Renewable and Sustainable Energy Reviews 199 (2024) 114462

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of macroeconomic modelling tools for analysing industrial transformation

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ARTICLE INFO

Keywords:
Macroeconomic models
Energy system models
CGE models
Circular economy
Industrial transformation
Technological change

ABSTRACT

This research presents a thorough evaluation of macroeconomic modelling tools in the context of analysing industrial transformation. It emphasizes the need to link macroeconomic models with energy system models to accurately depict industrial transformation. The study begins with a broad survey of macroeconomic modelling tools. A detailed database of 61 tools is then compiled, providing a critical analysis of the tools' structures and features. From this broad spectrum, the focus is narrowed to Computable General Equilibrium (CGE) models. The study develops a multi-criteria analysis framework, applied specifically to four CGE modelling tools, which encompasses 19 criteria categorized under four main pillars: Industrial/Sectoral representation, Technological change, Employment, and Environment. This framework critically evaluates these tools' suitability in analysing industrial transformation, highlighting the diversity of their capabilities and limitations. Although the GEM-E3 model demonstrates a high level of alignment with the framework's criteria, none of the four tools achieves a full score in any category, indicating potential areas for improvement. The broader analysis of the database's tools reveals issues such as limited accessibility, inadequate representation of social aspects, and insufficient geographical coverage. Additionally, the study notes a general lack of transparent information concerning the full features of macroeconomic modelling tools in public literature. Concluding with recommendations for further research, the study underscores the complexities in macroeconomic modelling and the need for comprehensive tools that effectively address the multifaceted aspects of industrial transformation. Such advancements will assist in making informed decisions towards a transformation that is both environmentally and economically sustainable.

1. Introduction

The year 2050 is approaching in which the Paris Agreement's carbon neutrality objective should be achieved [1], so accelerating the energy transition is imperative. One of the most challenging sectors to decarbonize in the energy system is industry, which was responsible for a quarter of global CO_2 emissions in 2021 [2]. Technological advancements have long been a driving force behind the evolution of industry. From economies-of-scale, automation, and artificial intelligence to the rise of the internet of things, technology has fundamentally altered the way in which we not only work but also produce goods and services. However, industrial transformation is not solely driven by technological advancements; it involves a complex interplay of economic, social, and environmental factors. The switch from fossil fuels to renewable fuels, is a definitive example of industrial transformation. This shift triggers growth in renewable energy technologies, such as wind turbines while diminishing other conventional industries such as, coal mining. Concurrently, the labour market adjusts to the expansion of job opportunities in renewable energy-related sectors and their contraction in fossil fuel industries. The impact on global trade can be significant, posing challenges for fossil fuel exporters while offering new export opportunities for countries that are excelling in renewable technologies. These ripple effects also extend to industries that supply materials and components for these technologies. Furthermore, governmental policies (e.g. renewable subsidies), which often guide such transformations, may change economic incentives and investment strategies across various industries. Industrial transformation can therefore have far-reaching

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https://doi.org/10.1016/j.rser.2024.114462
Received 1 May 2023; Received in revised form 25 December 2023; Accepted 22 April 2024
Available online 11 May 2024

Abbreviations

AEEI	Autonomous Energy Efficiency Improvement
AHP	Analytic Hierarchy Process
CGE	Computable General Equilibrium
CI	Consistency Index
CR	Consistency Ratio
DSGE	Dynamic Stochastic General Equilibrium
EPPA	Economic Projection and Policy Analysis
ESM	Energy System Model
GEM-E3	General Equilibrium Model for Economy-Energy-Environment
GTAP	Global Trade Analysis Project
I–O	Input-output
IEA	International Energy Agency
IGSM	MIT Integrated Global System Modeling
ILO	International Labour Organization
LULUC	Land-Use and Land-Use Change
MAGNET	Modular Applied General Equilibrium Tool
MCA	Multi-Criteria Analysis
MESM	MIT Earth System Model
OECD	Organisation for Economic Co-operation and Development
RI	Random Index
SDGs	The United Nations Sustainable Development Goals

effects that extend from changes in investment patterns, productivity, and international trade, to impacts on employment dynamics and environment.

Macroeconomic modelling can be employed to inform on the potential impacts of industrial transformation and assist in determining the optimal technological choices to be made therein, while taking into account its social, economic, and environmental dimensions. Due to the intricacy involved in analysing economic systems, macroeconomic models tend to use simplifying assumptions, which can result in certain limitations. One such limitation is the lack of detailed technical data about the energy system, which can lead to challenges in accurately gauging the influence of the energy transition on the economy. In contrary, bottom-up Energy System Models (ESMs) can provide highly disaggregated technological details [3]. However, as partial equilibrium models, they often disregard the interactions of the energy system with the rest of the economy, and thereby fail to inform on key socio-economic aspects, such as economic growth, employment, and households' consumption. Linking macroeconomic models with ESMs is therefore a way to partly overcome the drawbacks of each of these model types [4,5]. This linkage is particularly relevant for analysing industrial transformation since production factors and energy requirements may vary substantially according to the industrial activity – e.g. the iron and steel industry is an energy-intensive industry, whereas vehicle manufacturing is typically capital-intensive. In addition, the integrated approach proffered by macroeconomic model–ESM coupling can help in identifying potential synergies and trade-offs between different policy objectives, such as economic growth and emissions reduction. In turn, this can provide valuable insights for designing policies that foster an industrial transformation, which is both economically sound and environmentally sustainable.

This study distinguishes between 'modeling tools' and 'models'. The term 'modeling tools' refers to specific implementations of macroeconomic models, such as the Modular Applied GeNeral Equilibrium Tool (MAGNET), which are used for examining specific scenarios. These tools are practical applications of broader model types. In contrast, 'models' refer to the theoretical frameworks or types, such as CGE (Computable General Equilibrium) or macroeconometric models, which provide the foundational methodologies and structures for these tools. Our analysis predominantly focuses on the practical applications and effectiveness of modelling tools in the context of industrial transformation. The literature on macroeconomic modelling can be broadly classified into three categories: general methodological comparisons, tool specific analyses, and regional or country specific studies. The first category comprises studies that compare the methodologies used in macroeconomic modelling in general (CGE versus macroeconometric), without a specific focus on a particular tool. Examples include studies [6–9] that evaluated different models for their effectiveness in analysing specific policies (e.g. energy taxes). Other studies have also contributed to the understanding of macroeconomic models of specific type and its application in assessing climate change. Bergman, for instance, discussed environmental policy in relation to CGE models [10]. An et al. and Babatunde et al. have systemically reviewed the applications of CGE modelling in evaluating the impacts of low-carbon policies [11,12].

Second category includes research that delve into specific macroeconomic modeling tools, examining their approaches in addressing particular topics. For example, Faehn et al. reviewed the key approaches used by seventeen tools in representing the emissions abatement technologies [13]. In a similar manner, Hafner et al. compared eleven tools of different types with relevance to the transition in the power sector [14]. The incorporation of R&D and innovation policies in three tools of different spatial scales were examined by Akcigit et al. [15]. The final category features research that examines similar topics, but with a specific focus on a particular country or region. For instance, a number of studies examine the ability of different tools in proving insights specific to Ireland [18], Australia [19], Europe [20], and the United States [21] with regard to the macroeconomic impacts of environmental policies.

This research aligns with the second category but introduces a novel focus by specifically comparing macroeconomic modeling tools within the context of industrial transformation assessment. Initially, the study identifies and reviews 61 macroeconomic modelling tools in use by different stakeholders and organizations and documents all results in a comprehensive online database. From this comprehensive analysis, we create a shortlist of four CGE modeling tools which are then evaluated using a comparison framework. The framework is designed to provide an in-depth comparison of these tools based on their ability to address the multifaceted aspects of industry while also considering their adaptability for linking with ESMs.

The remainder of this paper is divided into three main sections. Section 2 describes the methodologies that we apply in our analysis. Section 3 reports and discusses the results of our review. Section 4 summarizes the study's conclusions and provides recommendations for further research. In each of these sections, we illustrate key macroeconomic terms, and expand on the types of macroeconomic models, as well as the limitations of macroeconomic modelling in general.

2. Methodology

We here describe the methodology used in creating the database for macroeconomic modelling tools (section 2.1). We also explain the process of creating the comparison framework that includes multiple criteria aimed at evaluating the suitability of macroeconomic modelling tools for examining industrial transformation. This framework serves as a foundation for conducting a multi-criteria analysis (MCA) on a subset of tools that we refer to as the 'shortlist' in the rest of this paper. Fig. 1 outlines the key stages of the research methodology.

2.1. Database of macroeconomic modelling tools

The creation of the database is aimed at comprehensively gathering

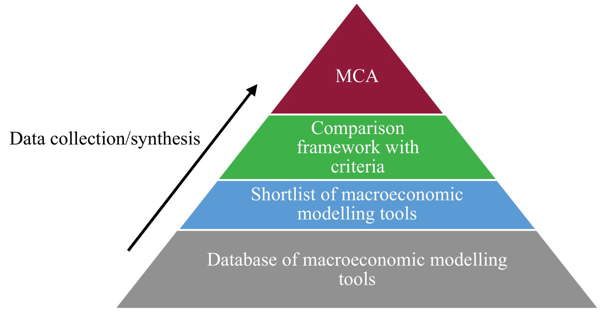


Fig. 1. A pyramid chart of the key stages of the research methodology.

data about available macroeconomic modelling tools. We started the research by conducting a literature survey utilizing a broad set of portals: Google scholar, ResearchGate, ScienceDirect, SpringerLink, Semantic Scholar, Google books, along with websites of organizations such as the World Bank and the Organisation for Economic Co-operation and Development (OECD). After identifying the tools, we collected data about each tool with respect to the attributes displayed in Table 1. These attributes can be divided into two categories: generic and specific. Generic attributes focus on practical overall information such as type of the model, which can be CGE, Macroeconometric, Input-output (I–O), and Dynamic Stochastic General Equilibrium (DSGE). Specific attributes, on the other hand, address more detailed information that is particularly relevant to the scope of this paper, such as the number of Sectors/Activities represented in the modelling tool (which indicates how many sectors are responsible for producing goods and services in the economy).

We compiled the data that we gathered into an online database by utilizing a Google spreadsheet. To gain a deeper understanding of the commonalities and disparities among the tools, we processed the data and generated systematic displays such as visualizations and tabulations, utilizing the Python programming language.

2.2. Framework development and MCA for the shortlisted tools

After a thorough review of the database, we decided that only Computable General Equilibrium (CGE) modelling tools would be considered for analysis, despite the presence of other model types. The reason for this lies in the specific requirements of our research, particularly the need for a detailed representation of the industrial sector, and the flexibility to model both supply and demand over extended periods of time. CGE models excel in these areas, which make them well-suited for analysing industrial transformation [16–18]. While other types of models may have their own advantages in analysing specific aspects of the economy, comparing pros and cons of different types of models is beyond the scope of this paper. In selecting the shortlisted CGE modelling tools, we based our decision on a variety of factors, including literature availability, accessibility by third parties, and the presence of active software support and updates. We narrowed down the focus to tools that had the most prominent features with regard to our scope of analysis, i.e. industrial transformation.

We created a comparison framework for the shortlisted tools, which served as a foundation for identifying the appropriate criteria needed for the MCA. This framework places considerable emphasis on the flexibility of the tools to be linked with ESMs, which play a crucial role in understanding the technical aspects of the industrial transformation as elaborated in section 1. The framework includes 19 criteria, which are classified into four categories, namely ‘Industrial/Sectoral

Table 1
Attributes of the database.

Attribute	Description
Type of Analysis	Two major categories of analysis are static and dynamic. Static models analyse the system state at one point in time. Dynamic models examine how the economy evolves over time by modelling how variables change from one period to the next. There are also other more specific types such as comparative static, recursive dynamic and Intertemporal.
Type of model	Examples of model types are CGE, Macroeconometric and Input-output. Each type has a different modelling approach. For example, macroeconometric models use statistical techniques to provide economic forecasts, while CGE models are mathematical tools that simultaneously solve a set of equations.
Developer	The developer of the tool, which can be an individual, an institution, or a consortium.
Number of Sectors/ Activities	The number of sectors or activities that produce commodities and services in the economy.
Accessibility	The accessibility to the software and/or data sources utilized in the tool. In some cases, one or more licenses are required to access the tool and sometimes it cannot be accessed at all.
Supporting software	The supporting software is the platform in which the model's equations and variables are defined, and where the model runs (e.g. MATLAB, GAMS).
Spatial scale	The spatial scale of the tool, which can be Global, National or Subnational.
Geographical coverage	The countries and regions that the tool covers. For example, a tool specific to the USA may include disaggregation into its individual states.
Temporal scale	The time duration during which the model runs (e.g., 1990–2050).
Technological change	Parameters and method (e.g. exogenous, endogenous) used to represent technological change in the economy.
Inclusion of modules	The macroeconomic model can have internal modules that represent some systems in the economy with extra details (e.g. water-use or emission trading).
Representation of labour/ employment	Parameters and insights generated by the tool in-line with the labour/employment representation in the economy. For example, some tools can show the unemployment rate as a result of a new policy or technology. Other models can examine the effect of changes in the minimum wage or social welfare programs on the different groups of workers, such as those with different levels of education or experience.
Data Source	Public resources, national accounts, or established databases (e.g. European statistics) used as input data for the tool.

representation', 'Technological change', 'Employment', and 'Environment'. The criteria focus on the various components of the industrial sector and endeavours to capture the pertinent social and environmental interactions Table 2 presents these criteria and their definitions. In identifying the criteria per category, we attempted to draw attention to particular aspects, as discussed in the following paragraphs.

Industrial/Sectoral representation: the focus here is to analyse the degree to which the industrial sector is represented in a given tool, with particular emphasis on the number of sectors included and the degree of flexibility in technology choices within each sector. These features are crucial for ensuring accurate industrial representation, as they can reduce the aggregation of industrial sectors. For instance, when considering electricity production, it is more reasonable to have independent wind, solar, and coal sectors, rather than aggregating them into a single sector, such as the power sector. This disaggregation enables higher sectoral resolution, providing better scrutiny of the details of each sector. Moreover, when linking macroeconomic models with ESMs, a significant challenge faced by modellers is the discrepancy in the number of sectors and technologies between the two models. ESMs often represent these aspects with detailed granularity, as exemplified by the IESA-Opt ESM, which comprises over 700 technologies distributed among multiple sectors [19]. Another example is the OPERA ESM, which represents industrial sector in about 104 subsectors [20]. To establish a link between the two models, the sectors and technologies in the ESM must be aggregated until they align with those of the macroeconomic model. However, this process of aggregation would lead to a considerable reduction in the level of detail in the industrial representation, which may impede the ability to obtain a comprehensive understanding of the energy system.

Technological change: when examining industrial transformation, it's essential to consider the critical role of technological change. At its core, technological change refers to the potential increase in output resulting from improvements in the production process [21,22]. Technological change can be categorized into three groups: exogenous, endogenous, and semi-endogenous. Exogenous variables are inputs provided by the user, while endogenous variables are calculated internally with a model's equations. Semi-endogenous variables, on the other hand, are a combination of exogenous and endogenous variables [23,24]. A key aspect of our comparative framework is maintaining consistency in assumptions across CGE models and ESMs. This is crucial for effective linkage between these models. Using exogenous parameters, such as Autonomous Energy Efficiency Improvement (AEEI), ensures that both models operate under the same set of assumptions about technological progress. While endogenous and semi-endogenous changes have their merits in modelling dynamic economic interactions, the choice of exogenous technological change in our analysis is a methodological decision tailored to the practical needs of models linking.

Employment: in examining the labour force, there are two fundamental factors to consider; unemployment types (e.g., cyclical, involuntary/voluntary), and categories of skills [25]. Despite the importance of such elements, most computable general equilibrium (CGE) models merely take into account unemployment rates and the division of labour into skilled and unskilled categories, with few incorporating involuntary unemployment. Despite these limitations, we endeavoured to identify criteria that would assess the broader interplay within the social loop of the macroeconomy, such as labour mobility between countries or regions, which is fundamental for enabling industrial transformation [26]. Incorporating these elements when examining changes in industry, can provide a more comprehensive and nuanced understanding of the labour force and its impact on the economy.

Environment: this category encompasses five criteria designed to assess the tools' capability in covering today's most critical environmental issues. In identifying these criteria, we take into account the limitations of CGE models when it comes to examining complex environmental issues. For instance, studying certain issues may require more

Table 2
The framework's criteria and their definition.

Index	Criteria	Definition/Aim
1	**Industrial/Sectoral representation**	
1.1	Number of sectors/activities	Identifies the number of sectors or activities in the modelling tool, if the number of sectors and activities are unequal, the more comprehensive one is considered.
1.2	More than one technology per one commodity	Assesses whether the modelling tool permits the utilization of more than one technology for producing the same commodity, such as the presence of a green and a conventional technology for steel production. Note that this criterion does not consider the electricity generation sector.
1.3	More than one commodity per sector	Evaluates the modelling tool's ability to accommodate the production of more than one commodity per sector (e.g. by-products).
1.4	Fuel substitution per technology	Verifies if the modelling tool allows for the substitution of one fuel by another for the same technology.
1.5	Flexibility of aggregation and disaggregation of sectors	Evaluates if the sectors can be aggregated into fewer sectors or disaggregated to include more sectors, which can allow researchers to adjust the level of sectoral detail according to the research question at hand.
2	**Technological change**	
2.1	AEEI/Technical progress	Assesses if the modelling tool uses AEEI/ Technical progress and their equivalent parameters to represent technological change.
2.2	Learning-by-doing	Assesses if the modelling tool uses the learning-by-doing approach to represent technological change.
2.3	Learning-by-searching	Assesses if the modelling tool uses the learning-by-searching approach to represent technological change.
2.4	Exogenous	Determines whether at least one of the technological change parameters in the modelling tool is exogenous.
3	**Employment**	
3.1	Skilled and unskilled labour	Checks if the modelling tool considers at least two types of labour.
3.2	Labour mobility	Determines if the modelling tool evaluates the labour mobility across regions or countries or sub-regions.
3.3	Involuntary unemployment (Imperfect market)	Determines if the modelling tool accounts for involuntary unemployment or imperfect market.
3.4	Sectoral employment	Checks if the modelling tool assesses the employment per sector even if the tool does so for only one sector (e.g. agriculture).
3.5	Unemployment rate	Checks if the modelling tool assesses the unemployment rate for the whole economy.
4	**Environment**	
4.1	Water-use	Verifies if the modelling tool analyses the water-use throughout the different sectors as well as the household.
4.2	Land-use	Checks if the modelling tool includes land demand per sector and/or accounts for land-use change (e.g. building on cropland).
4.3	Natural resources	Checks if the modelling tool evaluates and accounts for depletion of the natural resources (e.g. fossil fuel reserves).
4.4	Air pollution and health	Evaluates the analyses of GHGs emissions and/or air pollutants and/or the population's health in the modelling tool.
4.5	Material flow/demand/ recycling	Assesses if the modelling tool accounts for material demand per sector and/or includes sectors dedicated for material recycling.

than simply including a detailed environmental module; it may necessitate linking with Earth or atmospheric models. In this category, we try to shed light on materials and natural resources management, which are important global issues for several reasons. First, the Earth's natural resources are finite and their extraction and use can have negative environmental impacts, including air and water pollution, and deforestation [27]. Second, the increasing global demand for materials and natural resources, particularly in rapidly developing economies, has led to resource depletion and price volatility. This has important implications for global political, and economic stability, and social equity [28]. Finally, the management of natural resources requires international cooperation and coordination, as has been highlighted by the United Nations Sustainable Development Goals (SDGs) [29]. The sustainable management of materials, particularly through recycling, can reduce the need for extraction and processing of new resources, minimize pollution and waste, and contribute to the principles of circular economy [30]. However, despite these benefits, sustainable materials management practices tend to be underrepresented in both macroeconomic models and ESMs [31,32], which is a significant issue that we aim to highlight in this paper.

The steps of applying the framework are as follows:

(1) Identifying articles and reports that mention or use the shortlisted tools.
(2) Analysing and assessing each tool against the criteria listed in Table 2 for each article or report.
(3) Marking all the criteria that were met by each specific tool with an 'x', where x equals 1 if the criterion was met and 0 if it was not. For criterion 1.1, we multiplied x by the corresponding number of sectors. To ensure consistency, we normalized the values of criterion 1.1 to be in the range of [0,1] by applying the linear normalization method using Eq. (1). Criterion 1.1 is a beneficial attribute, meaning that the higher the number of sectors, the more favourable the tool. Thus, the tool with the highest number of sectors would receive the value of x = 1 while the remaining tools would be assigned a fraction of x.
(4) Repeating steps 2 and 3 for several articles and reports until it is improbable that any more criteria can be met.

$$\overline{Y}_{ij} = \frac{Y_{ij}}{Y_j^{Max}} \quad \text{Eq. 1}$$

To ensure a comprehensive evaluation of the shortlisted tools, we conducted a total of five MCAs: four individual MCAs, one for each category, referred to as local MCAs, and one MCA to evaluate the four main categories as a whole with relevance to one another, referred to as the global MCA. This allowed us to assess the performance of each tool in each category with greater precision. Moreover, such approach averted any confusion or entanglements that could have arisen from the differences in nature of the criteria within each of the four categories. For instance, criteria 1.1 to 1.5 (criteria relevant to industrial/sectoral representation) were evaluated relative to one another and not with reference to criterion 3.2 (labour mobility).

We utilized the Analytic Hierarchy Process (AHP) [33,34] to conduct the MCA. The AHP has been extensively utilized for weighting in MCAs and has been demonstrated to be competitive when compared to other methods [35–37]. To construct the pairwise comparison matrices, we mapped the criteria against Saaty's scale of relative importance [34]. The next step involved normalizing the pairwise comparison matrices by averaging each respective row to calculate the weights of the criteria. The consistency of the weights was subsequently checked and validated by determining the consistency ratio with relevance to the random index (RI) scale [38]. The steps for determining the consistency ratio were as follows:

(1) We calculated the weighted sum by multiplying the weights assigned to each criterion by their respective relative intensities of importance;
(2) To determine the lambda values, we used Eq. (2), and then calculated the lambda$_{Max}$(λ_{Max}) by averaging the lambdas;
(3) We calculated the consistency index (CI) and consistency ratio (CR) using Equations (3) and (4), respectively. In these equations, "c" denotes the number of criteria, and "RI" denotes the random index, which was determined based on the matrix size through a table that maps the matrix size to random indexes [39].

$$Lambda(\lambda) = \frac{Weighted\ sum_j}{Weight_j} \quad \text{Eq. 2}$$

$$Consistency\ index(CI) = \frac{\lambda_{Max} - c}{c - 1} \quad \text{Eq. 3}$$

$$Consistency\ ratio\ (CR) = \frac{Consistency\ index\ (CI)}{Random\ consistency\ index\ (RI)} \quad \text{Eq. 4}$$

It is important to note that for the weights to be considered consistent, the CR should be less than 0.1 [40]. In case this condition was not met, the pairwise matrices were re-evaluated accordingly. After verifying the consistency of the weights, the MCA results were used to compare the tools and rank them based on a preference score.

3. Results and discussion

3.1. The database

Table 3 presents the identified macroeconomic modelling tools as well as references used to gather the respective information. The complete database is accessible online at the following URL: [https://sites.google.com/view/macromodelingtools/home]. In subsection 3.1.1, we provide a summary of the features and characteristics of the tools with respect to some selected attributes (as shown in Table 1), and also offer a critical analysis of the relevant findings. However, it is important to acknowledge potential source of errors in our database. Given the vast array of tools examined, there is a possibility that some information might have been misinterpreted or not fully understood in its original context. Additionally, these tools are continually evolving, and updates or modifications made after our data collection could lead to discrepancies between our analysis and the current capabilities of the tools.

3.1.1. Insights on key attributes of the database

The database consists of 61 tools, 41 of which are CGE models while the rest are of different types. We present a summary of our analysis for the main attributes as follows:

3.1.1.1. Number of sectors/activities. The number of sectors in tools is depicted by Fig. 2a and b. Analysis of the distribution curve reveals that the majority of the tools has an average number of around 40 sectors. Conversely, the likelihood of tools having less than 5 or more than 100 sectors is comparatively low. It is important to note that a large number of sectors (>100) can increase the complexity of solving the model. Alternatively, having only 5 sectors may not suffice in addressing certain research questions. Nevertheless, the choice ultimately rests with the modelers and the tools at their disposal.

3.1.1.2. Type of analysis. Fig. 2c indicates that recursive dynamic is the most prevalent type of analysis followed by the dynamic type. Each of the other types of analysis is associated with about five modelling tools, with the static type has the fewest number of tools associated with it. This observation underscores the importance of dynamic modelling in providing time-independent insights, which is especially critical for policy makers.

Table 3
The tools contained in the database.

Index	Tool	References
1	ANARRES	[41]
2	CEEEA2.0	[42]
3	CETA	[43,44]
4	DELFI	[45]
5	DEMETRA	[46]
6	DICE	[47–49]
7	Dynamic Applied Regional Trade Model (DART)	[50,51], Personal communication
8	E3ME	[52]
9	ENVISAGE	[53,54], Personal communication
10	ENV-Linkages	[55–57]
11	EPPA	[58,59]
12	EXIOMOD	[60,61]
13	FTAP Model	[62–67]
14	FUND	[68,69]
15	G-Cubed	[70–73], Personal communication
16	GEM-E3	[74,75], Personal communication
17	GEMST	Personal communication
18	GEMINI-E3	[76–79], Personal communication
19	GINFORS-E	[80]. Personal communication
20	GLOBE	[18,81,82]
21	GRACE	[83–85], Personal communication
22	GTAP	[86–90]
23	GTEM	[91,92]
24	HERMES model	[93–97]
25	HMRC's CGE mode	[98,99]
26	I3E	[100,101]
27	ICES (Intertemporal Computable Equilibrium System)	[102,103], Personal communication
28	IEG-CGE	[104–106]
29	INTERLINK	[107,108]
30	LINKAGE	[109,110]
31	MAGNET	[111]
32	MAMS	[112]
33	MANAGE-Mitigation, Adaptation, and New Technologies Applied General Equilibrium model	[113,114]
34	MEDEAS-World MEDEAS-EU MEDEAS-Country level (Austria and Bulgaria)	[115,116]
35	MONASH	[117]
36	MIRAGRODEP-AEZ (MIRAGE (Modelling International Relationships in Applied General Equilibrium))	[118,119]
37	MSG3 model	[120,121]
38	MULTIMOD	[122–124]
39	MyGTAP	[125–127]
40	NEMESIS	[15,128–131], Personal communication
41	NiGEM	[132]
42	ORANI-G	[133–135]
43	PEP-1-t	[136]
44	PEP-w-t	[137]
45	Phoenix	[138]
46	POLES	[139–141]
47	PINGO	[142]
48	QUEST	[143–145]
49	RHOMOLO	[146–148]
50	RICE	[149–151]
51	Second Generation Model (SGM)	[152,153]
52	SNoW-NO	[154–156]
53	STAGE	[157,158], Personal communication
54	The ECLAC - CIAM model	[159,160]
55	TEA	[161]
56	Term	[162–164]
57	ThreeME	[165–167]
58	US Macro Model	[168,169]
59	WEGDYN	[170,171]
60	WITCH	[172]
61	WorldScan	[173,174]

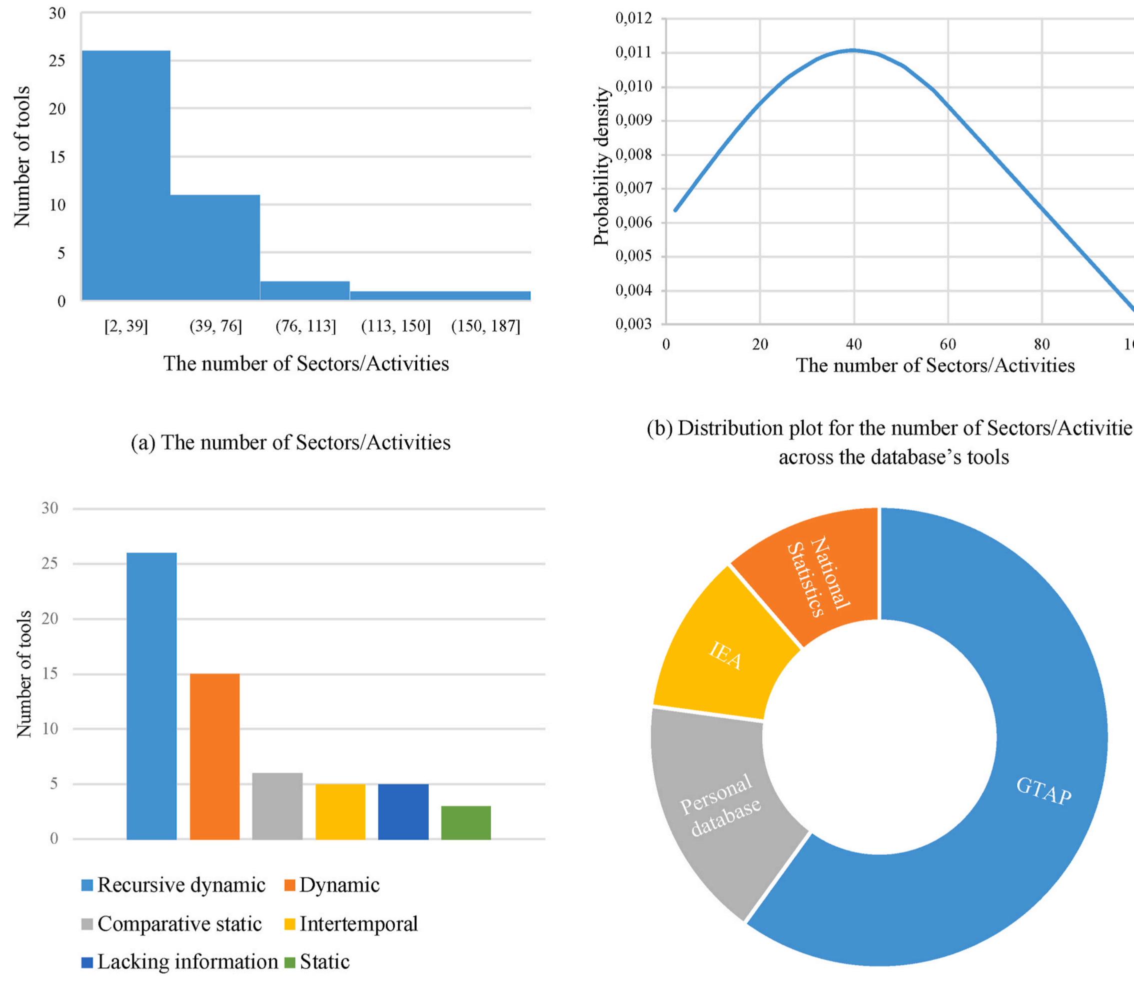
3.1.1.3. Supporting software and data sources. The analysis of the database shows that GAMS is the mostly used supporting software for all the tools. One possible reason behind this is that GAMS enables users to formulate their models in concise mathematical statements. In addition, GAMS provides discounted licenses to academics, and offers a diverse range of solvers that endorse the time efficiency aspect.

Fig. 2d illustrates the most commonly utilized data source by various tools. The Global Trade Analysis Project (GTAP) emerged as the most frequently used data source, surpassing the use of personal databases, the IEA, and national statistics. GTAP's comprehensive coverage of bilateral and multilateral cooperation among more than 140 countries/regions, combined with its high accessibility, frequent updates, and rigorous quality assurance of data, are likely factors contributing to its prominent position [175].

It is also possible that the widespread use of GAMS and GTAP within the CGE community and the fact that most of the tools in the database are CGE models, contribute to their prevalence.

3.1.1.4. Spatial scale and accessibility. Fig. 3 presents an overview of the spatial scale and accessibility of the 61 tools in the database. Among them, 39 tools have a global coverage, 16 tools focus on the national level, and the rest consider the subnational level. The popularity of global models in macroeconomic analysis can be attributed to the growing significance of the global economy in today's world. By simulating the global economy, macroeconomic modellers can capture and analyse the performance and prospects of the world's economies, especially with regards to the economic interactions between countries, and the potential consequences of national economic decisions and policies on other economies. However, the accessibility of the tools varies depending on the model at hand, whether it is global, national or subnational. Most global models can be freely accessed, while 16 models allow free access to the code and require licences for either the supporting software (e.g. GEMPACK) or the database (e.g. GTAP) and sometimes both. Some tools in the three spatial categories are not accessible at all and only consultancy services could be provided on a fee-basis per project. A further type of accessibility that is specific to global models is "Exclusive" accessibility, which means that the tool is solely available to the host institute and its close partners for their own projects without consultancy services being available. In some cases, this lack of accessibility can be due to contractual arrangements related to a specific project, or concerns related to data privacy.

3.1.1.5. Geographical coverage. Fig. 4 shows the number of tools that represent countries individually, rather than as part of a region. The world's largest economies (e.g. the USA) and countries that have bilateral trade with them, are individually represented by many tools, as depicted by the map. Most modelling tools, however, do not include many African, Middle Eastern, and Central Asian countries individually. This is mainly due to their limited impact on the global economy. It is important to note that some countries in these regions, particularly major oil and gas exporters such as Saudi Arabia and the United Arab Emirates, can have a substantial impact on the global economy. Nevertheless, many modelling tools group these countries together as part of the OPEC region because of their collective impact on global oil production and prices. As production relocation becomes more prevalent, there is a growing need for modelling tools to expand their geographical coverage and represent specific countries in greater detail. For example, with the potential for hydrogen production in North African countries [176,177], it becomes essential to include them



(a) The number of Sectors/Activities

(b) Distribution plot for the number of Sectors/Activities across the database's tools

(c) Type of analysis

(d) Most frequently used data sources

Fig. 2. Charts for the macroeconomic modelling tools in the database.

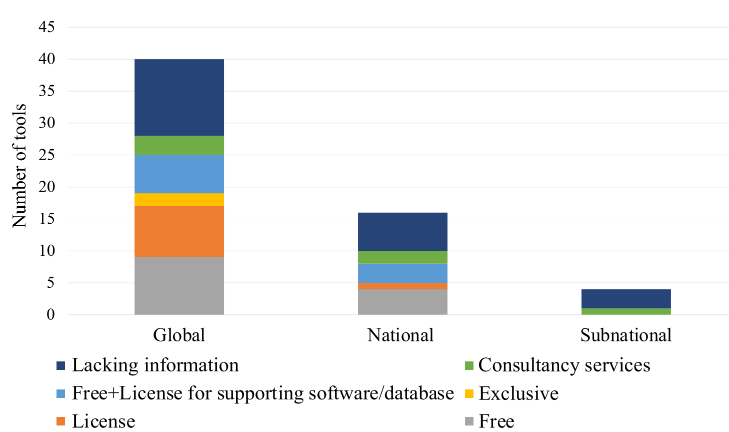


Fig. 3. Spatial scale and accessibility of the tools.

individually in the modelling tools as has been done with some tools such as GTAP [89] and TIAM-ECN [178].

3.1.1.6. Temporal scale. The analysis reveals that the majority of tools are designed to run up to the year 2050 or 2100. The underlying explanation for this can be attributed to the fact that most international climate strategies aim at 2050 as the year by which important emissions reductions and climate goals should be achieved. For the year 2100, it is

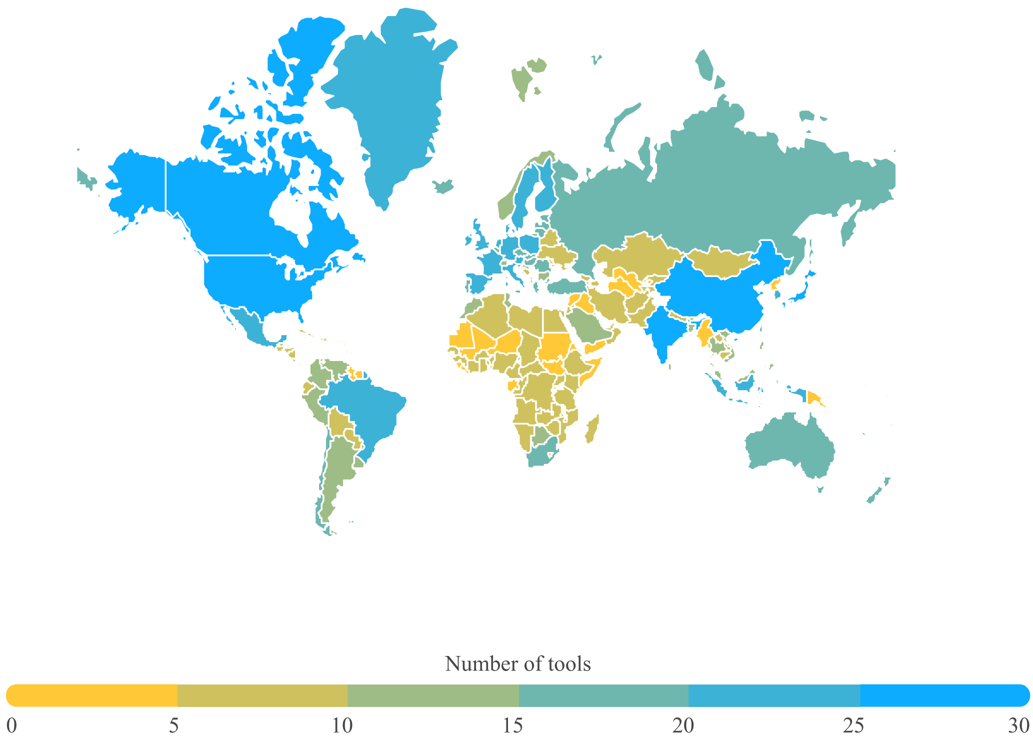


Fig. 4. Geographical disaggregation of the tools.

because climate changes can have long-term and far-reaching effects, with a 100-year timescale being a common benchmark. Thus, designing tools that are capable of projecting outcomes up to these years is a logical and strategic approach for analysing the impacts of climate change.

3.1.1.7. Technological change. Fig. 5 displays some of the most frequently used technological change parameters. An initial evaluation of this chart suggests that each parameter is uniquely different from the other, which is not entirely accurate. For example, apart from their nomenclature, AEEI, technological progress, technological change, and rate of technological change essentially measure the same concept that is the technology change through the rate of efficiency improvement. In the same way, technical progress, technical efficiency, and technical change differ only in terms of nomenclature, and it is not clear how developers of these tools determine the terminology for such similar parameters. In macroeconomic models, technical change and technological change play crucial roles in explaining economic growth and development. While these terms are often used interchangeably, they have different implications for macroeconomic models. Technical change is essentially concerned with the organizational changes in the production function per se such as the enhanced efficiency of the labour

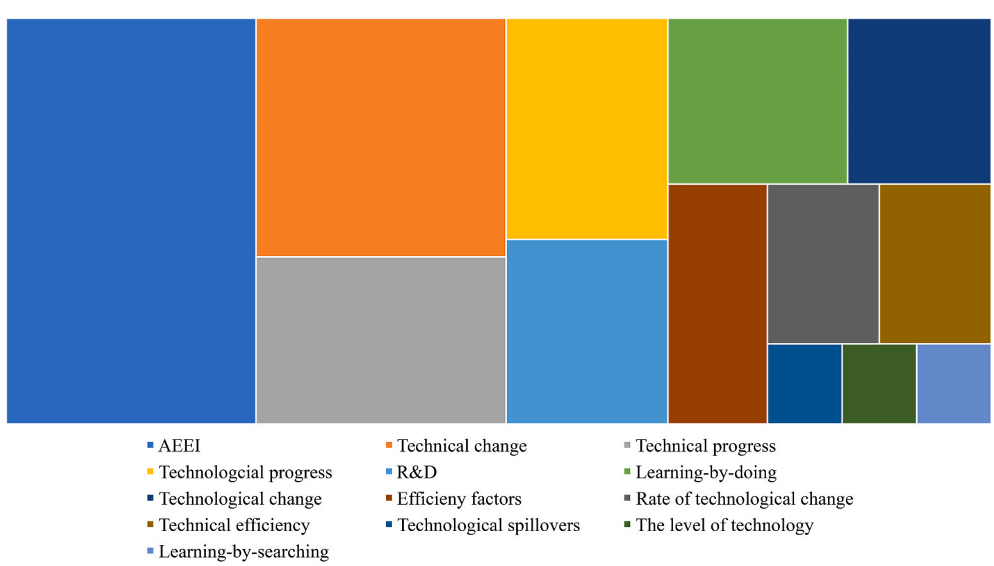


Fig. 5. The most frequently used technological change parameters.

force [179,180]. Thus, a more efficient labour force will result in a greater production output. Meanwhile, technological change manifests itself in various forms that are technologically relevant such as adopting state-of-the-art equipment with high efficiency or enhanced materials, which in turn will also improve the production efficiency [181].

In regard to other parameters, such as learning-by-searching, learning-by-doing and technology spillover, they mostly come as complementary to technological change, and there are slight yet distinctive differences between them. The reduction in costs of technology over time as a result of experience and learning is usually described with the learning curve concept, that correlates the historical increase of manufactured units, or installed capacity, to a fall in cost. Both parameters; learning-by-searching and learning-by-doing are based on the learning curve concept, however, the driver of the cost reduction in both approaches is different. Learning-by-doing is relevant to the reduction of costs due to the repetition of the manufacturing process that leads to a gain of experience and ultimately a more efficient production process. Conversely, the main drivers for cost reduction in the learning-by-searching approach are innovation and knowledge acquisition, which contribute to the improvement of manufacturing processes [182,183]. There is a conceptual similarity between learning-by-searching, R&D, and technology spillover parameters, though the latter specifically refers to knowledge acquired by one firm as a result of R&D conducted by other firms without sharing the costs [184]. For instance, consider a scenario in which Company 'A' conducted research aimed at improving the production efficiency of a specific commodity, and published its results. Company 'B', which had not provided funding for that research, was able to use the same results to enhance its production process. This type of knowledge transfer is known as a technology spillover.

Considering the types of technology change used by the tools, Table 4a demonstrates that exogenous technological change constitutes the majority of the tools at 60%, while endogenous and semi-endogenous technological change account for 22% and 3% of the tools, respectively. On another note, the technological change can be represented by one or more parameters, such as AEEI and learning-by-doing or AEEI only. Table 4b illustrates how many parameters are used to represent technological change in the tools. It compares the number of tools that uses one parameter versus those that use two or three parameters. The number of tools that use only one parameter is 37 while only 4 tools base their technological change on three parameters. This can be due to the positive correlation between the number of parameters and the complexity of the model, where adding more parameters makes the model more complex, and further affect the degree of freedom. Nine tools lacked any information on the technological change dimension, which can be seen on both tables.

3.2. Shortlisted CGE modelling tools

In section 2.1, a set of criteria was established to guide the selection of shortlisted tools. Despite meeting the criteria, some tools could not be shortlisted due to either inadequate documentation or the existence of multiple versions of the same model without proper documentation for the core version. To overcome this information deficit, we attempted to

Table 4
The technological change types and the number of parameters for the tools in the Database.

(a) The types of technological change for the tools		(b) The number of technological change parameters for the tools	
Types of technological change	Number of tools	Number of technological change parameters	Number of tools
Exogenous	37	1 parameter	38
Endogenous	13	2 parameters	10
Semi-endogenous	2	3 parameters	4
Lacking information	9	Lacking information	9

contact these tools' developers; however, this was not always a successful method of obtaining clear information. Additionally, we observed that despite the presence of some tools that have very interesting features, and developed by large organizations (e.g., the World Bank), the webpages of these tools were deserted, and did not contain any updated contact information. This in turn resulted in a very limited pool of tools that we can choose from. The tools that ideally met the criteria and were most suitable for the shortlist are as follows: Economic Projection and Policy Analysis (EPPA), General Equilibrium Model for Economy-Energy-Environment (GEM-E3), GTAP standard model, and Modular Applied General Equilibrium Tool (MAGNET). In following sections, we provide background information on each of these tools, and present the MCA results.

3.2.1. Background of the shortlisted tools

3.2.1.1. EPPA. EPPA is a CGE model developed by the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change. It is a multisectoral recursive dynamic model that can be used to assess the effects of different energy and environmental policies and regulations related to energy production and consumption, land-use, natural resource depletion, and technologies deployment [185]. EPPA also calculates the future GHGs emission and air pollutants, which can be fed to the MIT Earth System Model (MESM) creating the substrates of MIT Integrated Global System Modeling (IGSM). This can in turn can be utilized in carrying out advanced climate scenarios analyses. One of the merits of EPPA, is that fossil fuels can be substituted by clean fuels, such as hydrogen, which allows for studying the various pressing issues concerning the new green fuels [186]. GTAP is the primary database for EPPA, however, with its geographical resolution aggregated into 10 countries and 8 regions (e.g., Africa). While the industrial sectors are merely aggregated in EPPA, the power production sector is quite detailed, providing a robust foundation for representing the application of advanced technologies in this sector [187]. This is one of the reasons why EPPA has been extensively used in assessing technological advancements besides evaluating energy and climate policies. EPPA has also been used widely in land-use studies thanks to its distinctive features in that regard where it categorizes land into five types (e.g. cropland), and allows farmers to convert their land to a more competitive type given that they can afford the corresponding conversion costs [188–190].

3.2.1.2. GEM-E3. GEM-E3 is a global recursive dynamic CGE model that can run up to the year 2100, it is developed by a consortium of institutions with the National Technical University of Athens as the leading institution. One of the prominent features of GEM-E3 is its ability to provide a thorough display of the interlinkages between economy, environment, and energy system [191]. GEM-E3 typically covers 38 regions that include the world's major economies, and it represents 31 sectors with 50 activities, which allows for a profound representation of technologies. In addition to its superiority in technological representation, another interesting attribute of GEM-E3 is its semi-endogenous technological progress that incorporates learning-by-doing and learning-by-searching concepts [192]. This in turn allows for capturing important trends like the effects of R&D investments on technological advancements. Like many other macroeconomic modelling tools, GEM-E3 uses the GTAP database, however, it also uses multiple data sources besides the GTAP, most notably, IEA energy statistics and the International Labour Organization (ILO) database [191,193]. The GEM-E3 model distinguishes between skilled and unskilled labour, and estimates the corresponding unemployment rates for each category. Furthermore, it considers involuntary unemployment, which manifests the market's imperfection [194]. The model has a unique environmental module that covers about six of the major greenhouse gases, and tracks their emission from each sector along with an integrated structure for an emissions trading market [195]. This provides an opportunity to explore a variety of emission reduction and trading policies. Materials are considered as one of the core inputs of the production functions in GEM-E3, which further allows for tracking material flow and consumption [196]. Numerous studies have used GEM-E3 to explore various scenarios concerning the nexus of economy, energy, and environment, such as energy taxes implications, labour force role in economic development, and the effects of emissions reduction policies [197–199].

3.2.1.3. GTAP standard model. While GTAP is well-recognized as a database, there is also a macroeconomic model that holds the exact same name. It is a multi-sector global CGE model that runs in a comparative static mode [200]. The model covers 141 regions, and it comprises 65 sectors (based on GTAP database 10) that can be aggregated or disaggregated in line with the research in question [56]. Although GTAP does not fully meet the criteria to be shortlisted, it has been widely used as a core model for dozens of other CGE models (e.g. MAGNET. FTAP). Furthermore, the GTAP standard model has some unique features that make it stands out, such as the fine industrial/sectoral representation where the model allows for the production of more than one commodity from one sector (e.g. by-products) [86,201]. This kind of flexibility provides the users with means for controlling the resolution of their economic analysis, hence a wider pool of research questions to investigate. There are a number of other GTAP models that are extended from its standard model (e.g. GTAP-AEZ) [59]. These extended models are tailored to look into and establish interconnections among different sectors and systems that are closely linked to the most important issues of our modern world, namely, land-use, agriculture, labour migration, and power sectors [86,202].

3.2.1.4. MAGNET. MAGNET is a global CGE model developed by the MAGNET consortium, which is led by the Wageningen Economic Research in the Netherlands. It is a recursive dynamic model that is calibrated to the GTAP database and runs up to the year 2100, dividing the world into 141 regions. MAGNET is fundamentally based on the GTAP CGE model but with various new features and upgrades that are mostly closely related to environment and land-use [203,204]. The sectoral representation in MAGNET is comprehensive where it covers 114 sectors that can be aggregated and disaggregated at the user's convenience and the same flexibility in aggregation can also be applied for the geographical regions [204,205]. In the same context, all the model's extra features can be switched off/on, which allows users to tailor the model's parameters and features in accordance with their research questions. One of the attractive aspects of MAGNET is the representation of some specific sectors that are uncommon in most CGE models, such as sectors for waste collection as well as recycling of different types of materials [111]. In a similar vein, MAGNET also simulates emissions permits trading, and accounts for land-use and land-use change (LULUC) emissions [111,206]. Therefore, MAGNET can be regarded as one of the leading CGE models currently available for analysing land-use related environmental issues.

3.2.2. Framework and MCA results

Table 5 presents the corresponding results obtained by applying the framework for each tool in the shortlist, with an 'x' mark denoting each fulfilled criterion except for the number of sectors criterion, which was determined using Eq. (1) (as discussed in section 2.2). The table also shows the corresponding weights for each of the criteria, as well as for the four categories. The weights were calculated according to the steps outlined in Section 2.2. The last two columns of Table 5 show the results of the consistency ratios for the criteria's weights, and as can be seen, all ratios are below 0.1, indicating that the respective weights are consistent.

The results of the local MCA are depicted in the radar chart shown in Fig. 6. It can be seen that GTAP has the precedence for the industrial/sectoral representation category, succeeded by MAGNET, GEM-E3 and EPPA, in that order. Although the latter three cover only two out of the five criteria for that category, the different weights and values assigned to each criterion resulted in the scoring discrepancies shown. Among all the tools, GEM-E3 has the highest in the technological change category, as it exclusively covers the learning-by-doing and learning-by-searching criteria that are well-weighted (0,54 and 0,29, resp.) while the other three tools had a balanced score of 0.2 in this category.

In the environment category, MAGNET and GEM-E3 received slightly higher scores above 0.8, followed by EPPA and GTAP with scores of 0.6 and 0.1, respectively. In terms of employment representation, GEM-E3 received the highest score due to its coverage of four out of the five criteria in this category, while MAGNET and GTAP had balanced scores. EPPA did not cover any of the criteria and hence

Table 5
The framework's results and the corresponding AHP weights.

Index	Criteria	EPPA	GEM-E3	MAGNET	GTAP	Weight	Consistency Ratio	
							Criteria	The four-categories
1	Industrial/Sectoral representation					0,466		**0,011**
1.1	Number of sectors/activities	0,35×	0,44×	x	0,57×	0,55	0,094	
1.2	More than one technology per one commodity				x	0,20		
1.3	More than one commodity per sector				x	0,14		
1.4	Flexibility of aggregation and disaggregation of sectors			x	x	0,04		
1.5	Fuel substitution per technology	x	x			0,071		
2	Technological change					0,277		
2.1	AEEI/Technological change	x		x	x	0,12	0,077	
2.2	Learning-by-searching		x			0,29		
2.3	Learning-by-doing		x			0,54		
2.4	Exogenous	x	x	x	x	0,06		
3	Employment					0,096		
3.1	skilled and unskilled labour		x	x	x	0,48	0,061	
3.2	Labour mobility					0,23		
3.3	Involuntary unemployment (Imperfect market)		x			0,16		
3.4	Sectoral employment		x			0,04		
3.5	unemployment rate		x			0,09		
4	Environment					0,161		
4.1	Water-use					0,14	0,075	
4.2	Land-use	x	x	x	x	0,03		
4.3	Natural resources	x	x	x	x	0,08		
4.4	Air pollution and health	x	x	x		0,49		
4.5	Material flow/demand/recycling		x	x		0,26		

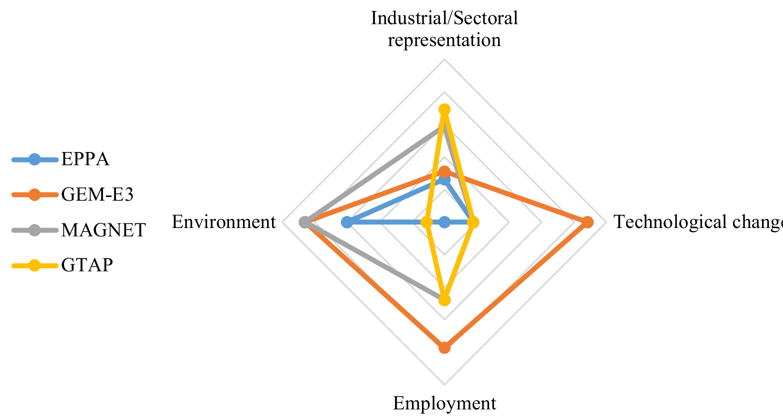


Fig. 6. Local MCA results; illustrating comparative performance across the four pillars.

received a score of zero for this category. Notably, none of the four tools achieved a full score in any of the four categories, indicating areas for improvement. Additionally, two important criteria, labour mobility and water use, were not accounted for by any of the four tools, despite their substantial significance. This is particularly noteworthy because both water scarcity and labour migration are recognized as significant challenges worldwide [207,208].

The results of the global MCA are presented in Table 6, where the normalized decision matrix with the weighted criteria is shown. GEM-E3 ranked first with a score of 0.602 points, followed by MAGNET and GTAP in second and third places, respectively. EPPA obtained the lowest score of 0.27, placing it in the fourth and last position.

Based on the analysis of the local and global MCA results, it can be inferred that GEM-E3 exhibits a strong potential as a modelling tool for analysing industrial transformation. While GEM-E3 did not perform the best in the industrial/sectoral representation category, it excelled in other categories, such as employment representation and environment, which are equally important when analysing industrial transformation (as discussed in section 2.2). Furthermore, upgrading a macroeconomic model to meet the criteria of the industrial/sectoral category may be relatively straightforward. However, incorporating environmental externalities and social aspects into macroeconomic models can be complex and challenging, which has also been emphasized by several studies (e.g. Refs. [156,209,210]). Therefore, we positively value macroeconomic modelling tools that account for multiple environmental and social factors.

4. Conclusion

This paper examines 61 macroeconomic tools on the basis of 13 dimensions. All the findings are publicly available in an online database. We provide a comprehensive presentation of our findings and a critical analysis in order to convey a deeper understanding of the multitude of macroeconomic modelling tools available in the literature.

In analysing the database, the results reveal that:

Table 6
Ranking and preference Scores of the shortlisted tools based on the global MCA results.

Tool	Preference Score	Rank
EPPA	0,268	4th
GEM-E3	0,602	1st
GTAP	0,436	3rd
MAGNET	0,508	2nd

- Many tools are not accessible by third parties. We here stress that accessibility to macroeconomic modelling tools is crucial for researchers in the field of economics and related disciplines, as it enables them to conduct robust and comprehensive analyses of various economic phenomena. In addition, the availability of these models can help to promote transparency in research, as it allows other researchers to replicate and build upon existing studies.
- Inadequate or absent representation of social aspects is present in a number of tools. It is essential to consider social aspects while utilizing macroeconomic models in general, and particularly when analysing industrial transformation. For instance, structural unemployment is a social aspect that can significantly impact industrial transformation. This type of unemployment is often caused by structural changes in the economy, such as technological advancements or shifts in industry demand, and can persist even in periods of economic growth. Incorporating such aspect into macroeconomic models can help policymakers to create a more adaptive and flexible labour market that drives industrial transformation in a way that benefits all members of society.
- Most of the tools have a relatively small number of sectors, averaging around 40, which we believe is inadequate to provide an accurate depiction of the industrial sector. Because the energy system is an integral part of the economy, a comprehensive analysis requires linking ESMs to macroeconomic models. If the ESM has more sectors than the macroeconomic model, then the impacts of policies on the energy system may be overestimated, while the impacts on the economy may be underestimated. Therefore, it is generally considered important to match the number of sectors between the two models as closely as possible, while also ensuring that the sectors are defined in a consistent manner between the two models. However, it is important to recognize that there may be practical limitations in matching the number of sectors exactly, and that some level of aggregation or disaggregation may be necessary depending on the specific research question being addressed.
- There is a paucity of individual geographical coverage for MENA and Central Asian countries. These countries are expected to play a key role in global hydrogen production given their vast renewable energy potential, which can be used to produce green hydrogen. Several projects are currently underway in MENA countries to develop hydrogen infrastructure and production facilities, including pilot projects for green hydrogen production in Morocco and Tunisia, as well as plans for blue hydrogen production in Saudi Arabia, the United Arab Emirates, and Egypt. These initiatives are expected to contribute significantly to the development of the hydrogen economy in the region and beyond. Therefore, we anticipate that most tools will expand their geographical disaggregation to include some

of these countries individually as it is becoming increasingly important to consider their role in the global energy transition.

For a more comprehensive analysis, we shortlist four modelling tools (EPPA, GEM-E3, MAGNET, and GTAP) and conduct an MCA using a comparison framework that has been specifically tailored for this study. Our results indicate that GEM-E3 yields the highest overall score. This does not rule out the other tools. Rather, it portrays the research opportunities manifested in developing and extending their capabilities. It is also important to acknowledge that our analysis was conducted from a particular angle (i.e. industrial transformation), which may have obscured other strengths that these tools might have in other facets. On the other hand, the MCA demonstrates that none of the shortlisted tools had a full score in any of the four categories: industrial/sectoral representation, technological change, employment, and environment. Furthermore, none of the tools met the criteria for labour mobility and water use. As we argue that linking with other models (e.g. hydrological model) can be a solution for the latter issue, the presence of some basic elements in macroeconomic models is crucial for such linking to take place.

Our framework is not impeccable, and it can indeed be improved. For instance, certain criteria are rather general in nature, as exemplified by the labour mobility. Here, we observed that when two tools consider labour mobility as a factor, the depth and manner in which labour dynamics are modelled can significantly vary, which may lead to different implications in the analysis. The different perspectives of economists, engineers, and policymakers can also be compiled as part of further research to identify more criteria. In addition, the framework does not delve into specific economic concepts (e.g. economic theories) as part of the criteria, given its focus on global CGE models where significant overlap exists among the various tools in this regard.

The ambiguity and lack of basic information in the literature about many of the tools constitute a major impediment to this study in terms of forming an integrated analysis. In this regard, we attempted to shed light on the importance of prospective users having a clear understanding of the characteristics, features, and limitations of the tools. Otherwise, they will lack the adequate basis to make an informed decision about which tool to use. We also observe that despite the growing global focus on sustainable and circular practices, macroeconomic modelling tools are failing to fully account for the positive impact these elements can have on economic growth and productivity. This lack of proper representation of circular economy principles could result in policymakers missing opportunities to make well-founded decisions that support sustainable economic development and preserve natural resources for future generations. Future research in this area should aim to improve and expand upon existing macroeconomic models to ensure they are better equipped to address these pressing issues. Developers of tools should also strive to include further features to their tools aiming at filling the criteria identified in this study. Thereby, the tools can be used in carrying out more holistic and inclusive analyses for industrial transformation.

Declaration of competing interest

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

Data availability

I have provided a website for the data in the article

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