Scenario	2025	2030	2035	2040	2045	2050
BAU	155	115	88	76	70	62
ET	155	103	69	46	23	0

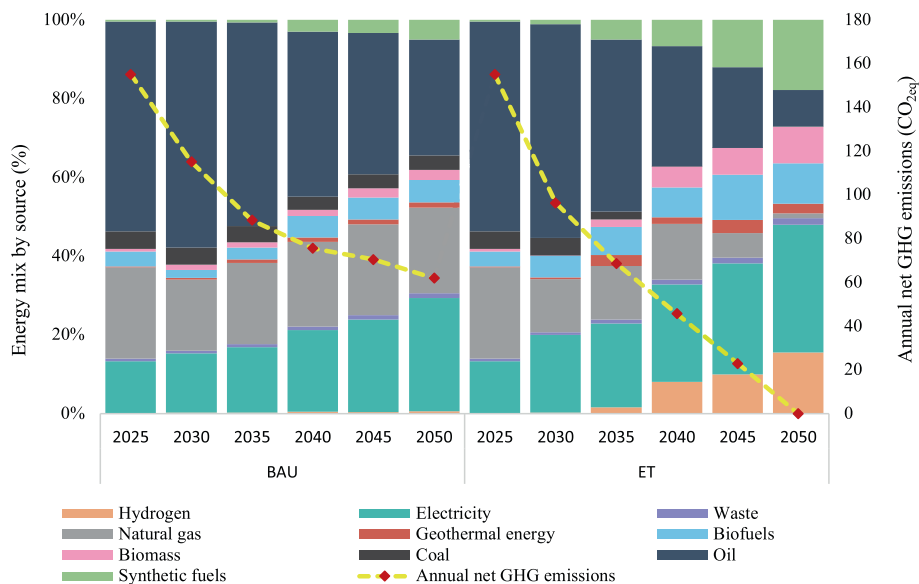


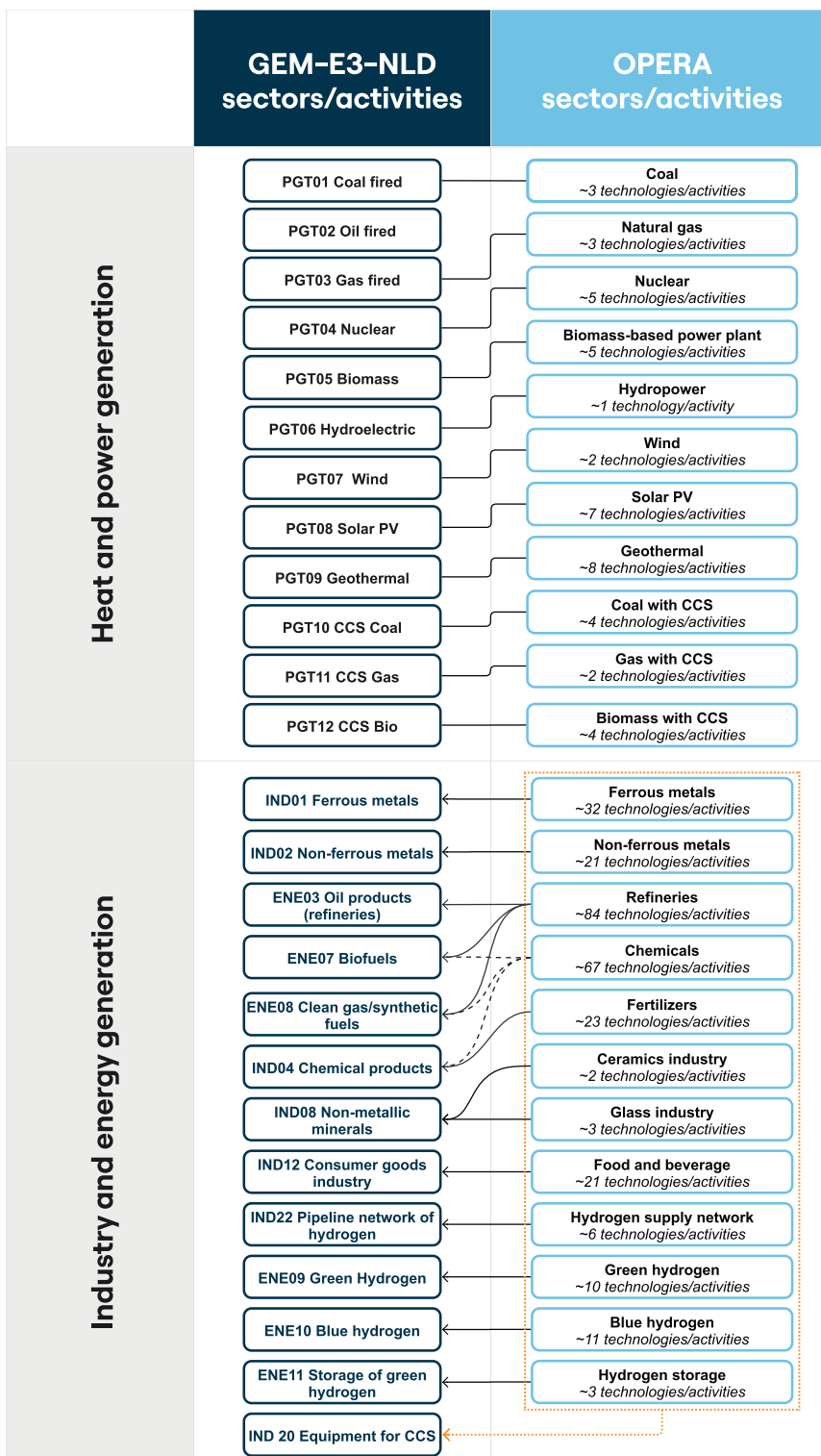
Fig. 2A. Energy mix by source (%) (left) and annual net GHG emissions (right) for the Netherlands under the BAU and ET scenarios.

Appendix B

Table 1B
Overview of energy production and related activities in GEM-E3.

Energy production activities	Directly related/supporting activities
Coal-fired power	Coal mining
Gas-fired power	Natural gas extraction
Oil-fired power	Oil extraction
Nuclear energy	Refineries
Biomass-fired power	Biomass harvesting
Hydro power	Manufacturing of batteries
Wind energy	Manufacturing of wind turbines
Solar energy	Manufacturing of PV
Waste energy	Biofuels production
Geothermal energy	Synthetic fuels production
Coal-fired power with CCS	Equipment for CCS
Gas-fired power with CCS	
Biomass-fired power with CCS	

Table 2B
The matching between sectors/activities of OPERA and GEM-E3-NLD.



Appendix C

Table 1C

The absolute difference between the employment per sector of the ET scenario and the BAU scenario for the Netherlands in 2050. These values should be understood as indicative of the direction and magnitude of differences between scenarios rather than as precise unemployment rates. GEM-E3 is calibrated on EU-27 input–output and labour data, which critically determine employment outcomes in the energy transition. Thus, our results are subject to assumptions about wage responsiveness, inter-sectoral mobility, and the distribution of skill types across sectors.

Sector	Employment (thousands of jobs) 2050
Refineries	−1.68
Biofuels	2.92
Synthetic fuels	9.89
Green hydrogen	4.12
Blue hydrogen	−0.02
Ferrous metals	14.75
Non-ferrous metals	−0.19
Chemical Products	−4.09
Other manufactured goods	−9
Other equipment goods	−1.64
Advanced electric and heating equipment	0.23
Construction	13.69
Transition equipment	0.28
CCS	2.05
Transport	7.32
Services	−35.22
Gas-fired power	−2.37
Nuclear energy	5.32
Biomass-fired power	−1.03
Hydro power	0
Wind energy	18.68
Solar energy	1.63
Geothermal energy	5.56
Biomass-fired power with CCS	0.03

Data availability

The data used in this manuscript are based on the GTAP databases, publicly available sources such as UN databases and Eurostat, and other publicly accessible datasets. All additional data sources are cited throughout the manuscript where possible.

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