Linking bottom-up TIMES-Italy model and top-down IRENCGE-DF model through two-way soft linking

TECHNICAL DOCUMENTATION

VERSION 1.0

Italian Ministry of the Economy and Finance – Department of Finance

Italian Agency for New Technologies, Energy and Environment (ENEA)

Rome, November 2025

DISCLAIMER

This methodological report has been prepared as the final deliverable of the research agreement between the Department of Finance and ENEA, signed on **11 March 2024**.

Contact:

Department of Finance
Address: Via dei Normanni 5, Roma
WWW: https://www.finanze.gov.it/it/

ENEA
Address: Lungotevere Thaon di Revel 76, Roma
WWW: https://www.enea.it/

Table of contents

1. Introduction: why is linking necessary?

Policymakers often face the challenging task of taking decisions in environments that are complex, uncertain and constantly evolving. The quality of these decisions is typically assessed against three core principles: effectiveness, efficiency and equity, relative to the policy's intended goals (OECD, 2022). Yet, policies frequently lead to outcomes that go beyond their intended targets, triggering spillovers that affect various economic factors and sectors both domestically and internationally. This is especially true for climate policies, whose primary objective—mitigating climate change—inevitably influences a wide range of sectors and transcends national borders. Moreover, these policies must strike a delicate balance between scientific knowledge, advances in technology, economic sustainability, and social impacts. In this context, advanced analytical tools can help policymakers navigate uncertainty by allowing them to simulate and assess the potential outcomes of different interventions before implementation.

To support effective policy making, requires that national administrations invest in the acquisition and development of suitable tools to conduct *ex-ante* impact assessments of various policy mixes and scenarios. Among the most relevant instruments for forward-looking assessments, a key distinction is made between partial equilibrium (or bottom-up) and general equilibrium (or top-down) models Computable General Equilibrium (CGE) models represent the whole economy, albeit in a simplified manner, and are capable to capture, in a dynamic and simultaneous way, the interlinkages among all economic agents - producers, consumers, government, investors - across multiple sectors and variables. Grounded in a theoretical framework describing the behaviour of economic agents, CGE models typically simulate "what if" scenarios, assessing the expected impact of economic shocks - such as changes in taxation - on market equilibrium, using actual data of the economy. While CGE models are well-suited to simulate the functioning of the whole economy, they lack the granularity needed to represent technological alternatives and diffusion processes. These features are, instead, captured by partial equilibrium models, which incorporate the cost trajectories of specific technologies and account for emerging technologies that are not yet commercially available. Although including these essential features, partial equilibrium models generally fail to capture broader economic interactions.

Consider, for example, a policy that increases taxation on conventional energy sources, thereby making green technologies relatively more cost-competitive. The sectoral model would capture the resulting shift in the national energy mix - that is, how the composition of products and technologies used to meet energy service demands (e.g., residential lighting, road transport) adjusts in response to changing relative costs - but it would not account for the indirect macroeconomic effects stemming from changes in the energy system, such as impacts on GDP, employment, or income distribution. For instance, if green technologies become more economically accessible, firms may substitute capital for labour in their production processes, potentially resulting in a decline in labour income, reduced household consumption, and, ultimately, changes in total emissions.

In general, sectoral models tend to underestimate abatement costs, as they overlook economic system constraints that may hinder the adoption of specific technologies. Conversely, top-down models tend to overestimate abatement costs, as they fail to consider, for example, technological improvements that could gradually reduce the cost of adopting cleaner solutions.

While each model type offers distinct advantages, relying solely on one may yield incomplete or potentially misleading evidence regarding the impact of a given climate policy. A more integrated approach is needed to capture both the technological and macroeconomic dimensions of policy interventions. Linking sectoral and CGE models offers a promising avenue to enhance analytical robustness and enable more realistic simulations of climate policy impacts.

To this end, the Department of Finance of the Italian Ministry of the Economy and Finance and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), decided to link top-down and bottom-up models that are part of their respective modelling toolkit.

The Department of Finance has developed, in collaboration with the World Bank, an environmental CGE model, funded by the European Commission. The model is very detailed and advanced, relying on the basic framework of endogenous relative prices which drive the decision of the economic agents with respect to production, consumption and investments. Despite offering a granular representation of Italy's fiscal system, the model lacks details on technologies since its technological representation is highly aggregated and different technologies are treated as imperfect substitutes.

ENEA maintains and operates the "TIMES-Italy" model, a partial-equilibrium model built on the TIMES framework, which represents the domestic energy system and its main emissions. Bottom-up energy models, exemplified by the TIMES model, provide highly detailed information at the sectoral level and offer insights into specific technologies. These models typically take the form of optimization problems, identifying the cost-minimizing array of technologies required to meet a specified demand for energy services. Originating from the engineering community, the bottom-up (BU) approach emphasizes available technological options and cost minimization under a specified energy demand level.

The inclusion of detailed technological parameters and the optimization process for cost minimization enable the identification of the most efficient technological portfolios in response to policy shocks, such as a carbon tax. These portfolios encompass technologies that may not yet be commercially available and are therefore excluded in top-down (TD) models. Noteworthy examples include emerging technologies like carbon capture and storage or innovative zero-carbon energy solutions, which are expected to play a pivotal role in the future energy landscape. Moreover, these models are fully intertemporal, allowing for the inclusion of technological innovation process. Under perfect foresight assumptions, agents can anticipate the impacts of economic policies and adjust their decisions accordingly, thereby fostering the deployment of such technologies with their optimizing behaviour. As a result, BU models can provide benchmark scenarios that complement the analyses carried out with CGE models.

Linking the two modelling frameworks is the most obvious direction in which to enhance the analytical capabilities of both institutions. By combining BU with TD approaches, it becomes possible to account for the broader economic implications of changes in the energy system - such as shifts in demand patterns - and to gain insights into the interplay between the energy system and the economy as a whole.

A substantial body of literature exists on the coupling of TD economic and BU energy models, encompassing a wide range of methodological approaches. Accordingly, the present work begins with a review of the relevant literature as a foundational step. It proceeds with an outline the main features

of the two models under consideration. The selected linking approach is then presented and examined in detail. Finally, the simulation results obtained before and after the linking are discussed, highlighting the significance and improvements in analytical capacity enabled by the coupling process.

2. Linking bottom-up and top-down models: conceptual framework and literature review

Depending on the analytical objective pursued by researchers, a range of approaches can be employed to link sectoral and economy-wide models, these approaches differing in the degree of model integration. Higher integration enhances consistency across models but comes at the cost of requiring detailed disaggregated data and a significant computational burden.

Following the classification in OECD (2024), linking approaches can be categorized into one-way and two-way linking. In the case of one-way linking, the output of one model flows directly, as an exogenous input, into the other model, with information flowing only in one direction. As such, this approach allows one model to affect the results of the other, without considering any feedback effects. This might be the case, for instance, of a bottom-up model estimating the effect of higher energy prices on the energy mix, with this output then being fed into an economy-wide model to assess the effects on other sectors and on the economy as a whole. One-way linking can be classified as either bottom-up or top-down. In bottom-up linking, outputs from the sectoral model flow into the economy-wide model. In top-down linking macroeconomic parameters from the economy-wide model - such as GDP or international fossil fuels price - are factored-in the bottom-up model, allowing it to adjust for predictions of the economy-wide model concerning growth or price effects.

In two-way linking, information flows bidirectionally between the two models, with the goal of achieving convergence in the common variables. This approach is generally motivated by analytical interest in results of both models. Although it adds complexity to the exercise, it presents the advantage of considering feedback effects and aims at reaching consistency between the two models.

Two-way linking can be achieved through either soft-linking or hard-linking. In the first case, the two models are kept separate, although selected outputs from one model serve as inputs for the other and vice versa, in an iterative process until convergence is reached. In contrast, hard-linking aims at integrating the two models and seeks to find a solution that satisfies the equations simultaneously.

Each linking approach presents specific trade-offs and the choice between them is shaped by the researcher's analytical interests and practical constraints. One-way linking is less cumbersome in terms of data harmonisation and consistency across models and offers a higher degree of scalability, i.e. it can be replicated for different models and for single or multi-country models. This is particularly relevant when several sectoral models are linked to a single CGE framework. Conversely, as previously noted, two-way linking accounts for feedback effects coming from the two models, which is particularly important when assessing policies that may generate signiciant second-order effects.

2.1. The linking methodologies: a survey of the literature

As mentioned before, the classification of the linking exercise was investigated by scholars in recent years, with the aim of exploring the seamless connection between national CGE models and the TIMES model.

Bohringer and Rutherford (2008) categorize these endeavours into three distinct typologies, where the first two forms can be reconducted to the hard-link, while the third is represented by the soft-link:

- **Reduced Form**: this approach focuses on one model while streamlining the treatment of the counterpart.
- **Integrated**: this typology involves using the Mixed Complementarity Problem (MCP) format to seamlessly incorporate BU technological details into the TD approach. It aims to fully integrate the technological intricacies of the BU model within the broader framework of the TD model.
- **Soft-Link**: in this approach, independent TD and BU models are interconnected. Instead of full integration, a soft link establishes a connection between these models, allowing for coordinated analysis while preserving some degree of autonomy for each model.

In a broader context, both the reduced form and the Mixed Complementarity Problem (MCP) approaches need the complete integration of TD and BU methodologies within a unified framework. The reduced form proves advantageous when the emphasis is on a global or macro-regional overview where intricate national details play a lesser role. However, within a national policy context, the reduced form has limitations as it, by definition, omits either sectoral or technological specifics.

On the other hand, the integrated MCP method involves a thorough amalgamation of BU technologies into the TD framework. Despite its elegance and mathematical formal rigor, this approach grapples with a dimensionality issue, making it computationally challenging to integrate multiple sectors effectively.

As said, another method is the soft-linking approach. Although it contends with coherence challenges arising from inconsistencies in behavioural assumptions and accounting concepts across models, it offers transparency in the effect chain. This is achieved by maintaining completeness in both models, while managing complexity and running time effectively. From a national policy perspective, soft linking holds the advantage of addressing complex energy and climate policy issues within a detailed representation of both technical and sectoral effects.

Within the realm of soft linking methods, recent years have witnessed a surge in studies (Fortes et al., 2014; Krook-Riekkola et al., 2017; Dai et al., 2016; Andersen et al., 2019) linking the MARKAL-EFOM System (TIMES) modelling framework (Loulou et al., 2005) and a national CGE model. TIMES can be regarded as the latest development and successor to the MARKet ALlocation (MARKAL) model (Loulou et al., 2004). Developed over almost two decades in a cooperative multinational project by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA), MARKAL is a technology-rich BU model generator that utilizes linear programming to optimize a least-cost energy system over medium to long-term time horizons, considering various user constraints.

These recent developments witness how the integration of sectoral and economy-wide models has emerged as a critical methodological frontier in climate policy analysis. The growing complexity of

climate mitigation strategies—spanning technological innovation, economic restructuring, and international coordination—demands analytical tools capable of capturing both the granular detail of energy systems and the broader macroeconomic feedbacks. This has led to a proliferation of hybrid modelling approaches, particularly those linking BU energy system models such as TIMES with TD - CGE models.

A foundational contribution to this field is offered by Fortes et al. (2014), who developed a soft-linking between the TIMES-PT and GEM-E3-PT models to assess energy and climate policies in Portugal. Their approach exemplifies a full-form, full-link hybrid model that preserves the technological richness of the BU model while incorporating the economic feedback mechanisms of the CGE framework. By applying the soft-link to three policy scenarios—a continuation of current policies, a CO_2 tax, and a renewable energy subsidy—the authors demonstrate that hybrid models can moderate the sensitivity of BU models to price elasticities and provide more realistic estimates of macroeconomic impacts. Notably, the study underscores the importance of revenue recycling in mitigating the economic costs of carbon pricing, a feature often absent in standalone BU models (Fortes et al., 2014).

Krook-Riekkola et al. (2017) extend this line of inquiry by soft-linking the Swedish CGE model EMEC with the TIMES-Sweden energy system model. Their methodological innovation lies in the introduction of direction-specific connection points (DSCPs), which facilitate the alignment of sectoral definitions and data structures between models. Applied to a climate policy scenario involving increased CO_2 pricing, the soft-linked model reveals significant reductions in industrial energy demand and emissions compared to standalone models. The study highlights the value of iterative calibration and the preservation of model integrity, demonstrating that soft-linking can uncover sector-specific dynamics that are otherwise obscured in aggregated frameworks.

A broader, regional perspective is provided by Dai et al. (2016), who integrate a multi-regional CGE model (AIM/CGE-China) with the TIMES Integrated Assessment Model (TIAM) to analyze China's energy and emissions trajectories. By disaggregating China into East, Central, and West regions, the authors capture regional disparities in economic development and energy use. Their soft-linking methodology harmonizes socio-economic assumptions and aligns energy service demand and efficiency parameters across models. While the approach narrows the gap between TD and BU projections, particularly in the power sector, it also reveals persistent divergences due to structural and data differences. The study thus underscores both the potential and the limitations of soft-linking in large, heterogeneous economies.

Complementing these empirical studies, the OECD has developed a structured framework for linking sectoral and economy-wide models, particularly within the context of the Inclusive Forum on Carbon Mitigation Approaches (IFCMA). The OECD's three-step framework provides a practical roadmap for operationalizing hybrid modelling strategies (OECD, 2024). The first step, harmonization of inputs, involves aligning historical data, macroeconomic projections, and policy inventories across models. This step addresses common challenges such as inconsistent sectoral classifications and divergent data sources and emphasizes the importance of using both national and international datasets to ensure comparability and scalability.

The second step, constructing a reference scenario, entails building a harmonized baseline that reflects consistent assumptions about economic growth, energy prices, and policy settings. In CGE models, this often requires calibrating structural parameters such as elasticities and productivity coefficients

to match the outputs of sectoral models. Conversely, sectoral models may incorporate macroeconomic projections from CGE models to ensure coherence in demand forecasts. This bidirectional exchange of information ensures that both models are anchored in a shared analytical foundation.

The third and final step involves assessing the impact of policy interventions by developing counterfactual scenarios. Sectoral models are used to estimate the direct effects of specific policies—such as carbon taxes or renewable energy subsidies—on energy consumption and emissions. These results are then translated into the CGE model, which captures the broader economic feedbacks and spillover effects. This step often requires adjusting structural parameters in the CGE model to align its responses with those of the sectoral model, or alternatively, imposing sectoral results directly to bypass endogenous adjustments (OECD, 2024a).

Taken together, the reviewed literature and OECD guidance converge on several key insights. First, soft-linking offers a flexible and transparent approach to hybrid modelling that preserves the strengths of both TD and BU models. Second, successful implementation depends on careful calibration, consistent data harmonization, and iterative refinement. Third, the choice of linking methodology should be guided by the analytical objectives, data availability, and policy context. While one-way linking is less resource-intensive and more scalable, two-way linking is essential for capturing feedback effects and ensuring analytical consistency in complex policy scenarios.

In conclusion, the integration of sectoral and economy-wide models represents a powerful tool for climate policy analysis. The empirical studies from scholars demonstrate the practical feasibility and analytical value of soft-linking, while the OECD's frameworks provide a robust methodological foundation for broader application. As climate policy becomes increasingly multifaceted and interconnected, the ability to link models effectively will be crucial for designing interventions that are both technically sound and economically viable.

Table 1. Review of literature

Paper	**Year**	**Approach**	**Coverage**
McFarland et al.	2004	Full integration	Global
Ian Sue Wing	2008	Full integration	USA
Böhringer and Rutherford	2008	Full integration	Global
Strachan and Kannan	2008	Full integration	UK
Sugandha et al.	2009	Full integration	USA
Fujimori et al.	2014	Full integration	Global
Bosetti et al.	2016	Full integration	Global
Böhringer and Rutherford	2009	Decomposition	Theoretical
Rausch and Mowers	2014	Decomposition	USA
d'Aertycke	2014	Decomposition	Europe
Tapia-Ahumada et al.	2015	Decomposition	USA
Messner and Schrattenholzer	2000	Soft Link	Global
Schafer and Jacoby	2005	Soft Link	Global
Drouet et al.	2010	Soft Link	Switzerland
Martinsen	2011	Soft Link	Norway
Fortes et al.	2014	Soft Link (TIMES-CGE)	Portugal

Labriet et al.	2015	Soft Link (TIAM-CGE)	World
Dai et al.	2016	Soft Link (TIMES-CGE)	China
Arndt et al.	2016	Soft Link (TIMES-CGE)	South Africa
Krook-Riekkola et al.	2017	Soft Link (TIMES-CGE)	Sweden
Andersen et al.	2019	Soft Link (TIMES-CGE)	Denmark

As stated in the literature, linking is thus necessary: BU models estimate the variation in energy services due to a mitigation policy but do not consider the interaction between the change in the energy mix and the rest of the economy, while CGE models consider for direct and indirect effects on the economic system of a mitigation policy, but do not reflect innovation and the emergence of new technologies in the energy mix.
Given the different approaches, the best option available for the present exercise, is a two-way soft link between TP and BU model. Despite the increase in complexity for reaching convergence in the common variables, the two-way ensures that the two models are able to capture feedback effects and present a higher degree of consistency. Moreover, the soft link enables the modelling team to manage their own models, without imposing full integration that would require simplifying assumptions to solve all the equations simultaneously. The following section presents the two models and describes the linking process.

3. Overview of single models

3.1. ENEA TIMES-Italy

ENEA has developed, maintains and utilizes the "TIMES-Italy" model, a partial-equilibrium model that represents the domestic energy system and its main emissions. TIMES is an energy-economic model generator for local, national or multi regional energy systems, and provides a technology-rich basis for calculating energy dynamics over a long-term, multi-period time horizon.

TIMES (The Integrated MARKAL-EFOM System) is a widely applied energy system modelling tool developed by ETSAP (Energy Technology Systems Analysis Program), one of the longest running Technology Collaboration Programme of the International Energy Agency (IEA)[1].
TIMES is designed as a mathematical programming model, computing a dynamic inter-temporal partial equilibrium on energy markets, assuming competitive markets for all commodities and perfect foresight (it is said to be clairvoyant), i.e. all investment decisions are made in each period with full knowledge of future events. The result is a supply-demand equilibrium that maximizes the net total surplus, i.e. the sum of producers' and consumers' surpluses. This is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints (Loulou et al., 2005). The net total cost of the energy system is calculated as the sum of the net present values of various technical energy system costs, encompassing expenses related to the investment and operation and maintenance of all energy technologies represented in the model, plus the costs of imported fuels minus the income from exported fuels, minus the residual value of technologies at the end of the model's time horizon (plus welfare losses due to endogenous demand reductions if it is used the elastic demand version of the model).

[1] <http://iea-etsap.org/>

TIMES models typically represent the entire energy system, from resource extraction through to end-use demands, through a detailed Reference Energy System (RES) network, and produce long-term projections (scenarios) of the system, i.e. future energy system configurations which meet end-use "energy service" demands (e.g. passenger-km or tons of steel) at least cost, within given technological and socioeconomic constraints. The model's decision variables represent choices made endogenously, such as the selection of specific energy technologies and commodities: a model solution (a "scenario") simultaneously determines the least cost evolution of the installed capacity and operation of each energy technology represented in the model, the flows of energy commodities as well as their shadow price and the CO_2 emissions associated to them. By adding up these technology level data it is then possible to project the whole energy balance of a country/region, i.e. total energy demand by fuels and sector, as well as total CO_2 emissions and the total cost of the energy system.
The model works to determine the combination of energy technologies and fuel utilization that minimizes these costs while meeting predetermined demands and adhering to specific constraints. It incorporates a wide range of both current and anticipated future energy technologies, accounting for their current and assumed future energy conversion efficiencies and costs.
TIMES models approach energy as a system instead of a set of elements, giving the advantage of identifying the most important substitution options between technologies and fuels in each market as well as the interdependences and complementarities between different sectors of the energy system, which cannot be understood looking at a single technology or commodity or sector. For example, a focus on the power sector risks excluding possible unforeseen step changes in electricity demand, stemming for instance from the electrification of transport or heating. By considering energy supply and demand across all sectors simultaneously, systems analysis applies systems principles to aid decision makers in problems of identifying, quantifying, and controlling a system. Although taking into account multiple objectives, constraints, resources, it aims to specify possible courses of action, together with their risks, costs, and benefits (Gargiulo and Ó Gallachóir, 2013). TIMES models take a long term view of energy system dynamics (typically to 2050, e.g. Chiodi et al., 2013) and generally capture seasonal changes in energy use and supply in addition to limited diurnal variations (i.e. day, night and peak).
TIMES's versatility extends to analyzing a countless number of diverse scenarios, e.g. to explore the costs and benefits associated with various climate policies. As such it has been widely used to develop energy models to depict and assess energy transition scenarios.

TIMES-Italy provides a comprehensive description of the Italian energy system: its Reference Energy System, summarized in Figure 1, spans from the extraction of resources to the conversion of primary energy carriers (two sectors, fuel production and electricity & heat), to the trade of all the main energy commodities and to the use of final energy carriers in end-use technologies across 42 energy service demands (within five demand sectors: agriculture, services, residential, industry, and transport).
This structure aligns with Eurostat's energy statistics framework, as illustrated in Figure 1. Within each sector, various sub-sectors are defined, each employing different technologies to fulfil the ultimate demand for products and services.
All demand segments are external inputs to the model, specified with quantified values for each time period, known as demand projections. Energy-intensive industries are meticulously represented, incorporating detailed reference energy systems that account for specific process steps and material flows.

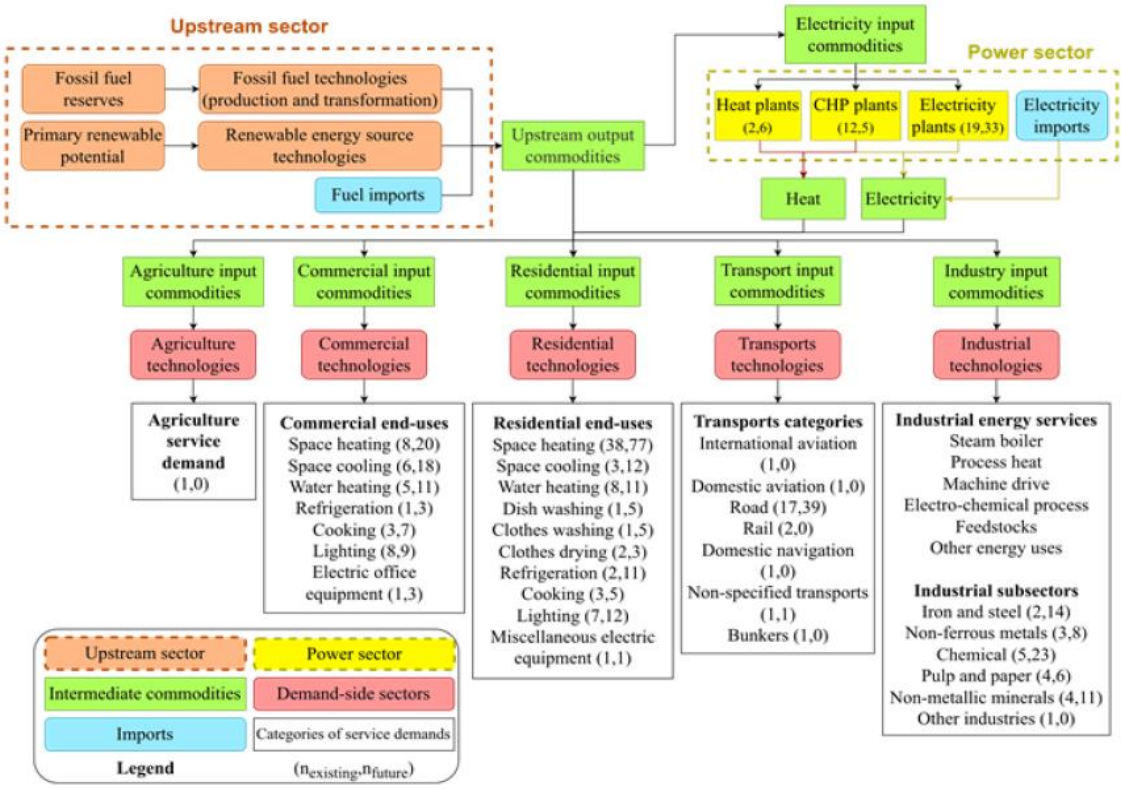

Figure 1. The TIMES-Italy model

3.1.1. Upstream sector

In TIMES-Italy the energy supply sector encompasses fossil fuel reserves, renewable and biomass potentials, extraction and transformation processes (such as refineries), and environmental parameters. The "starting point" of the Reference Energy System is the extraction phase, where fossil fuel reserves and renewable energy potential are represented. Each energy resource is modelled independently, with its own supply curve. The model also includes primary and secondary energy transformation phases and accounts for the exogenous import/export of fuels and electricity. Coal is modelled through two domestic reserve types—hard coal and brown coal—and allows for external imports. It can be used directly in final-use sectors or for electricity generation or processed into by-products. Oil reserves are categorized into located reserves; reserves growth and new discovery, in line with UNMIG definitions. Extraction includes primary production technology and pipeline infrastructure feeding crude oil to refineries. Similarly, natural gas reserves follow the same classification and are divided into cost-based tiers.

Renewable energy supply includes a wide range of sources: hydro, geothermal, solar, wind, tidal, and various forms of biomass and waste. Biomass is further categorized by origin—forestry, agriculture, landfill biogas, fermentation, and urban or industrial waste—with distinctions in pricing and availability.

Regarding energy transportation and distribution, each primary or final energy carrier is associated with specific distribution processes, characterized by sector and fuel-specific technical and economic parameters, including sector-specific transmission and distribution costs, taxes, incentives, and network losses (electricity and heat).

3.1.2. Power sector

In the base year TIMES-Italy includes 20 different types of electricity-only plants and 10 cogeneration plants, classified by technology and/or primary energy source and calibrated to their actual net installed capacity. Moreover, a wide number of power plants, available across the time horizon under analysis, are characterized through a set of techno-economic parameters: fuel type or mix, conversion efficiency, specific investment costs, fixed and variable annual operating costs, year of installation, technical and economic lifespan, ability to meet peak electricity demand, and average availability factor. The model also distinguishes between centralized and decentralized electricity generation, based on plant size and energy distribution mode.
The TIMES-Italy model includes a specific module to manage new power plants, separating those already in service before 2025 from those that will start or continue operation afterward. Among the pre-2025 technologies, the model features multiple renewable options: six rooftop and five utility scale PV types, four solar thermodynamic plant types, and six wind technologies (four onshore and two offshore, depending on water depth). Additionally, three fossil-fuel-based thermoelectric plant types—gas, coal, and oil—remain operational until 2025. The model differentiates these technologies based on production profiles, technical characteristics, and deployment contexts. Post-2025 installations include four types of biomass plants (distinguished by size), one bio-liquid plant, two small hydroelectric plants, and two geothermal ones (Figure 2). Additionally, two thermoelectric biogas plants, two centralized fuel cell plants (differentiated by capacity), and one conventional thermoelectric unit are included (Figure 2).

The model also incorporates nuclear technology, allowing for the installation of two types of nuclear power plants: an advanced fourth-generation AMR LWR and a Small Modular Reactor (SMR) (Figure 2).

Solar power is modelled by considering the seven Italian market zones, maintaining the distinction between rooftop and ground-mounted systems. Wind power is similarly zone-based, with a further differentiation between high and low-capacity factor systems, leading to 21 total options. Five cogeneration units are modelled: four powered by natural gas and one by municipal waste (Figure 3).

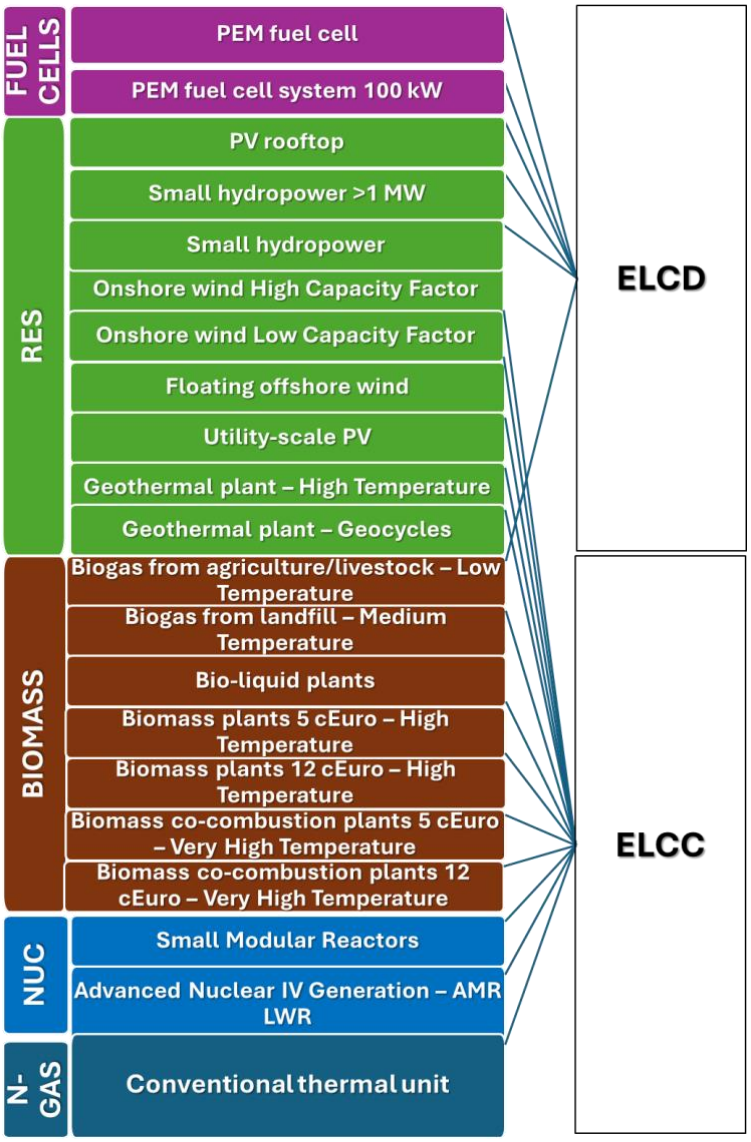

Figure 2. New technology power plants (electricity generation only)

The micro-cogeneration technologies group is designed for residential, commercial, and industrial applications (Figure 4). The technologies differ by type of engine—such as internal combustion engines, gas turbines, steam turbines, microturbines, Stirling engines, and fuel cells—and by the fuel used, including natural gas, bioliquids, methane, and hydrogen. The fuel cell systems are available in both solid oxide (SOFC) and proton exchange membrane (PEMFC) versions. The combined cycle systems are aimed at achieving higher efficiency, and all technologies are tailored to their specific application context.

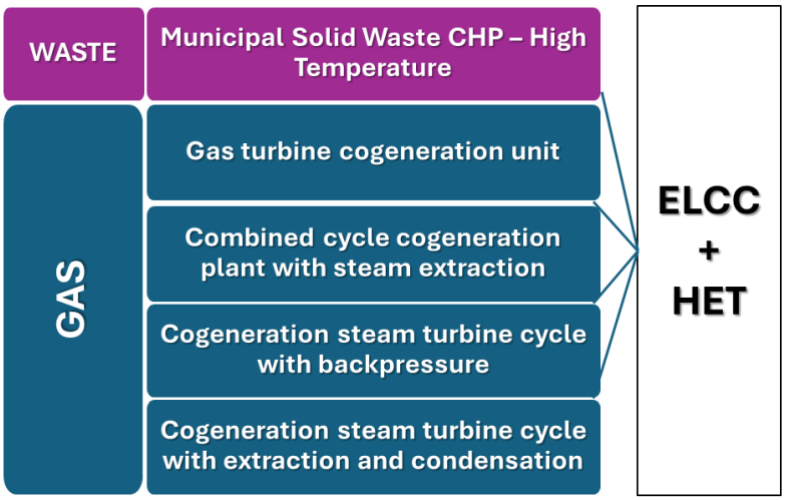

Figure 3. New cogeneration plant

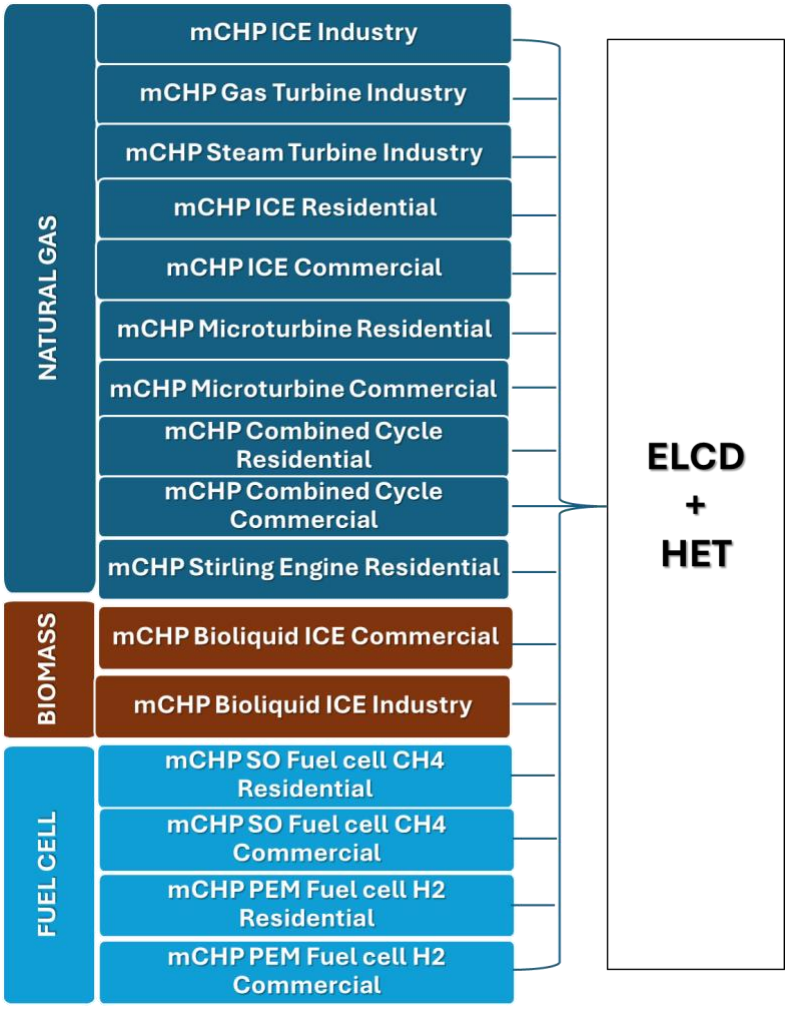

Figure 4: micro-Cogeneration plant

3.1.3. Industrial sector

The industrial sector in TIMES-Italy is grouped into six subsectors, aligning with the classification used in IEA energy statistics [IEA Statistics, 2006]:Iron and Steel Industry (IIS) (ISIC5 group 271 and class 2731); Non-Ferrous Metals (INF) (ISIC group 272 and class 2732); Chemical and Petrochemical Industry (ICH) (ISIC division 24); Manufacturing of Non-Metallic Minerals (INM) (ISIC division 26); Paper, Pulp, and Printing Industry (ILP) (ISIC divisions 21 and 22); All other industrial sectors (IOI). In addition to these, there are two additional aggregates: ONO (Other Non-Specified Consumption), which includes consumption related to the industrial sector but not easily attributable to a specific branch; NEO (Industrial and Other Non-Energy Uses), which covers both industrial and non-industrial non-energy uses.

Since most of the sector's energy consumption comes from the production of "high-intensity" goods, TIMES-Italy considers and models in detail the main manufacturing processes, including their physical production volumes and specific energy consumption. The demand for each sector is projected over time, starting from the reference year, based on assumptions regarding sectoral value-added growth.

Regarding energy consumption, each process absorbs energy both directly, in the form of fuels, and indirectly, through six energy services (Figure 5): Steam (Steam Boiler - IS); Process Heat (Process Heat - IP); Machine Drive (Machine Drive - IM); Electro-Chemical Processes (Electro-Chemical Process - IE); Feedstocks/Non-Energy Uses (Feedstocks - IF); Other (Other - IO).

Each of these six industrial energy services is characterized by multiple technologies, depending on efficiency levels and the type of fuel used. Since steam production and machine drive services are common to all subsectors, with similar cost, efficiency, and process characteristics, they have been modelled in a "centralized" manner (i.e., across industrial subsectors). The remaining services, however, are sector specific.

In the reference year, Italy's industrial sector consumed around 45 Mtoe of energy, with key sectors relying on centralized technologies for steam production, machine drives, and process heat. The chemical, petrochemical, and pulp and paper industries were major steam users, while steel production relied on blast furnaces and electric arc furnaces. The non-metallic minerals sector needed substantial process heat, and the non-ferrous metals sector, including aluminium and copper production, depended on process heat and electrochemical methods. The chemical and petrochemical sectors had significant energy consumption, with a focus on steam and machine drives. TIMES-Italy models the industrial sectors by differentiating between final energy, which powers specific technologies, and service demand, which represents the useful energy required, highlighting the critical role of efficiency in determining energy needs.

Among the main new technologies available in the projection years which is worth mentioning, new industrial steam production technologies can use blast furnace gas and ethane for the steel and chemical sectors, respectively, with a 30-year lifespan and a utilization factor of 0.75. New machine drive technologies will feature more efficient electric motors, as well as motors powered by natural gas and LPG, with a 15-year lifespan and a utilization factor of 0.7. The iron and steel sector will adopt the DRI-EAF process, combining direct iron reduction with an electric arc furnace, also with a 30-year lifespan and a 0.9 utilization factor. For the cement sector, new clinker production

technologies will be introduced, utilizing different fuels and separating clinker from cement production processes.

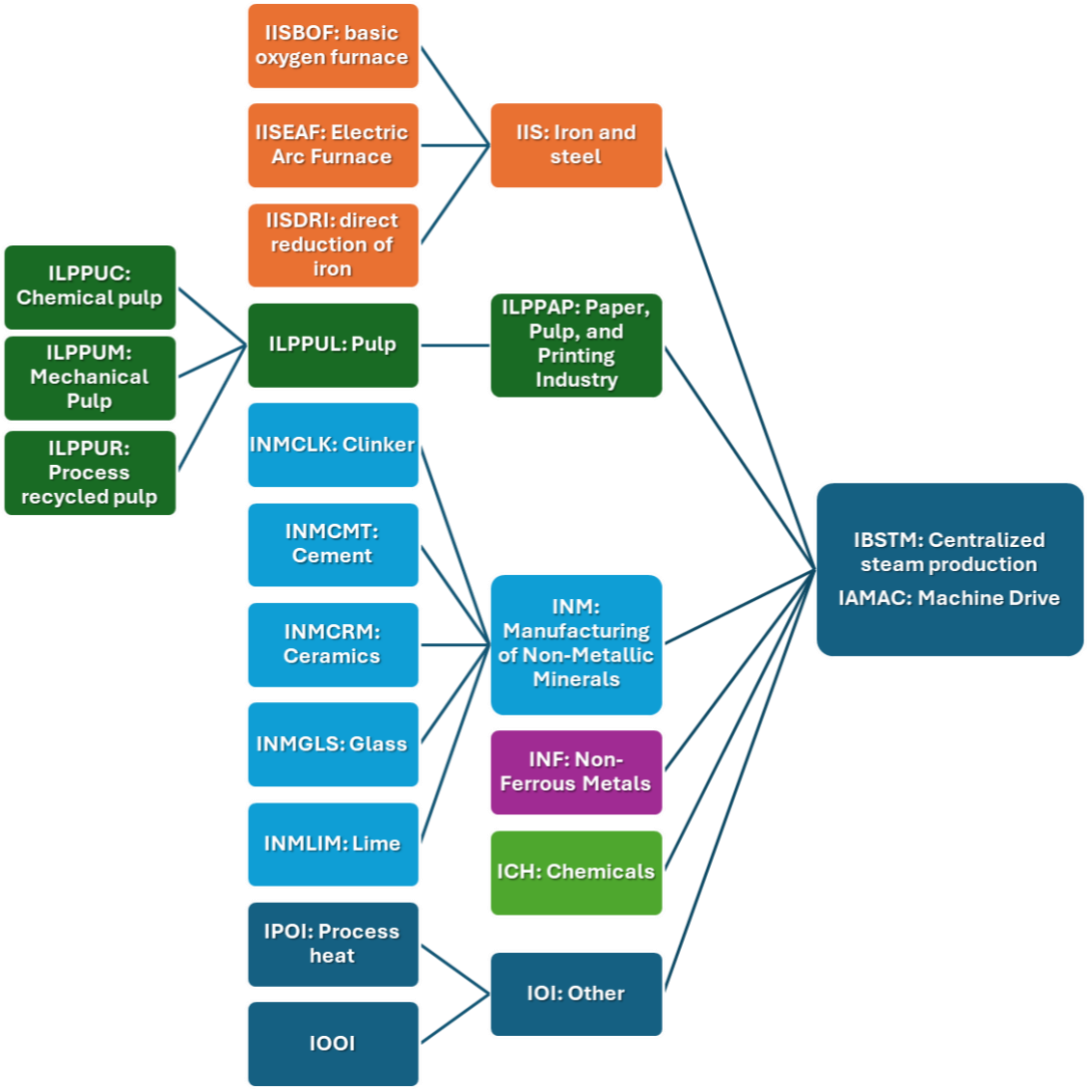

Figure 5. Technology options in Industry sector, TIMES-Italy

3.1.4. Demand-side sectors: Residential and Commercial

In TIMES-Italy several categories of residential energy service demands are defined (see the following Table 2). The demand for each energy service in the Base Year are calibrated to JRC-IDEES data and are projected over the years in relation to socio-economic development assumptions which are the basis of an energy scenario.

Table 2. Residential energy service demands' characterization

Energy service	Unit of measure
Residential heating	Mtoe
Residential hot water	Mtoe
Residential cooling	TWh

Residential cloth washing	Billions of washes
Residential dish washer	Billions of washes
Residential cloth driers	Billions of washes
Residential refrigeration	Billions of liters
Residential lighting	Billions lumen
Residential cooking	PJ
Residential equipe miscellaneus	PJ

Heating is divided into four sub-services, depending on the building type and conditions of the building (new or existing), in heating for existing houses and condominiums (respectively RH_1 and RH_2), or newly built (RH_3 and RH_4). The demand for heating is projected over the time horizon at annual average growth rates. Cooling is still a crucial energy service, given the increasing level of spread among families during the years. The evolution of demand for energy services guaranteed by common household appliances depends both on population growth and on the assumptions of use and diffusion of each technology.

A wide set of current and future technological options can be chosen by the model to satisfy energy service demands, on the basis of their technical and economic parameters. The main heating and insulation technologies are listed in the Table 3:

Table 3. Residential heating and insulation technologies

Boilers	Heating technologies
Wood stoves	
Heat pumps	
Autonomous heater	
Solar thermal	
Thermal insulation	Insulation technologies

Cooling service is mainly satisfied by heat pumps, while for each electrical appliance one technology (or technology group) is defined as representative for the whole technology park.
In the commercial sector, a total of seven energy services are required:

- Commercial Heating (CH);
- Commercial hot water (CHW);
- Commercial Cooling (CC)
- Commercial Refrigeration (CRF);
- Office Electrical Equipment (COE);
- Commercial Lighting (CL);
- Commercial Cooking (CCK).

As with other end use sectors, energy service demand in the commercial sector may change from scenario to scenario, depending on whether a more or less sustained economic growth is assumed.

The list of future technologies available to satisfy future energy service demand is similar to the one included in the residential sector, even though for certain technologies some characteristics may differ from those indicated for the domestic sector, given the different powers involved in the installations.

3.1.5. Demand-side sectors: Transportation

In TIMES-Italy the transportation sector includes road, rail, aviation, and marine subsectors for passenger and freight transport (Figure 6). Road passenger transport is divided in private cars (TRT), public road transport (TRB), motorcycles (TRW); road freight transport in light commercial vehicles (TRC), medium (TRM) and heavy-duty vehicles (TRH). Air transport and navigation are divided into routes: air domestic (TAD) and international (TAI) transport, domestic (TWD) and international (TWI) navigation; rail transport in passenger (TTP) and freight transport (TTF).

For the base year sectorial energy consumption has been calibrated to IEA data, while the demands are obtained by national (CNIT) and international sources (IDEES database) on stocks, energy efficiency and mileage. The demands (in billion vehicles kilometres) are projected for each transport modes using the IDEES database.

As regards the menu of future transport technologies, there are more of 70 options, each characterized by technical (efficiency, life, start year availability) and economic (investment and variable cost) parameters. For road transportation the main technologies are: Internal Combustion Engine Vehicle (ICE vehicles, distinguished by fuel type), Hybrid Electric Vehicle (HEV), Plug-in Electric Vehicle (PEV), Battery Electric Vehicle (BEV), Hydrogen Fuel Cell Vehicle (HFCV).

In rail transport new technologies can use diesel, electricity or hydrogen. In aviation the model can switch from jet kerosene to biofuels, synfuels or H_2 options, in navigation from oil to alternative fuel (synthetic, biofuel, ammonia and methanol) and H_2.

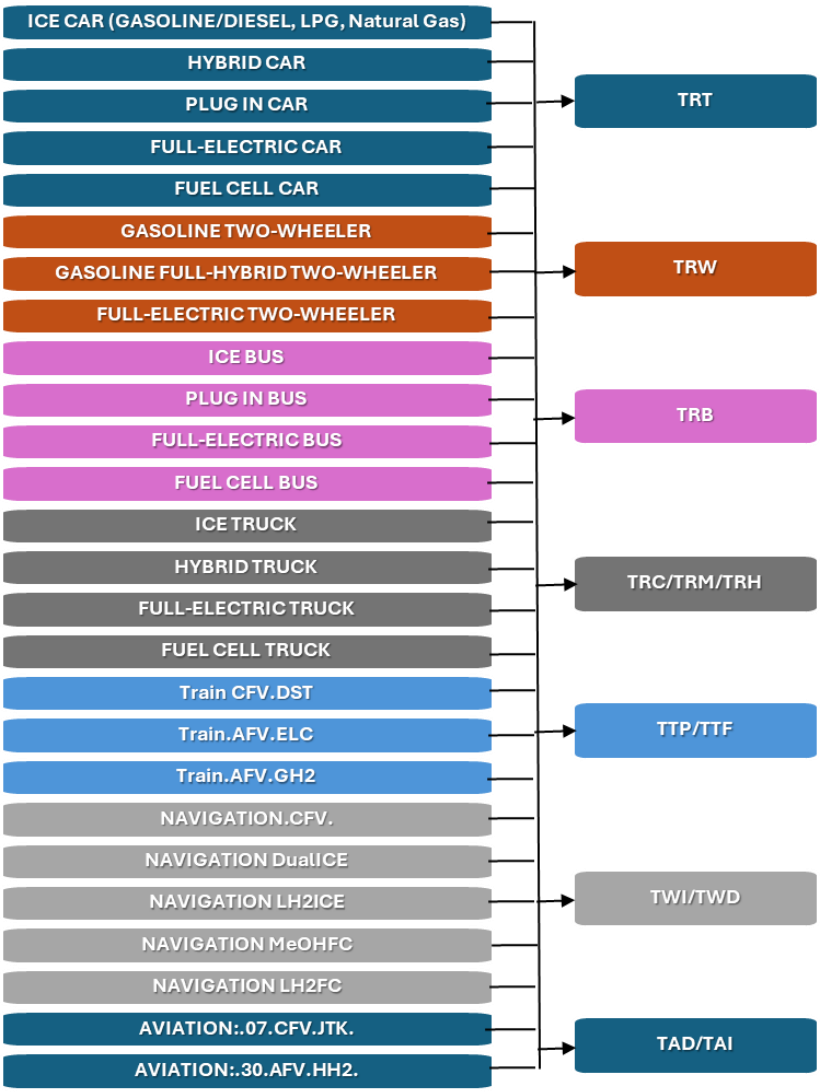

Figure 6. Technology options in transport sector, TIMES-Italy

3.1.6. Innovative energy technology clusters: hydrogen and synfuels

In TIMES-Italy some innovative energy technology clusters, among which hydrogen and Carbon capture and storage, are represented through modules added to the main model.

The hydrogen module captures the full hydrogen value chain, from production and storage to distribution and end-use (Figure 7). Hydrogen production is differentiated by infrastructure size—small, medium, or large—and by whether facilities are centralized or decentralized, with each configuration assigned specific investment costs and lifespans based on literature data. The model includes multiple production pathways: from fossil fuels (steam methane reforming HNGA and coal gasification HCOA) either without or with carbon capture and storage (HZNGA, HZHCO), from biomass through gasification, with or without CCS (HBIO, HZBMU), and from electrolysis using various technologies such as alkaline (HELCALK), PEM (HELCPEM), SOEC (HELCSOEC), and AEM (HELCAEM) electrolysers (green or yellow hydrogen). Partial oxidation is also considered among the production options. Economic inputs, expressed in M€/PJ$_{(H_2, LHV)}$, include fixed and variable maintenance costs calculated as percentages of capital expenditure (4% and 1%, respectively). All the parameters used to characterize the technologies are derived from a systematic

literature review. The model incorporates storage solutions tailored to the hydrogen source, such as centralized and decentralized tanks, including underground options (STH2). Transport and distribution chains are designed to meet the needs of specific end-use sectors and include processes like compression, liquefaction, and pipeline transmission. A total of 21 different configurations are represented, combining these elements. Hydrogen consumption is modelled across several economic sectors. In buildings, it is used for blending and in micro-CHP systems to supply both heat and power. In industry, it supports emissions reduction in processes like steel production using direct reduction iron technology and serves as a feedstock in chemical manufacturing. In the energy sector, hydrogen contributes to electricity generation via fuel cells, particularly in decentralized setups or in combination with renewables. In transport, hydrogen powers fuel cell vehicles and adapted internal combustion engines, with applications ranging from road vehicles to trains, ships, and aircraft, including uses in synthetic fuel production.

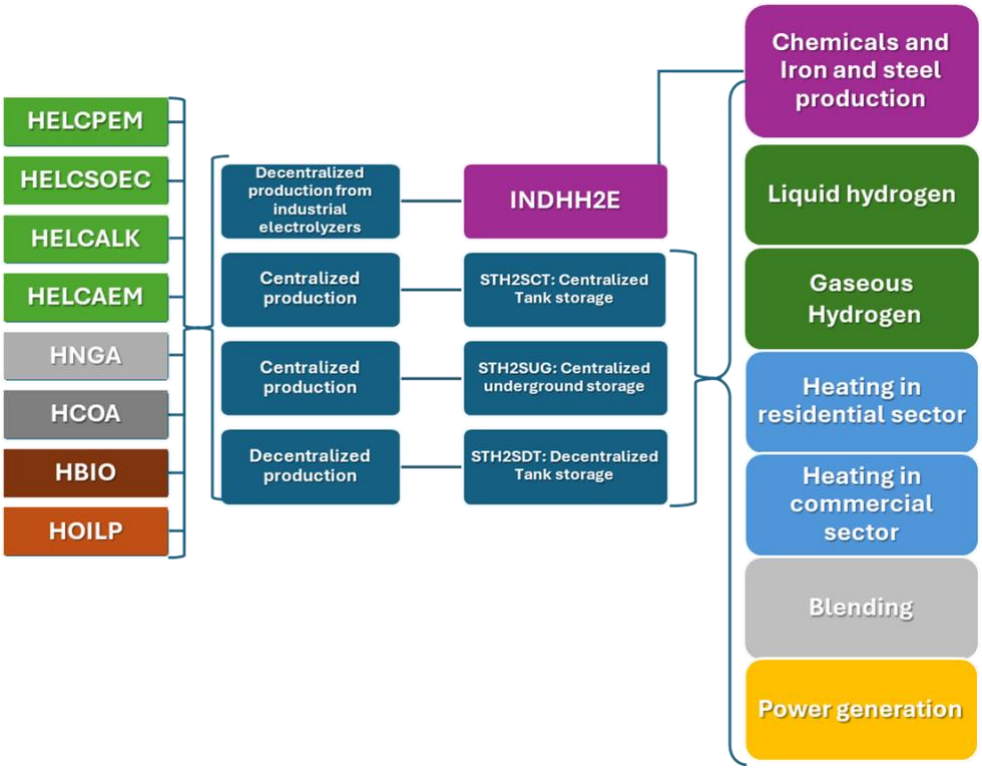

Figure 7. Hydrogen technology options, TIMES-Italy

In the TIMES-Italy model, synthetic fuels (synfuels) are produced by combining captured carbon dioxide (CO_2) with energy inputs like electricity or hydrogen. The model includes three main production processes (Figure 7): methanation, which produces synthetic natural gas; hydrogenation, which yields various fuels such as synthetic diesel or kerosene; and co-electrolysis, which combines CO_2 and electricity to produce fuels like synthetic methanol. These synfuels are integrated into the energy system to meet sectoral demands and can either be blended with fossil fuels in conventional technologies or used directly in innovative applications. Cost data for these processes were updated using sources from the Danish Energy Agency and JRC.

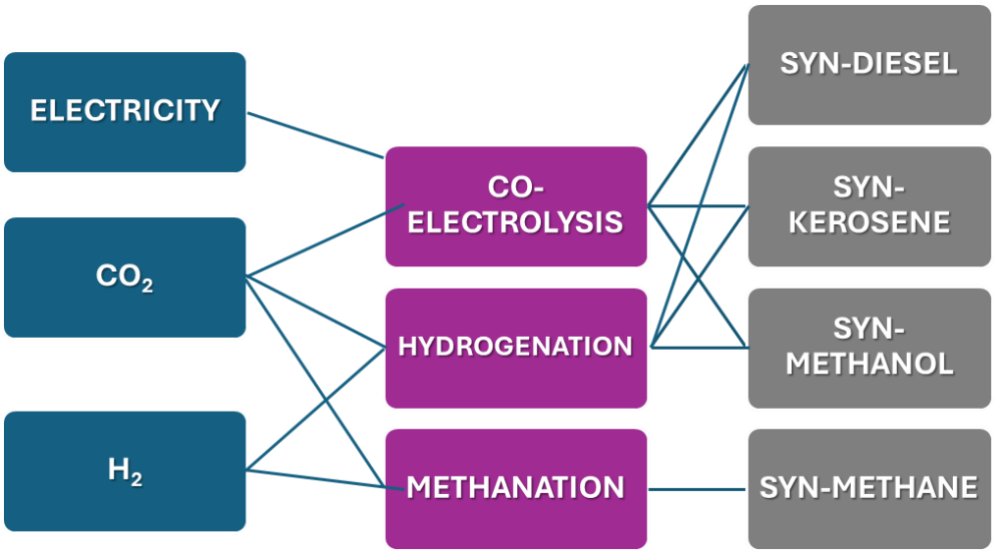

Figure 8. Synfuels technology options, TIMES-Italy

3.2. IRENCGE-DF

The Italian Regional and Environmental Computable General Equilibrium Model (IRENCGE-DF) was developed by the Department of Finance of the Italian Ministry of Economy and Finance, in collaboration with the World Bank. The model builds upon the MANAGE-WB model of the World Bank which is in turn based on the MANAGE model that is documented in van der Mensbrugghe (2021). A comprehensive technical documentation of the model is available on the Department of Finance official website. [2]

Figure 9 illustrates the interactions among various actors captured by the model. In broad terms, it depicts supply and demand dynamics. On the left, activities produce commodities using intermediate inputs and primary factors like labour and capital, which are then supplied to different demand agents—households, firms, and the government. The government, in turn, collects taxes and provides public services. Part of the production is exported, while some demand is met through imports. This overview underscores the capacity of a CGE model to represent a highly detailed and disaggregated system.

[2] Available here: https://www.finanze.gov.it/it/il-dipartimento/Modelli-economici-e-strumenti-di-analisi/irencge-df/

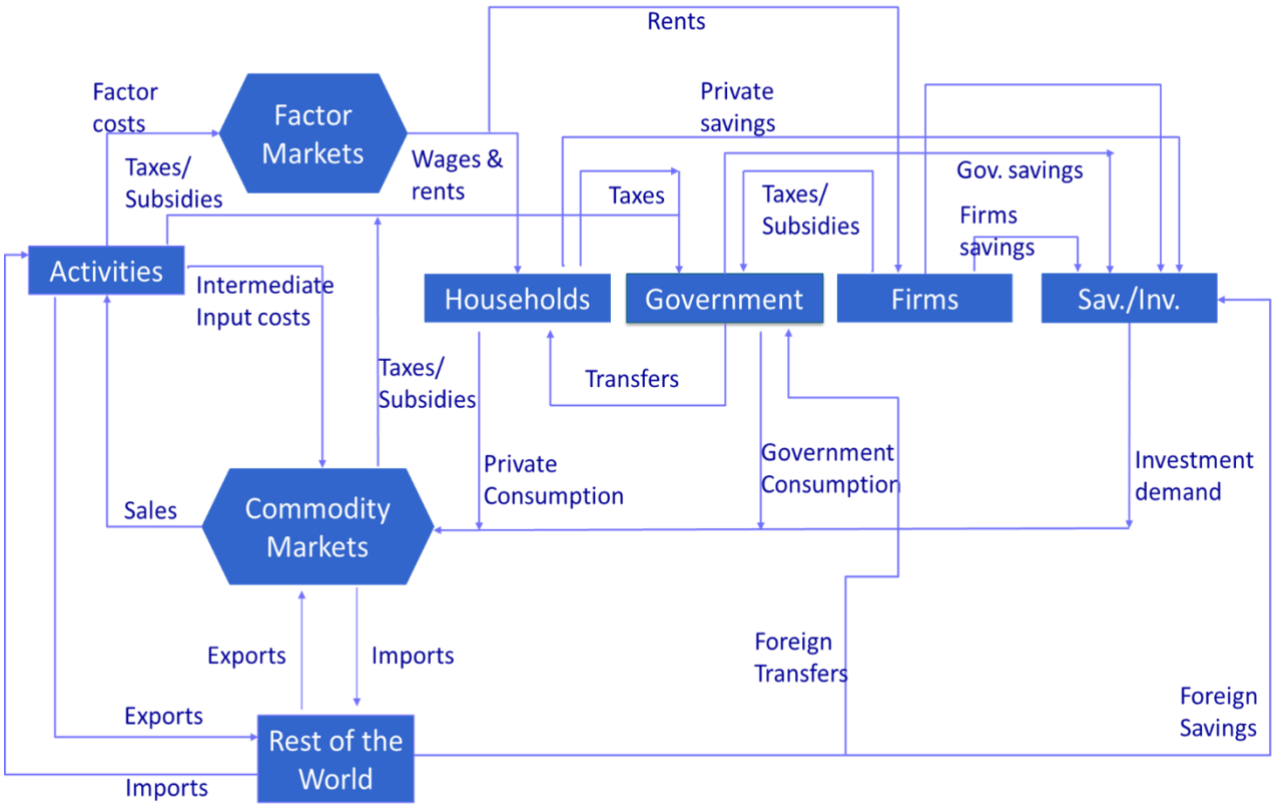

Figure 9. Overview of IRENCGE-DF

IRENCGE-DF is a recursive dynamic computable general equilibrium model. Each year, a scenario is solved as a static equilibrium, while dynamic equations link exogenous factors - such as population growth and capital accumulation - across years. Additionally, the model includes update equations for productivity factors. Each static equilibria relies on a relatively standard set of equation specifications.

Production is modelled using a series of nested Constant-Elasticity-of-Substitution (CES) functions designed to capture the substitutions and complements among the various inputs - notably capital and labour, but also with a focus on energy inputs (Figure 10). This emphasis underscores the model's core objective of analysing energy and environmental policies.

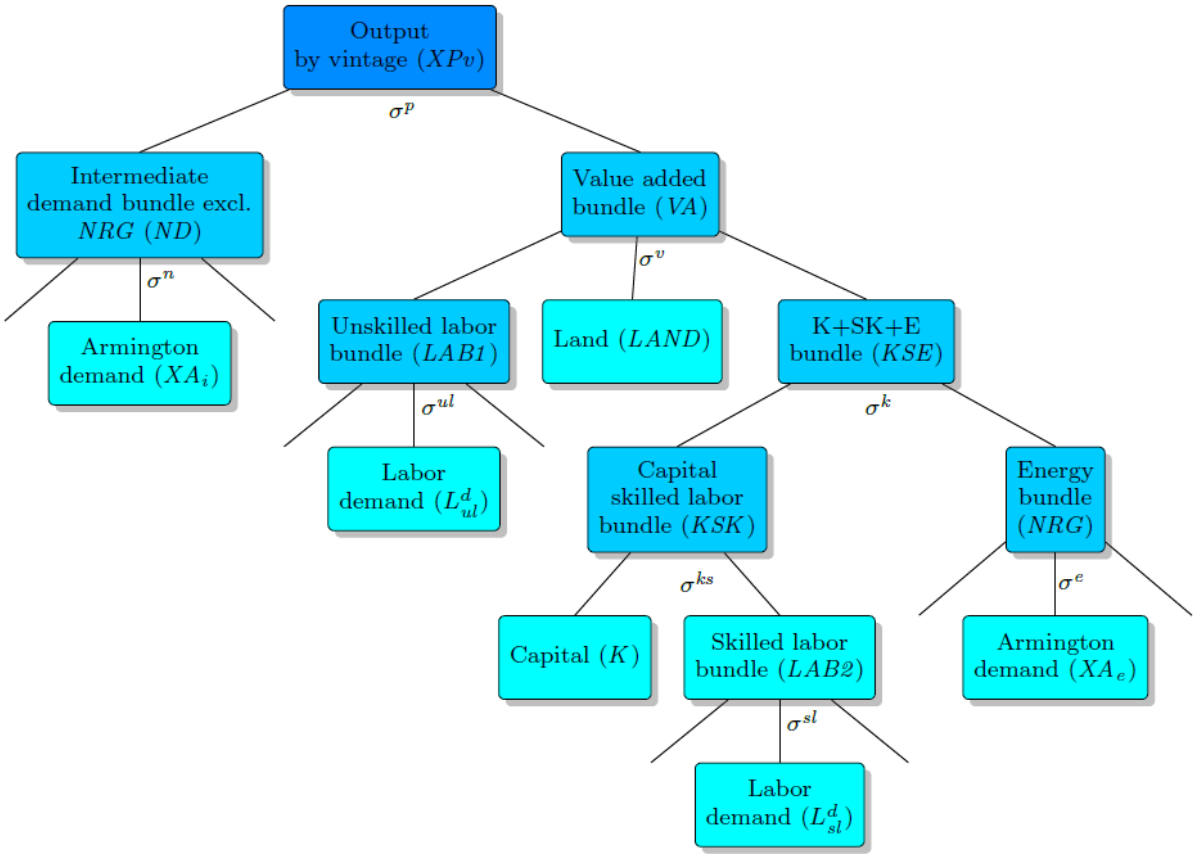

Figure 10. Production structure, IRENCGE-DF

Energy is assumed to be a near-complement to capital in the short-run, whereas it becomes a substitute in the long-run. Thus, increases in energy prices tend to raise production costs in the short-run - when substitution is low - but in the long-run firms respond by adopting energy-saving technologies, thereby dampening the cost-push factor. This feature of the model is embodied in a vintage capital structure that captures the semi-putty/putty relations across inputs, allowing for more elastic long-run behaviour as compared to the short-run.

The model supports both multi-input and multi-output production structures. The former, for example, would allow for electricity supply to be produced by multiple activities - thermal, hydroelectric, solar and other renewable sources. The latter allows a single production activity to yield multiple output; for example, oilseed crushing produces both vegetable oils and oil cakes used in animal feed.

Labour and capital income are largely allocated to households, with pass-through accounts to enterprises. Government revenue is derived from both direct and indirect taxation.

Household demand is modelled using the Constant-Differences-in-Elasticity (CDE) demand function, consistent with the standard utility function used in the GTAP model (Hertel et al. 1997). The model allows for a different specification of demanded commodities (indexed by *k*) from supplied commodities (indexed by *i*), employing a transition matrix approach – based on a nested CES approach - to convert consumer goods to supplied goods. In the current version, the transition matrix is largely diagonal, implying that consumed commodities are directly mapped to supplied commodities. Energy demand is bundled into a single commodity and disaggregated by energy type

using a CES structure that allows for inter-fuel substitution. Other final demand components are handled similarly, although the aggregate expenditure function follows a CES rather than a CDE specification.

Goods are valued at basic prices, incorporating tax wedges. The model includes trade and transport margins, that add an additional wedge between basic prices and final consumer prices. These margins are differentiated by transport nodes – farm or factory gate to domestic markets and the border in the case of exports), and from port to end-users in the case of for imports.

Import demand is modelled using the ubiquitous Armington assumption, i.e., goods with the same nomenclature are differentiated by region of origin. This allows for imperfect substitution between domestically produced goods and imported goods, with the degree of substitutability across regions of origin Determined by the CES elasticity parameter. Similarly, domestic production is differentiated by region of destination using the constant-elasticity-of-transformation (CET) function, which determines the CET elasticity level, governing the ability of producers to switch between domestic and foreign markets. The model allows for perfect transformation in which case the law-of-one price must hold.

Market equilibrium for domestically produced goods sold domestically is assumed through market clearing prices. By default, the small country assumption is adopted for export and import prices, thus treating them as exogenous, i.e., export levels do not influence the price received by exporters and import demand does not influence cost-insurance-freight (CIF) import prices. The model does allow for implementation of an export demand schedule and an import supply schedule in which case the terms-of-trade would become endogenously determined.

The current version of the model assumes market clearing wages on the labour markets, with the possibility of an upward sloping labour supply schedule and sluggish inter-sectoral mobility.

The dynamic structure of IRENCGE-DF is composed of three elements. First, population and labour stock growth are exogenous, with the latter being often equated to the growth of the working-age population. Second, the aggregate capital stock grows according to the overall level of saving - across enterprises, households, public and foreign - but is also influenced by the investment price index and the rate of depreciation. The third component relies on productivity assumptions. By default, labour productivity in the services sector is either assumed or calibrated dynamically to achieve a per capita growth target. Labor productivity in other sectors is calculated relative to labour productivity in services using a linear schedule that admits both multiplicative and additive components, allowing the model to calibrate inter-sectoral labour productivity to historical trends (either domestic or international).

In dynamic simulations, capital is modelled by vintages distinguishing old and new assets. *New* capital is allocated across sectors to equalize the rate of return, while *old* capital remains sector-specific unless the sector contracts. A sector is considered to be in decline when its potential supply, as measured by the capital/output ratio, exceeds *ex post* demand. This outcome may arise from a variety of demand-side shocks affecting specific commodities. If a sector is in decline, it releases its installed capital using an upward sloping supply schedule and its *ex post* return on capital falls below the economy-wide average. *Old* capital in expanding sectors earns the same rate of return as new capital.

The model is calibrated on the 2022 Social Accounting Matrix (SAM). The SAM is constructed by combining national accounts data - including the national accounts matrix and supply-use tables for the latest available year - with Eurostat data. National accounts data provide detailed information on the final and intermediate consumption at activity and commodity levels, though they lack detailed information on taxation. Hence, we use the tax return data available at the Department of Finance to distribute taxes and subsidies per commodity. The SAM distinguishes between 77 activities, 68 commodities, 10 household groups and 10 tax categories. A detailed description of economic activities is provided in Table 4.

Table 4. Sectoral coverage of IRENCGE-DF

Agriculture	Sewerage-Waste
Forestry	Construction
Fishing	Trade-of-motor-vehicles
Mining	Wholesale-trade
Coal	Retail-trade
Oil	Land-transport
Gas	Water-transport
Food-products	Air-transport
Textiles	Warehousing-and-stransportation
Wood	Postal
Paper	Accommodation-food-serv
Printing	Publishing
Coke-and-pp	Motion-picture-TV
Chemicals	Telecommunications
Pharmaceutical	Computer-prog-Information-serv
Rubber-and-plastic	Financial-serv
Non-metallic-mineral-products	Insurance
Basic-metals	Aux-to-financial-svcs-insurance
Metal-products	Real-estate
Computer-electronic	Legal-accounting-consultancy
Electrical-equipment	Architectural-engineering
Machinery-Equipment-nec	Scientific-research-development
Motor-vehicles-trailers	Advertising
Other-transport-equipment	Other-professional-Veterinary
Furniture-Other-manufacturing	Rental-leasing
Repair-installation	Employment-activities
Transmission and Distrib. of Electricity	Travel-agency-Tourism
Coal-BaseLoad-Electricity	Other-serv
Gas- BaseLoad-Electricity	Public-administration
Wind-BaseLoad-Electricity	Education
Hydro-BaseLoad-Electricity	Health
Oil- BaseLoad-Electricity	Residential-care
Other- BaseLoad-Electricity	Creative-arts-cultural
Gas-Peak-Electricity	Sports

Hydro-Peak-Electricity	Membership-organisations
Oil-Peak-Electricity	Repair-of-computers-and-personal-goods
Solar-Peak-Electricity	Other-personal-serv
Gas distribution	Households
Water	

3.2.1. Environmental Features of the CGE Model

Figure 11 illustrates the core structure of a dynamic, multi-sector CGE model augmented with environmental and technological extensions.

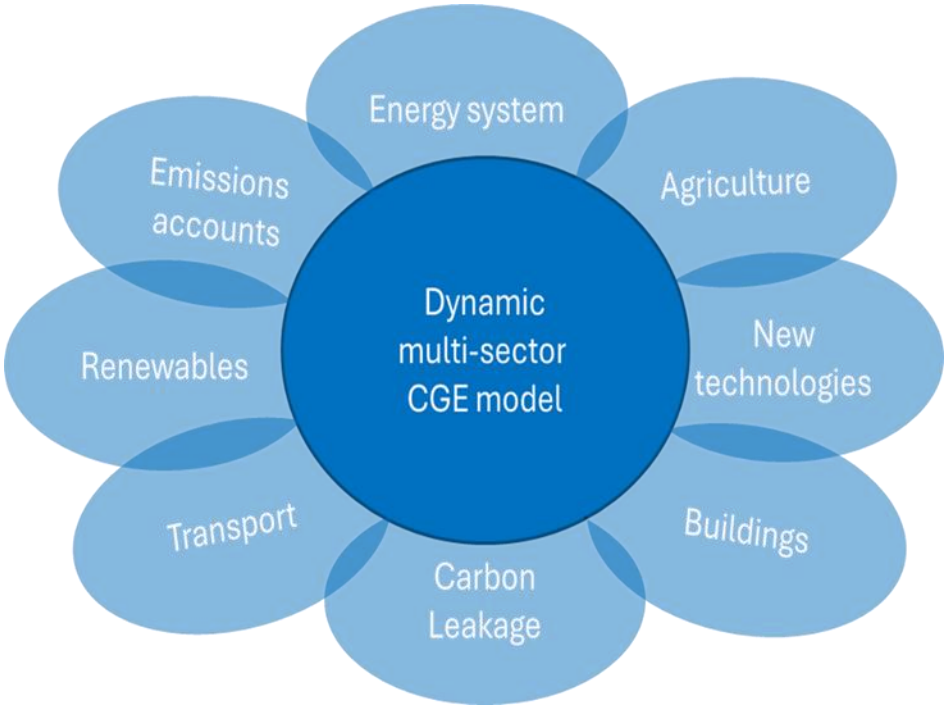

Figure 11. The model different dimensions

At its centre lies the economic engine—capable of representing production, consumption, trade, and investment dynamics over time. Surrounding this core are thematic components that enrich the model's analytical depth. These extensions allow the CGE framework to go beyond aggregate economic variables and engage with energy systems, sectoral emissions, and technological transitions. They enable it to:

- Represent the full energy supply chain, from resource extraction to power generation and final energy use;
- Capture greenhouse gas emissions across a range of sources, including agriculture, waste, buildings, and transport;
- Incorporate emerging low-carbon technologies, supporting realistic pathways for decarbonization;
- Reflect structural phenomena like carbon leakage or the uneven distribution of impacts across sectors and regions.

By integrating these environmental and technological layers, the model becomes a powerful tool for climate and energy policy analysis. It combines macroeconomic general equilibrium with sector-specific insights, allowing for an assessment of not just what decarbonization costs, but how it can be achieved through systemic transformation.
In particular, the model incorporates a number of enhancements to improve the representation of the energy system and its interaction with the economy. First, a revised energy specification introduces capital–energy substitution in production, allowing producers to respond more realistically to changes in relative input prices. In addition, the model enables intra-fuel substitution across all demand agents, capturing the possibility of fuel switching within both fossil and non-fossil categories in response to price signals or policy incentives.

Furthermore, it incorporates an energy system with six different technologies for electricity generation. These technologies are disaggregated from the original electricity sector in the Supply-Use tables, using different source, the GTAP-Power Database (Chepeliev 2023) and data on levelized costs (annualized cost per GWh) for capital, operation and maintenance (O&M), and fuel, sourced from the International Energy Agency (IEA). To assure consistency the new Social Accounting Matrix (SAM) is balanced using Cross-Entropy and Bayesian Highest Posterior Density methods.

The model explicitly tracks the main greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Emissions are generated through multiple channels, including:

- Commodity consumption, particularly fossil fuels;
- Factor use, such as livestock production (e.g., methane from enteric fermentation and manure);
- Process-based emissions, such as methane emissions from landfills and other waste management activities.

A range of climate policy instruments is implemented in the model framework, including:

- Carbon taxation, introduced exogenously, which can be differentiated by commodity, and end-user, allowing for partial or full exemptions;
- Emission caps, applied flexibly across sectors, with the possibility of grouping sectors into sets with shared targets;

These mechanisms enable the model to simulate a wide range of climate policy scenarios, capturing both distributional implications and sectoral adjustment dynamics. The model has recently been applied in policy analysis, assessing the distributional and macroeconomic impacts of alternative revenue recycling schemes associated with climate policy in Italy (Orecchia et al. 2023).

4. Two-way soft linking

The methodology for establishing a two-way link between the CGE model and the TIMES-Italy model involves an iterative process divided into four key steps, as illustrated in Figure 12. This linkage aims to enhance the integration of economic and energy systems by harmonizing socio-economic assumptions, emissions pathways, marginal abatement costs (MAC), and energy supply mixes between the two models. The figure details the iterative linking process, emphasizing the steps required to achieve consistency in socio-economic drivers, energy projections, MAC estimates, and energy mix alignment.

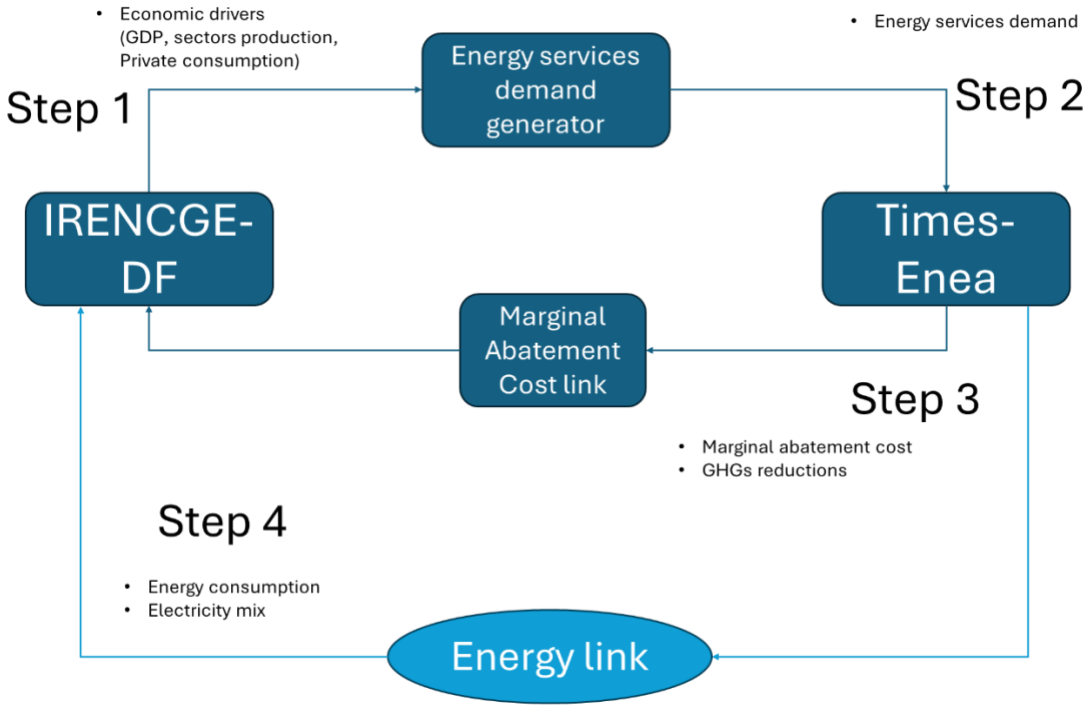

Figure 12. Linking process of IRENCGE-DF and TIMES-Italy

The first step involves aligning exogenous socio-economic assumptions and emissions pathways across both models. The CGE model provides key inputs, serving as the main energy service demand drivers for the BU TIMES model. These drivers, including changes in sectoral outputs and *per capita* income, allow the TIMES model to project future energy service demand trends up to 2040. Harmonizing socio-economic drivers between the TD CGE model and the BU TIMES model ensures consistency in projections of marginal abatement costs and energy supply mixes.

Table 5 summarizes the exchange of key variables between the two models. The CGE model provides macroeconomic indicators such as GDP growth, population growth, sectoral production growth in energy-intensive industries, and household income growth. On the other hand, the TIMES model supplies energy system details, including marginal abatement costs, the use of fuels in electricity and heat production, and the fuel consumption patterns across major aggregate sectors such as agriculture,

industry, services, transport, and residential sectors. This exchange ensures a coherent framework for projection alignment.

Table 5. Information exchange between IRENCGE-DF and TIMES-Italy

From IRENCGE-DF → To TIMES	From TIMES → To IRENCGE-DF
Population growth → heating and electricity residential demand	Marginal abatement cost (MAC)
Sectoral output (industry, services) → sectoral energy demand	Fuel mix in electricity & heat (coal, gas, oil, renewables)
Household petroleum demand → small vehicles transportation demand	Fuel use by aggregate sectors (agriculture, industry, services, transport, residential)
Transport output → large vehicles & freight transportation demand	
Economy-wide emissions cap → overall GHG constraint	

Since the two models differ in structure and sectoral details, establishing a direct link between every economic sector in the CGE model and each energy end-use sector in the TIMES model is not feasible. Instead, from the CGE model to TIMES, the following main drivers of energy demand are transferred: population growth determines residential electricity and heating demand, sectoral output in industry and services shapes their respective energy requirements, and household demand for petroleum products feeds into small vehicle demand. Similarly, transport production drives the demand for large vehicles and freight, while the economy-wide emissions cap provides TIMES with the overall constraint to be respected. In the opposite direction, TIMES enriches the CGE framework by supplying the marginal abatement cost, which ensures coherent carbon price signals across the models, and by providing detailed information on the fuel mix (coal, natural gas, oil products, renewables) used in electricity and heat generation. TIMES also reports fuel use across the major aggregate sectors—agriculture, industry, services, transport, and residential—thereby complementing the CGE model's stylized energy structure with a more realistic sectoral representation. Through this two-way exchange, the macroeconomic dynamics captured by IRENCGE-DF are anchored to technology-rich pathways from TIMES, resulting in a more consistent and detailed assessment of decarbonization strategies.

As a preliminary step toward aligning the energy mix, the marginal abatement cost was first synchronized between the CGE and TIMES models. This alignment was crucial to ensure that the signals related to the cost of emissions reductions were consistent across both models. Both models operate under the assumption of a cap on emissions in the baseline scenario, meaning they each incorporate a limit to the total emissions allowed in the system. By aligning the marginal abatement costs, the models could accurately reflect the economic and technological dynamics required to meet this emissions cap. This step provided a cohesive framework for integrated energy and environmental policy analysis, ensuring that the transition to a sustainable and economically optimized energy mix could be modelled effectively, with both technological and economic factors working in concert to achieve the emissions reduction targets.

In the TIMES model, technologies are selected based on their cost-effectiveness in achieving the emissions reduction targets. If the introduction of a high-cost technology (e.g., a cutting-edge renewable energy technology, carbon capture and storage, or new energy efficiency measures) is optimal for meeting the emissions cap, the model incorporates it into the solution. The cost of these

technologies, including both investment and operational expenses, directly influences the marginal abatement cost. This higher marginal abatement cost in TIMES, driven by the inclusion of costly technologies, can influence broader policy decisions, such as setting carbon prices or providing subsidies for these technologies.

If the TIMES model identifies the introduction of expensive technologies as optimal for reducing emissions and meeting the emissions cap, this choice should be reflected in the CGE model. In other words, the CGE needs to account for the economic costs of adopting these expensive technologies when evaluating the overall impact of policies like a carbon tax or subsidies for low-emission technologies. For example, if the TIMES model suggests that carbon capture technology (which is costly) is needed to reduce emissions, the CGE model must consider how this technology will impact the broader economy, including production costs, consumption changes, and investment patterns.

When the CGE model reflects high marginal abatement costs due to the adoption of expensive technologies (like carbon capture or other costly measures), this can have a ripple effect throughout the economy. Specifically, the higher carbon prices resulting from these high costs would influence firms and households to adjust their behaviour. For example, businesses might face higher operational costs as a result of the carbon prices, which could lead to changes in how they produce goods and services. They might reduce production in high-emission sectors, invest in cleaner technologies, or pass on the increased costs to consumers through higher prices.

Similarly, households might change their consumption patterns due to the higher costs of goods and services driven by carbon pricing. They might cut back on energy-intensive products or shift to more sustainable alternatives if they are financially viable.

Moreover, the high cost of abatement could prompt changes in investment patterns—for example, shifting investments away from carbon-intensive sectors (such as fossil fuels) and toward cleaner or more energy-efficient technologies. The sectors that are more cost-effective in reducing emissions (like renewable energy or energy-efficient technologies) might see increased investment, while those that rely on high-carbon technologies might experience reduced investment.

So, in essence, the introduction of costly technologies in the TIMES model leads to economic adjustments across multiple sectors, as firms and households respond to the financial implications of higher emissions reduction costs.

Initial model runs revealed significant discrepancies between the two models in marginal abatement cost (MAC) estimates. The CGE model projected a MAC of €170 per ton of CO_2e, whereas the TIMES model estimated €60 per ton of CO_2e. These differences stem from the intrinsic characteristics of each model: the CGE model is less capable of capturing energy system dynamics, such as changes in energy intensity due to technological advancements, shifts in energy mix, and energy price fluctuations due to sectoral competition. The TIMES model, as a BU optimization model, tends to be overly optimistic, assuming perfect technological substitution, which can lead to unrealistic cost projections. Moreover, BU models do not fully incorporate endogenous market adjustments, such as demand reductions following the imposition of a carbon constraint, which can exaggerate price increases.

To reconcile these differences, we adjusted the flexibility of the CGE model by modifying substitution elasticities—specifically, capital-energy substitution, intra-fuel substitution, and trade elasticity. These modifications aligned cost estimates between the two models while capturing key behavioural

effects, such as rebound and leakage. By progressively increasing the CGE model's flexibility, we achieved convergence in MAC estimates, with both models arriving at approximately €100 per ton of CO_2e. This iterative process underscores the necessity of careful parameter calibration to ensure consistency and accurately reflect economic and energy system dynamics.

Following MAC convergence, the focus shifts to harmonizing energy efficiency improvements (EEI) in the CGE model to match final energy consumption results obtained from the TIMES model. To replicate the TIMES-projected electricity mix, an equation was introduced to compute electricity generation shares, while productivity shifters were incorporated into the value-added (VA) nest of the CGE model. For final energy consumption, Autonomous Energy Efficiency Index (AEEI) shifters were applied to differentiate energy efficiency improvements across sectors and household types. Figure 13 presents a high-level overview of the soft-link process, emphasizing the iterative calibration and adjustments required to align projections between the two models. This figure highlights the stepwise integration process and the information exchange necessary to ensure consistency between economic and energy system projections.

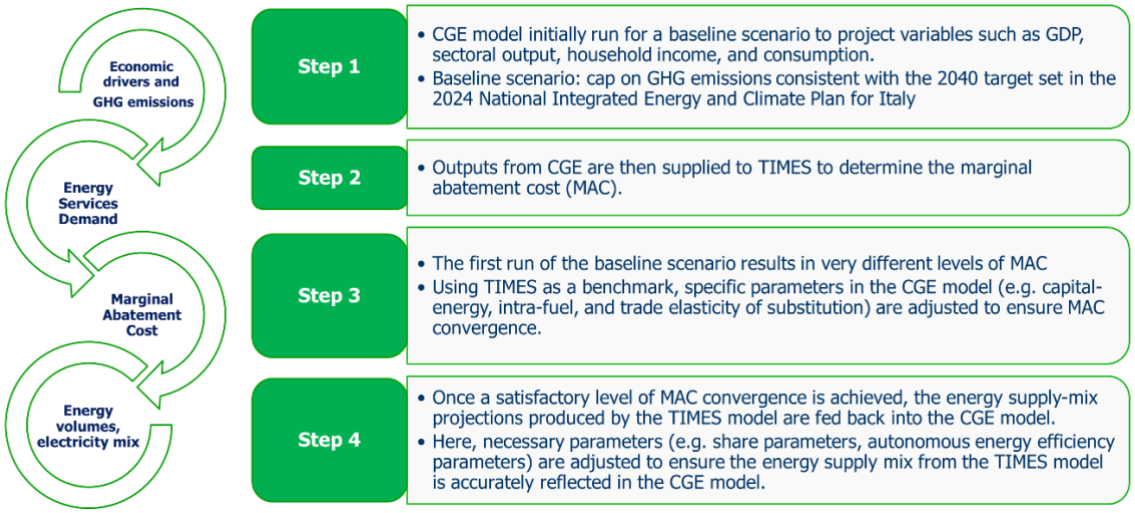

Figure 13. Overview of the soft link process

Integrating the CGE and TIMES models in this manner ensures alignment of both economic and energy system projections. This is particularly critical for sectors where technological substitution plays a significant role in emissions reductions, such as power generation and heavy industry. By aligning MAC estimates and energy mixes between the two models, we ensure that the economic costs of emissions reductions remain consistent across sectors and that technological shifts—such as the transition from fossil fuels to renewables—are adequately captured.

This methodology also enhances our understanding of how different model assumptions influence final outcomes. Soft-linking the CGE and TIMES models bridges the gap between TD and BU modelling approaches, producing more robust and policy-relevant projections. The results from this linkage can inform the design of market-based policy instruments, such as carbon pricing, and provide valuable insights into the long-term energy and economic transitions required to achieve climate goals.

5. Iterations

In an iterative linking process, key variables are aligned between the two models, with a particular focus on the Marginal Abatement Cost (MAC). In any standard CGE model, the abatement cost is not defined by an explicit functional form. Instead, it emerges implicitly from the substitutions between inputs (such as capital, labour, and energy) and the resulting changes in relative prices.

This substitution mechanism is governed by a hierarchy of Constant Elasticity of Substitution (CES) production functions defined at the sectoral and input level. Their parameters—namely the elasticities of substitution and efficiency shifters—are iteratively adjusted so that the energy mix by sector and fuel type and the implied carbon price in the CGE model reproduce the trajectories obtained from TIMES.

In particular, the production function of a standard CGE model typically takes the form:

$$Y = (\alpha_1(\gamma_1 X_1)^{\sigma} + \alpha_2(\gamma_2 X_2)^{\sigma} + \cdots \alpha_n(\gamma_n X_n)^{\sigma})^{\frac{1}{\sigma}}$$

where:

- Y is the output of the sector.
- X_1 …. X_n are the inputs (such as labor, capital, energy).
- $\alpha_1 \ldots \alpha_n$ are the input shares.
- $\gamma_1 \ldots . \gamma_n$ are the efficiency shifters
- σ is the elasticity of substitution between inputs.

The elasticity of substitution (σ) affects the curvature of the cost function and the ease with which production factors can be substituted for each other. A high value of σ implies that factors are easily substitutable, while a low value indicates that the factors are less substitutable.

The share parameters (α) determine the relative weight of each production factor (such as energy, capital, labour) in the production function. By changing α, you modify the intensity of the use of each factor, which will influence the MAC.

The efficiency shifters (γ) could represent reductions in energy use per unit of output due to cleaner or more efficient energy sources.

Emissions reduction (or abatement) can occur through changes in the input mix used in production. For example, emissions can be reduced by increasing the use of cleaner or more efficient technologies. The model simulates substitution between inputs and changes in relative prices of those inputs. These substitutions and price changes affect the MAC, which increases depending on the intensity of emission reductions.

To demonstrate the relevance of the MAC in soft-linking top-down and bottom-up models, we need to show how the MAC can serve as a common link between these two types of models. The MAC is critical in determining the cost-effectiveness of various emission reduction strategies, and its proper

calibration allows for the formulation of efficient and economically optimal policies, both in the short term and over longer horizons as technology and costs evolve.

For simplicity, we can assume that the abatement cost function takes a quadratic form, similar to:

$$C = \sum_n C_n = \sum_n \beta_n M_n^2 \qquad (1)$$

where C are the total costs, $C_n$are the costs of sector n, M_n are the level of emission abatement of sector n, and β represents a sector-specific cost parameter, which determines the slope of the quadratic cost curve for that sector.

This is a common assumption in economic models because it reflects the fact that initial emission reductions may be less costly, but as more stringent reductions are required, the cost increases at a non-linear rate. Thus, by assuming a quadratic cost function, we are modelling the idea that the cost of further reducing emissions rises at an increasing rate.

Then, the least-cost emission solution follows from the following minimization problem

$$\min_{M_n} \sum_n C_n$$

$$\text{s.t.} \quad \sum_n M_n \geq M$$

Forming the Lagrangian,

$$L = \sum_n \beta_n M_n^2 - \lambda(\sum_n M_n - M)$$

and taking the first partial derivative to the policy instruments (i.e., the emission reduction effort), we derive the first-order conditions for optimality:

$$\frac{\partial L}{\partial M_n} = 2\beta_n M_n - \lambda = 0 \qquad (2)$$

From the quadratic cost function (1), we can derive the MAC for each sector:

$$\frac{\partial C_n}{\partial M_n} = 2\beta_n M_n \qquad (3)$$

And thus comparing (2) and (3) we can see that

$$\frac{\partial C_n}{\partial M_n} = \lambda \qquad (4)$$

That is, least-cost emission reduction requires that all emitters face the same abatement cost at the margin. Now it is clear that to ensure that the MAC in the CGE and TIMES models are aligned, we need to ensure that the calibration of the cost parameters in both models results in the same MAC over time. This ensures that both models provide consistent outcomes when estimating the total abatement cost.

Given that the marginal abatement costs are calibrated to match, the total abatement cost (C_{total}) in both models is the integral of the marginal cost over time:

$$C_{total}(t) = \int_0^t \lambda(t)dt$$

As long as the marginal abatement costs λ(t) are calibrated correctly in the CGE model (by adjusting σ and other parameters in the CGE model), the total abatement costs in both models will converge over the entire modelling horizon.

Thus, the convergence of the MAC in the two models has two key implications: cost-effectiveness and consistency of total abatement costs. First, ensuring that all emitters face the same MAC across models guarantees an efficient allocation of emission reductions. Abatement efforts are directed toward sectors where mitigation is most economical, thereby minimizing overall costs for a given reduction target. Second, the convergence of total abatement costs ensures that the cumulative costs estimated by both models are consistent over the entire simulation horizon. This alignment is crucial to ensure that integrated policy assessments and long-term planning deliver comparable and reliable estimates of the economic implications of mitigation strategies.

6. Results and discussion

This section presents the results of the same emission reduction effort before and after the soft-linking exercise:

- **NL (No Link)**: the IRENCGE-DF operates independently from the TIMES-Italy model, with no exchange of information between the two models.
- **Link**: the two models are integrated following the approach described in Sections 4 and 5. In particular, the TIMES-derived power generation mix is integrated in the CGE model, enabling a more detailed representation of the structural transformation in the electricity sector.

Both simulations operate under identical GDP and emissions constraints. GDP trajectories are aligned with official projections from the Italian Ministry of Economy and Finance for the available forecast horizon. Beyond this period, the model assumes a convergence toward a Balanced Growth Path (BGP), where the economy grows by 0.5-0.3% each year until 2040.

The emissions pathway is consistent with the profile set in the reference scenario of the National Integrated Energy and Climate Plan for Italy, roughly a -40% reduction in 2040 compared to 1990 levels.

Comparing the outcomes of the two simulations shows that the structural differences between the two models lead to divergent outcomes in terms of mitigation effort distribution among sectors, cost-effectiveness, and technological transformation. In standard CGE models, emissions reductions are achieved through three primary channels, each constrained by structural modelling assumptions:

1. Activity contraction: emissions decline as economic output or household consumption is reduced in response to carbon pricing or abatement costs. While this is a technically effective mechanism, it implies direct welfare losses and is generally undesirable as a dominant policy outcome.

2. Energy mix adjustment: producers respond to higher carbon prices by substituting carbon-intensive energy inputs with cleaner alternatives (e.g., switching from coal to gas or electricity). This is implemented via nested CES production functions, which rely on fixed substitution elasticities. As such, the flexibility to reallocate energy inputs is limited and calibrated to historical behaviour.
3. Energy efficiency improvements: emissions can also fall through reductions in energy use per unit of output. In most CGE models, such gains are introduced via exogenous shocks to energy productivity, based on scenario assumptions rather than endogenous decision-making. Critically, the uptake of energy-saving technologies—such as heat pumps, high-efficiency motors, or electric vehicles—is not modelled explicitly. The CGE model does not simulate the behavioural and economic drivers behind energy efficiency investments, nor does it account for deployment constraints or learning effects. As a result, the pace and direction of efficiency improvements are externally imposed and not shaped by carbon prices or internal dynamics. Crucially, this mechanism does not capture the introduction and diffusion of new technologies—such as green hydrogen, industrial electrification, or carbon capture—despite their central role in long-term decarbonization. The energy system transition in the CGE framework is therefore stylized as a reallocation among existing fuels, rather than a shift enabled by technological innovation.

These three mitigation mechanisms correspond closely to the main drivers of emissions identified in the decomposition literature. A significant strand of work, following Ang and Zhang (1999), decomposes changes in total CO_2 emissions into components related to economic activity, energy structure, and energy intensity, using the Logarithmic Mean Divisia Index (LMDI) approach. Along similar lines, the IPACT identity expresses emissions as the product of four key factors: population, GDP per capita, energy intensity, and carbon efficiency.

$$CO_2 Emissions = Population \frac{GDP}{Population} \times \frac{Energy\ use}{GDP} \times \frac{CO_2}{Energy\ Use}$$

In the context of a CGE model, this decomposition closely resembles the structure outlined above:

- Reducing GDP (or output) corresponds to lower affluence, i.e., a contraction of economic activity. However, under the assumption of fixed GDP and population—as specified in the simulations examined in this study - this channel instead reflects a sectoral reallocation of output, where more carbon-intensive sectors reduce their activity relative to cleaner ones.
- Shifting to a cleaner energy mix reduces carbon intensity.
- Improving energy efficiency translates into a lower energy intensity;

Since technological innovation in CGE models is typically absent or highly stylized, emissions reductions stemming from stringent climate targets are usually driven by shrinking economic output, thus underestimating the role of technological innovation in changing the way output is produced and powered.

As such, although both simulations - the No Link and the Link - are subject to the same emissions cap, they tell two fundamentally different stories about how decarbonization unfolds in practice.

In the No Link simulation, the CGE model lacks information about how the energy system can evolve structurally. As a result, it relies primarily on reducing demand, marginally adjusting the energy mix within the constraints of substitution elasticities, and applying exogenous efficiency improvements. This is reflected in the carbon price trajectory shown in Figure 14 (a): carbon prices rise steeply and remain high throughout the simulation horizon, signalling the economy's limited flexibility in reallocating mitigation effort toward cost-effective options.

In contrast, the Link simulation incorporates detailed electricity sector insights from TIMES-Italy, which allow the CGE model to internalize a realistic and cost-optimal deployment of clean generation technologies. This leads to a significantly lower and more stable carbon price, indicating that emissions reductions are achieved more efficiently. The economy no longer relies on contraction or stylized assumptions but instead leverages structural transformation in the energy system to meet its climate target.

This transformation is clearly visible in the electricity generation mix shown in Figure 14 (b). In the Link simulation, the power sector undergoes a substantial shift toward renewable and low-carbon sources, driven by the TIMES model's technology-rich optimization. The share of wind and solar (variable energy sources) rises significantly, as the TIMES model allows for the replacement of old fossil fuel plants with new Renewable Energy Sources (RES) plants. Hydroelectricity decreases compared to the No Link simulation, as its contribution is corrected for geophysical limitations and gas declines even further. This cleaner power mix enables downstream decarbonization in a way that the No Link simulation cannot replicate.

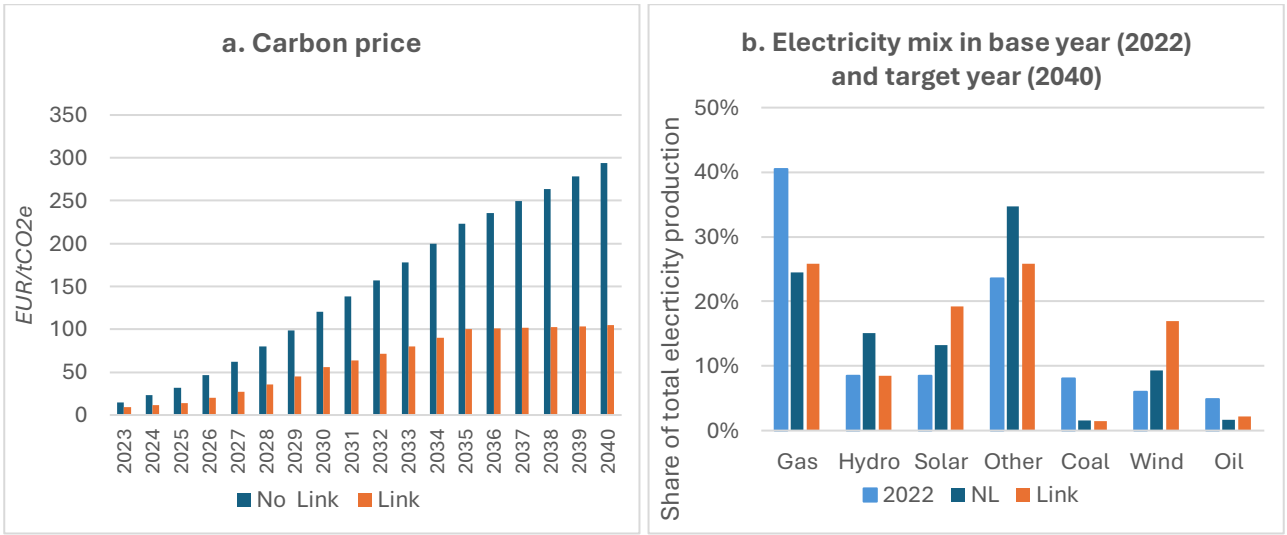

Figure 14. Carbon price trajectory (a) and Electricity mix (b) before and after linking

These changes also affect energy prices. As shown in Figure 15, electricity consumption prices increase more sharply in the No Link simulation, reflecting higher abatement costs and less efficient energy investments. By contrast, in the Link simulation, price trajectories are more moderate, thanks to better planning of technology deployment and system-wide optimization. This enables electricity

production to increase more sharply in the Link scenario and electrification to proceed without imposing unsustainable costs on households and businesses.

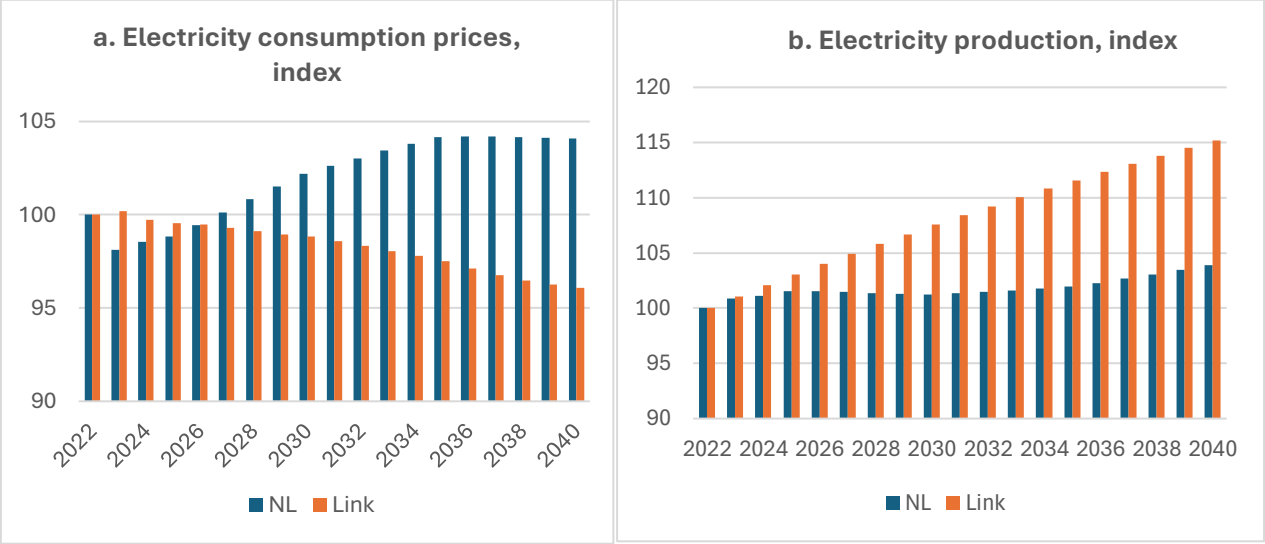

Figure 15. Electricity: production index (a) and consumption prices (b)

An additional layer of insight emerges from Figure 16, which illustrates how emissions reductions are distributed across sectors. In the No Link simulation, the electricity sector produces less output and relies on a smaller share of renewables, providing fewer clean energy inputs to the rest of the economy. As a result, other sectors—particularly industry and services—must undertake a disproportionate share of the mitigation effort. Given the limited availability of clean energy inputs and the absence of new technologies, these sectors are often forced to reduce emissions by contracting output, resulting in higher economic loss.

In the Link simulation, the more pervasive transformation of the electricity sector fundamentally reshapes this picture. The higher availability of clean electricity enables greater electrification in end-use sectors, including the residential sector (through the adoption of electric heating systems such as heat pumps) and the transport sector (through the uptake of electric vehicles). But critically, for industry and services the burden of emissions reduction is eased compared to the No link simulation.

In both industry and services, the higher emissions observed in the Link simulation reflect the different way abatement is achieved once technological detail is introduced. In the stand-alone CGE framework, which lacks sector-specific technological representation, emissions are reduced primarily through a quite uniform contraction of fossil fuel consumption, while electrification and the uptake of renewables occur only gradually due to the substitution constraints imposed by CES production functions. This leads to lower carbon intensity across these sectors. By contrast, when TIMES information is integrated, sectoral energy mixes evolve in a more differentiated manner. In both services and industry, reliance on fossil fuels remains significant and electricity use does not expand markedly, reflecting the relatively modest emission-reduction targets embedded in these simulations. Consequently, the carbon intensity of these sectors does not decline as in the No Link case, leaving their emissions higher even though the overall decarbonization pathway at the economy-wide level becomes more efficient.

Figure 16. Emissions by sector before and after linking (MtCO2e)

Overall, results demonstrate that the integration of TIMES expands the CGE model's capacity to simulate technologically enabled and economically sustainable transitions. Clean electricity becomes a general-purpose input for decarbonization, alleviating pressure on sectors with limited abatement options and enabling a more efficient allocation of mitigation effort across the economy.

7. Conclusions

This study has presented a two-way soft-linking framework between the top-down Computable General Equilibrium (CGE) model IRENCGE-DF and the bottom-up energy system model TIMES-Italy, developed respectively by the Department of Finance of the Italian Ministry of Economy and Finance and ENEA. The integration of these two modelling paradigms addresses the inherent limitations of each: the lack of technological granularity in CGE models and the absence of macroeconomic feedbacks in bottom-up frameworks.

The iterative linking process—centred on the alignment of marginal abatement costs, energy system configurations, and socio-economic drivers—demonstrates that soft-linking can significantly enhance the analytical robustness and policy relevance of climate-economy modelling. By incorporating the detailed technological pathways from TIMES into the CGE framework, the model captures a more realistic representation of decarbonization dynamics, particularly in the electricity sector. This integration enables the simulation of mitigation strategies that are not only cost-effective but also technologically feasible and economically sustainable.

The results show that clean electricity, as modelled in TIMES, functions as a general-purpose input for decarbonization, facilitating the electrification of end-use sectors and reducing the mitigation burden on those with limited abatement potential. This leads to a more efficient and equitable distribution of mitigation efforts across the economy, while also lowering the macroeconomic cost of achieving emissions targets.

Moreover, the soft-linking approach preserves the structural integrity of both models, allowing each institution to maintain and evolve its own analytical tools while benefiting from the enhanced consistency and feedback mechanisms introduced by the linkage. This modularity makes the framework scalable and adaptable to future extensions, including multi-country applications, distributional analyses, and the evaluation of complex fiscal and climate policy packages.

In conclusion, the two-way soft-linking methodology developed in this work offers a pragmatic and theoretically grounded approach to integrated assessment modelling. It provides a valuable tool for policymakers seeking to design and evaluate climate strategies that are both technologically credible and economically sound, thereby contributing to more informed and resilient policy decisions in the face of the climate transition.

References

Andersen KS, Termansen LB, Gargiulo M, O' Gallachoirc BP, 2019. Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models, Energy, 169: 277-293.

Ang, B. W., & Zhang, F. Q. (1999). Inter-regional comparisons of energy-related CO2 emissions using the decomposition technique. *Energy*, *24*(4), 297-305.

Arndt, C., Davies, R., Gabriel, S., Makrelov, K., Merven, B., Hartley, F., Thurlow J, 2016. A sequential approach to integrated energy modeling in South Africa. Applied Energy, 161, 591-599.

Bohringer C, Rutherford TF, 2008. Combining bottom-up and top-down. Energy Econ, 30, 574-96.

Bohringer C, Rutherford TF., 2009. Integrated assessment of energy policies: decomposing top-down and bottom-up. J Econ Dynam Contr, 33: 1648-61.

Bosetti V, Carraro C, Galeotti M, Massetti E, Carrarof C, Tavoni M, 2006. WITCH a world induced technical change hybrid model, vol. 27.

Chepeliev, M. (2023). GTAP-power data base: Version 11. Journal of Global Economic Analysis, 8(2).

d'Aertrycke G de M, Durand-Lasserve O, Schudel M., 2014. Integration of power generation capacity expansion in an applied general equilibrium model. Fondazione Eni Enrico Mattei (FEEM).

Dai H, Mischke P, Xie X, Xie Y, Masui T., 2016. Closing the gap? Top-down versus bottom-up projections of China's regional energy use and CO2 emissions. Appl Energy, 162:1355-73.

Drouet L, Haurie A, Labriet M, Thalmann P, Vielle M, Viguier L, 2005. A coupled bottom-up/top-down model for GHG abatement scenarios in the Swiss housing sector. In: Loulou R, Waaub JP, Zaccour G (Eds.), Energy and Environment. Cambridge, pp. 27–62.

Fortes P, Pereira R, Pereira A, Seixas J., 2014. Integrated technological-economic modeling platform for energy and climate policy analysis. Energy, 73: 716-30.

Fujimori S, Masui T, Matsuoka Y, 2014. Development of a global computable general equilibrium model coupled with detailed energy end-use technology. Appl Energy, 28:296–306.

Hertel, T. W., & Tsigas, M. E. (1997). Structure of GTAP. Global Trade Analysis: modeling and applications, 13-73.

Hourcade J-C, Jaccard M, Bataille C, Ghersi F., 2006. Hybrid modeling: new answers to old challenges introduction to the special issue of the energy journal. Energy J, SI2006:1-11.

Howitt, R.E., 1995. Positive Mathematical Programming, American Journal of Agricultural Economics 77: 329-342.

Krook-Riekkola A, Berg C, Ahlgren EO, Soderholm P., 2017. Challenges in top-down and bottom-up soft-linking: lessons from linking a Swedish energy system model with a CGE model. Energy, 141:803-17.

Labriet, M., Drouet, L., Vielle, M., Loulou, R., Kanudia, A. and Haurie, A., 2015. Assessment of the effectiveness of global climate policies using coupled bottom-up and top-down models.

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL Family of Models. ETSAP.

Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES Model - PART I 1–78.

Martinsen T., 2011. Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models. Energy Pol, 39:3327-36.

Manne A, Wene C-O, 1992. MARKAL–Macro: a Linked Model for Energy-Economy Analysis. Brookhaven National Laboratory. Report BNL-47161.

McFarland JR, Reilly JM, Herzog HJ, 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26 (4), 685–707.

Messner S, Schrattenholzer L, 2000. MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving iteratively. Energy — The International Journal 25 (3), 267–282.

OECD (2024), Approaches to linking models to assess the impacts of climate change mitigation actions on greenhouse gas emissions, Inclusive Forum on Carbon Mitigation Approaches Papers, OECD Publishing, Paris.

OECD (2022), Recommendation of the Council on Public Policy Evaluation, https://legalinstruments.oecd.org/en/instruments/OECD-LEGAL-0478 (accessed on 10 July 2025).

Orecchia, C., Cala, V. F., de Cristofaro, F., & Dudu, H. (2023). Assessing the Efficiency and Fairness of the Fit for 55 Package toward Net Zero Emissions under Different Revenue Recycling Schemes for Italy.

Rausch S, Mowers M, 2014. Distributional and efficiency impacts of clean and renewable energy standards for electricity. Resour. Energy Econ. 36 (2), 556–585 (May).

Schafer A, Jacoby HD., 2005. Technology detail in a multisector CGE model: transport under climate policy. Energy Econ, 27:1-24.

Strachan N, Kannan R., 2008. Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Econ, 30:2947-63.

Sue Wing I, 2008. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. Energy Econ, 30:547-73.

Sugandha TD, Yuan M, Bernstein P, Montgomery WD, Smith A, 2009. A top-down bottom-up modeling approach to climate change policy analysis. Energy Econ. 31, S223–S234.

Tapia-Ahumada K, Octaviano C, Rausch S, Perez-Arriaga I., 2015. Modeling intermittent renewable electricity technologies in general equilibrium models

Gracceva F., Zeniewski P., Exploring the uncertainty around potential shale gas development - a global energy system analysis based on TIAM (TIMES integrated assessment model), Energy, 57 (2013), pp. 443-457, 10.1016/j.energy.2013.06.006

Vaillancourt K., O. Bahn, E. Frenette, O. Sigvaldason, Exploring deep decarbonization pathways to 2050 for Canada using an optimization energy model framework, Appl Energy, 195 (2017), pp. 774-785, 10.1016/j.apenergy.2017.03.104

C. Andrade, L. Desport, S. Selosse, Net-negative emission opportunities for the iron and steel industry on a global scale, Appl Energy, 358 (2024), Article 122566, 10.1016/j.apenergy.2023.122566

Kouchaki-Penchah H., O. Bahn, H. Bashiri, S. Bedard, E. Bernier, T. Elliot, et al., The role of hydrogen in a net-zero emission economy under alternative policy scenarios, Int J Hydrog Energy, 49 (2024), pp. 173-187, 10.1016/j.ijhydene.2023.07.196

M. Pavičević, A. Mangipinto, W. Nijs, F. Lombardi, K. Kavvadias, J.P. Jiménez Navarro, et al., The potential of sector coupling in future European energy systems: soft linking between the Dispa-SET and JRC-EU-TIMES models, Appl Energy, 267 (2020), Article 115100, 10.1016/j.apenergy.2020.115100

M.C. Pinto, S.G. Simões, P. Fortes, How can green hydrogen from north Africa support EU decarbonization? Scenario analyses on competitive pathways for trade, Int J Hydrog Energy, 79 (2024), pp. 305-318, 10.1016/j.ijhydene.2024.06.395