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openMASTER: The open source Model for the Analysis of SusTainable Energy Roadmaps

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ABSTRACT

Strategic energy planning models play a crucial role in facilitating well-informed decision-making processes for the energy transition. However, the limited accessibility of most energy models has led to the emergence of open-source alternatives, promoting transparency and inclusivity. In this context, this paper presents openMASTER, an open-source version of the Model for the Analysis of SusTainable Energy Roadmaps (MASTER), which has more than a decade-long history in strategic energy planning. openMASTER makes some significant contributions to the existing field of open-source models, including: (i) being the only reviewed open-source model that incorporates all exogenous demand as energy services, (ii) integrating behavioural changes in an endogenous and linear manner, (iii) modelling non-energy raw material consumption and circular economy in the industrial sector, and (iv) being the first open-source model to introduce the technological vintage of end-use technologies. This paper provides a comprehensive overview of openMASTER's structure, equations, and diverse applications, analyzing its contributions and limitations in comparison with similar open-source models from scientific literature. The model's reasonable computational load supports its utility in strategic energy planning. Furthermore, considerable efforts have been dedicated to ensuring accessibility and modularity, with the design of user-friendly data treatment and visualisation modules. In spite of certain limitations of openMASTER for which future research directions are suggested, we believe that it offers an open and innovative platform to drive informed decision-making for a sustainable energy future.

1. Introduction

The transition to a carbon-neutral energy system represents a complex and urgent challenge that requires both technological and social transformations. To achieve this goal in a short timeframe, decision-makers must understand the behaviour of energy systems and anticipate the consequences of their decisions. Analytical tools such as strategic energy planning models are crucial to enable appropriate decision-making processes.

Although numerous energy models have been developed by academic, business, and institutional entities, the majority of these models are not publicly accessible. To address this issue, open-source energy models are being made available and published in peer-reviewed scientific journals, enabling collaboration and use within the scientific community. Openmod [1] and openENTRANCE [2] are examples of platforms that facilitate and promote the development of open-source models in the field of energy modelling. Particularly, within the Openmod manifesto [1], it is stated that "*in the context of energy modelling, "open" means for us that data and code are published and shared*". This perspective coincides with our shared understanding of open models, where "*using open software licenses [...] is an important element*".

Within this framework, this paper presents openMASTER, the novel open-source version of the Model for the Analysis of SusTainable Energy Roadmaps (MASTER), designed specifically for strategic energy planning. The MASTER model was first developed in 2012 by López-Peña et al. [3] using the GAMS programming language. This model has been continuously updated to address emerging needs and changing demands, described in several scientific works. Now, the open-source version, openMASTER, is implemented in Pyomo, offering improved usability, accessibility, and additional enhancements compared to prior versions of MASTER.

The remainder of this paper is organised as follows. In Section 2, we

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examine the contribution of openMASTER compared to other open-source strategic energy planning models. In Section 3, we provide a detailed description of the model, including its fundamentals and formulation. In Section 4, we illustrate the model's applications and potential uses. Finally, Section 5 contains a discussion about the strengths and limitations of openMASTER as a decision-making tool within the context of the energy transition.

2. Literature review

This section presents an overview of existing open-source strategic energy planning models, and specifically focuses on the unique contributions offered by openMASTER. To be considered open-source for our purposes, a model must have publicly accessible code that can be used without any subscription requirements or additional costs. For instance, we have excluded the TIMES model [4] from our consideration despite its code being accessible, as it operates through a paid environment (VEDA) and a fee-based optimisation software (GAMS).

Moreover, to ensure comparability with openMASTER's capacity to facilitate decision-making processes, our analysis only considers models that incorporate both operation and investment aspects within their scope. Additionally, we have included models that provide a multi-sectoral representation, while excluding models such as Balmorel [5] that do not consider mobility demand.

In this context, we conducted a literature review, using the works of Limpens et al. [6] and Groissböck [7] as our point of departure. These studies examined energy models using several key attributes for comparability, including multi-sector representation (including, at least, electricity, heat, and mobility sectors), open-source character, optimisation of operation and/or investment, temporal resolution, and computational characteristics and time.

Our first evaluation focused on extending the temporal scope of the original literature review, initially performed in 2019, to account for potential changes in model characteristics or the emergence of new models comparable to openMASTER. Our assessment did not reveal any significant changes that would alter the findings of this literature review. Therefore, based on the aforementioned criteria, we have considered three models as potentially comparable to openMASTER: EnergyScope, Oemof and OSEMOSyS.

But besides enlarging the temporal scope of the review, we also expanded its methodological scope considered by Limpens et al. [6] and Groissböck [7], looking in particular at 12 questions regarding these four models (including openMASTER) and extensively reviewed the available documentation to address them. This comprehensive comparison allows us to discern modelling gaps and highlight the contributions of openMASTER within the family of open-source strategic energy planning models.

Notably, this review doesn't account for the potential capability of these models to incorporate these features by introducing the corresponding modifications in the model structure and equations. Undoubtedly, open-source models offer the advantage of facilitating such changes more readily. However, this review considers whether there is existing literature evidence supporting the implementation of these advancements in the models under consideration. Significantly, the advantage of openMASTER is that these changes and features are already included in the code available. Being open-source, the elements in openMASTER modelling these features can be easily transferred to other platforms or models, contributing to the open model family and its collaborative spirit.

The following are the 12 issues upon which these models are analyzed:

(i) Does the model have the ability to perform dynamic planning and solve the investment roadmap over the entire considered timeframe, rather than exclusively focusing on a goal year? The significance of integrating the dynamic character into an energy planning model stems from the fact that decision-making concerning the investment and operation of energy technologies occurs across the entire temporal period. Dynamic models allow planners to account for changes and understand the effects of decisions over time [8].

(ii) Can the model effectively handle uncertainties? Does it utilise (a) probabilistic or (b) non-probabilistic methods? Strategic energy planning involves deciding on necessary energy investments to meet societal demands, considering factors such as timing and required policies. The extended lifespan of energy technologies (typically 20–50 years) introduces parametric uncertainties, including climate change, technological advances, and geopolitical stability [9]. Managing uncertainties in strategic energy models is crucial but challenging in terms of both model formulation and computational burden [10]. Prior successful applications of uncertainty methodologies in similar models offer a valuable comparative advantage [11]. Additionally, distinguishing between probabilistic and non-probabilistic methods is vital, impacting both conceptual considerations and computational aspects, making this differentiation critically important [10].

(iii) Does the model define exogenous demand in terms of energy services? Instead of defining energy demand as final energy consumption, there is a better alternative in considering the demand for specific services, such as the usage of appliances (e.g., washing machines or refrigerators), lighting or mobility, among others. This enables to model technological competition, innovation and efficiency improvements in the adoption of end-use technologies, which notably affects energy consumption [12].

(iv) Does the model have the capability to represent technological and modal choice? In the context of exogenous demand being defined as energy services, technological choice refers to the model's ability to make optimal decisions regarding the investment and operation of end-use technologies (e.g., gasoline cars vs electric cars for providing mobility). Modal choice refers to the ability to make decisions concerning the distribution of mobility modal shares (e.g., cars, motorcycles, buses, bicycles, or metro), instead of rigidly specifying predetermined quantities for them. Illustrating the complexity of modal choice, in the context of urban transport, when an optimisation model aims to minimise costs and determine mobility modes, it naturally leans toward pedestrian or cyclist-based solutions due to their lower costs and lack of emissions. Additionally, modal choices depend on various factors, including the availability of different transportation modes (e.g., subways, trams, or none for metropolitan distances) and the variations in modes based on the type of mobility (e.g., interurban distances allowing plane or high-speed train travel but not all routes, with no option for walking or tram). Incorporating these complexities requires defining structural aspects of the model to ensure realistic decision-making *(see e.g.* Ref. [13]).

(v) Does the model incorporate an endogenous representation of agent behaviour, enabling modifications or reductions in energy consumption through behavioural changes (e.g., energy-efficient housing, car-sharing or remote work)? Considering changes in behaviour in an endogenous and linear manner poses a challenge in strategic energy planning models [14].

(vi) Does the model include non-energy commodities, such as raw materials for the industrial sector? As emphasised by Fais et al. [15], "*although energy systems models focus on energy flows, it is evident that materials are an important part of the system, especially in the industry sector*". Some models, like TIMES, integrate this feature. However, it is an aspect frequently overlooked in open-source models.

(vii) Is the model capable of capturing circularities, such as the incorporation of recycled materials? The circular economy involves optimising resource use across the production chain to achieve a closed loop in product life cycles, promoting self-

Table 1
Open-source models comparison. Criteria are satisfied (✓), partially satisfied (–), no data were found (blank) or unsatisfied (×).

	EnergyScope [6]	Oemof [22,23]	OSeMOSYS [24–27]	openMASTER
(i) Dynamic planning	×	-[a]	✓	✓
(ii.a) Probabilistic uncertainty	×	×	✓[b]	×
(ii.b) Non-probabilistic uncertainty	✓[c]	×	×	✓[c]
(iii) Energy services demand	-[d]	-[d]	-[d]	✓
(iv) Technological and modal choice	×[e]	×	-[f]	✓
(v) Endogenous agent behaviour	×	×	×[g]	✓
(vi) Non-energy commodities	×	✓	✓	✓
(vii) Circular economy	×	×	×	✓
(viii) Technology hibernation	×	×	×	✓
(ix) Technology vintages	×	×	×	✓
(x) Technology decommission	×	-[a]	✓	✓
(xi.a) Power system reliability	×	✓	✓	✓
(xi.b) Storage and load shifting	✓	✓	✓	✓
(xii) Carbon budget	×	×	✓	✓

[a] A feature for periodic investment decisions in oemof.solph is work in progress, although it is not part of any stable release. It includes a lifetime tracking.
[b] OSeMOSYS-PuLP incorporates a stochastic version [28].
[c] These models incorporate a robust version that addresses uncertainties [10].
[d] Integrate the demand for final energy (e.g., electricity and heat) with the demand for energy services (e.g., mobility).
[e] It allows for decision in allocating passenger transport between public and private transportation, as well as freight transport by train. The model operates within predetermined ranges, excluding modal shift within private and public transportation.
[f] In Ref. [29], they introduce a novel approach for origin-destination optimisation in urban mobility, considering modal choice. Notably, this approach has not been applied to a national-scale system nor for mobility demand over other distances (metropolitan, inter-city, etc.), and there are no other existing applications that incorporate modal choice.
[g] In Ref. [30], they propose coupling OSeMOSYS with a top-down approach (i.e., discrete choice model), resulting in an exogenous behavioural modelling from the energy planning modelling perspective. In Ref. [31], they analyse this possibility, pointing out the difficulty of doing so because of the appearance of non-linearities and the need of further research.

regeneration by transforming waste into resources. This continual increase in recycling and reuse reduces the demand for raw materials, effectively containing waste [16]. However, incorporating these circular flows into strategic energy planning entails complexity [17].

(viii) Does the model have the capability to activate and hibernate installed capacity of energy conversion technologies? For a more realistic modelling approach, the installed capacity of a technology can be put into hibernation (saving O&M costs but rendering it unusable) and then reactivated (bringing back O&M costs and making it available for use) with a reactivation cost. Considering this capability is highly relevant for policy design, as supported by literature and real-world events. For example, the European Commission's report [18] on reactivating lignite-fired power plants in Germany highlights its significance for energy security, electricity cost, and emissions.

(ix) Does the model consider the vintages of demand technologies? This allows for the consideration of changes in technology characteristics based on their manufacturing year (e.g., cars have different efficiencies or emissions based on their age) [12].

(x) Does the model consider the decommissioning of technologies? As highlighted by Invernizzi et al. [19], "*decommissioning of existing and future energy infrastructures is constrained by a plethora of technical, economic, social and environmental challenges that must be understood and addressed if such infrastructures are to make a net-positive contribution over their whole life*".

(xi) Does the model incorporate a realistic representation of the power generation sector? Does it possess an adequate temporal resolution to effectively incorporate these factors? This may include (a) the integration of reserve and adequacy constraints and (b) energy storage technologies and/or load shifting options. These aspects are crucial for realistically modelling the operation and installation of capacity [20].

(xii) Is it possible to account for and impose carbon budget constraints? Specifically, is it possible to establish a cumulative limit on carbon emissions for a specified multi-year period? Considering the growing importance of the remaining carbon budget in national policy discussions, its incorporation into strategic energy planning models is imperative [21].

The extent to which the different models examined respond to these inquiries is shown in the following Table 1.

2.1. Limitations of openMASTER

Although openMASTER offers several contributions compared to other similar models, as shown in section 2.2., this section first introduces its limitations and current problems that warrants consideration. On the one hand, a notable limitation lies in its absence of spatial modelling for electricity and gas grids, as well as other critical infrastructures within the energy system. This deficiency hampers the model's ability to effectively represent regional or global energy systems with interconnected networks. To address this limitation, future iterations of openMASTER could explore integrating spatial modelling capabilities, akin to approaches seen in existing models such as TIMES [4] or GENeSYS [32]. However, implementing spatial modelling would come at the expense of increased computational complexity due to the addition of variables required to represent regional interactions and energy flows.

Moreover, openMASTER's bottom-up approach, coupled with its detailed technological specifications and temporal resolution, results in a significant number of equations and variables. This intricate structure necessitates a delicate balance between model detail and computational complexity. While openMASTER has been successfully applied to real-world case studies, such as the Spanish national energy system [33], extending its scope to encompass more complex applications may pose challenges. Such expansions may require adjustments to temporal resolution and could potentially strain computational resources. Therefore, future enhancements to openMASTER could focus on optimising its computational efficiency while maintaining model fidelity.

Another area of limitation for openMASTER pertains to its lack of exploration into continent-wide or global applications. While structurally adaptable for such endeavors, openMASTER has yet to undergo comprehensive testing and validation on this scale. Additionally, scaling up openMASTER's application may necessitate compromises to manage computational demands effectively. Therefore, further research is warranted to explore the feasibility and performance of openMASTER in broader geographic contexts.

Overall, while openMASTER demonstrates significant promise in strategic energy planning, its limitations underscore the need for

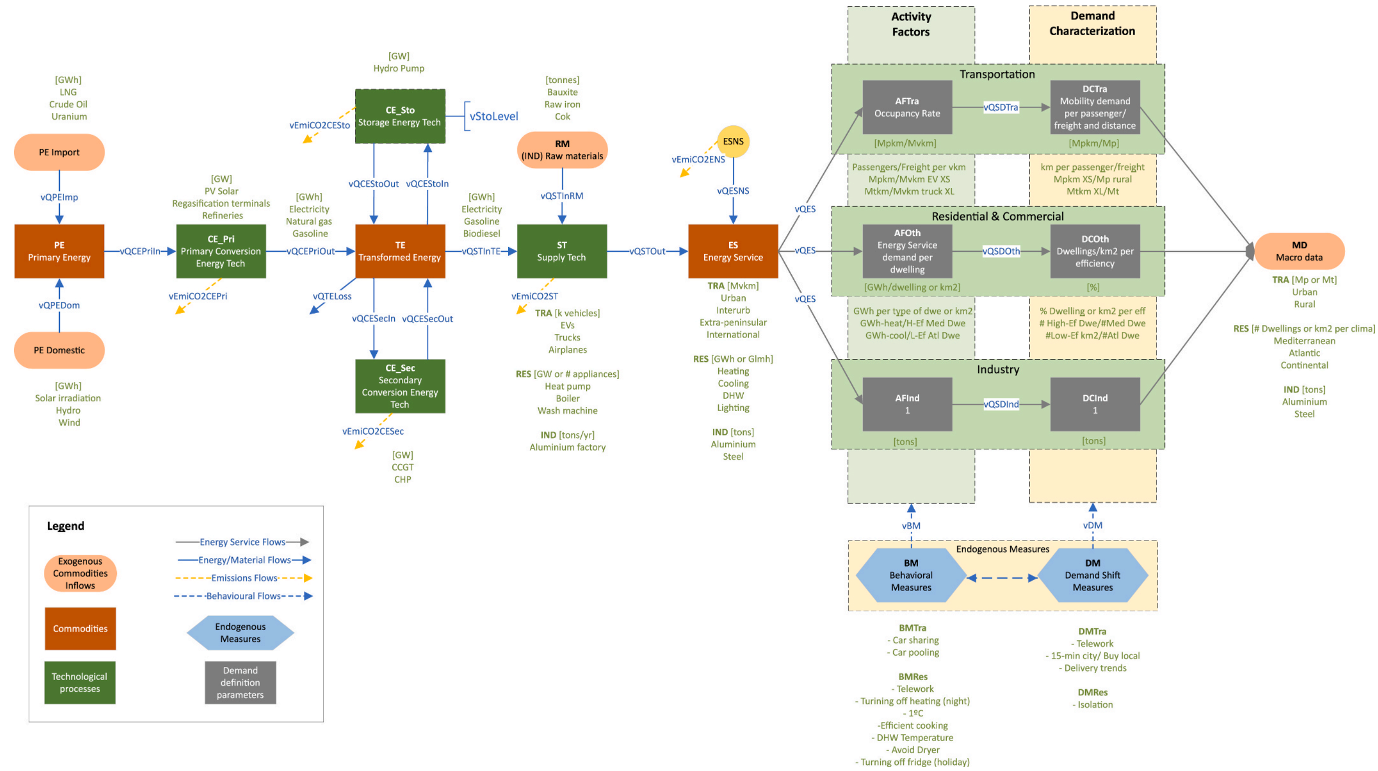

Fig. 1. openMASTER core structure. To facilitate understanding, units and some examples of various processes, commodities, and flows are shown in green.

ongoing refinement and development to maximize its utility and applicability in addressing complex energy challenges.

2.2. The contribution of openMASTER

As may be seen in Table 1, the openMASTER model addresses significant gaps identified in the existing models.

Firstly, openMASTER is the only reviewed model that introduces all exogenous demand in the form of energy services (see Table 1, criterion iii). By energy service we refer to those activities that require energy, but which are not expressed in energy terms, but in activity terms (e.g. m2 to be heated, p.km to be travelled, tons of steel to be produced, etc.). When demand is introduced in this fashion, additional structure needs to be incorporated into the model to represent how energy is converted into energy services (which will require investment and operation expenses, and result in different emissions or energy consumption) and more importantly, how these energy services can be provided by competing technologies, how this competition may evolve with time, and also how its demand may be affected by changes in behaviour or technology, allowing for the implementation of energy efficiency or behavioral measures and emissions reduction through the investment and operation of end-use technologies. In this regard, it also enables modal shifts in transportation, a crucial aspect for effective decarbonization of this sector. It is important to emphasize that defining all exogenous demand as energy services has significant structural implications (see Table 1, criterion iv). This approach necessitates the model to make decisions not only on Conversion Energy (CE) technologies, but also on end-use Supply Technologies (ST). It means adding significant complexity in terms of computation, but also defining the processes (which differs in the case of CE technologies and ST technologies, as will be explained in the following) and input data (techno-economic characterisation of technologies, etc).

Secondly, our thorough literature review indicates that our proposal is the first to introduce behavioural changes in an endogenous and linear manner within an open-source energy planning model (see Table 1, criterion v). This novel approach allows the model to determine *optimal* agent behaviour considering intangible costs such as discomfort, as well as to assess trade-offs, as occurs in the case of remote work, where mobility demand is reduced at the cost of an increase in residential energy consumption. Unlike other proposals such as SOCIO-MARKAL [14], our approach does not rely on *virtual technologies*, but directly allows to modify the energy services demand through a linear formulation applied in a novel way in this type of strategic energy models.

Additionally, openMASTER allows for the modelling of non-energy raw material consumption and circular economy in the industrial sector (see Table 1, criterion vii). It should be noted that this is possible because the industrial sector is also represented, like all other sectors, on the basis of the demand for energy services (in this case, tons of materials). OpenMASTER not only designs the data input, but also incorporates the formulation defining these technological processes and their relationships, including circular material flows, material requirements and recycling rates. Therefore, this not only facilitates modelling the reduction in material consumption through recycling but also energy and emissions savings through less energy-intensive processes.

Moreover, our literature review reveals that openMASTER is the first open-source model to incorporate such technological granularity by considering the vintage of end-use technologies (see Table 1, criterion ix). This approach facilitates the representation of technological innovation, including learning curves for efficiency improvements and emissions reductions. Consequently, improvements in vehicle emission standards or household appliances efficiency, among others, can be incorporated along with a detailed definition of technology decommissioning over their lifecycle.

Lastly, openMASTER offers a more realistic approach to the dynamics of investing in energy conversion technologies compared to existing literature. Its dynamic, multi-step character, which encompasses investments and decommissions, is advanced compared to most strategic energy planning models but still simplifies the real-world decision-making process for energy technologies. Managing energy assets can involve deactivating/hibernating technologies and reactivating them as needed, incurring reactivation costs but achieving substantial O&M savings. Thus, this attribute, overlooked in open-source strategic energy planning models, represents a substantial gap addressed by openMASTER (see Table 1, criterion viii).

All these modelling elements have been shown to convey significant advantages to energy planning exercises, as shown by the previous literature summarized in Table 1 [6,10,22–31].

3. Model description

3.1. Overview

openMASTER is a Pyomo-based model designed for sustainable energy policy analysis. It operates as a dynamic, bottom-up, partial equilibrium, linear programming (LP) model, with the primary objective of meeting an exogenously-determined demand of energy services across various sectors. It achieves this by adhering to technical and policy constraints while minimising a comprehensive objective function. This function includes the total economic costs of energy supply, the social costs associated with greenhouse gas emissions and pollutant releases, as well as to intangible costs such as discomfort.

The openMASTER model is structured according to a scheme of processes and flows, which is detailed in Section 1 of the Supplementary Material. Fig. 1 provides an overview of the structure of the model, which comprises the entire energy sector, including the import and domestic consumption of primary energy, energy conversion and storage technologies for final energy production, energy services supply technologies, and the exogenous demand for energy services from various sectors of the economy. Additionally, to aid comprehension, green text has been added as illustrative examples of elements that could constitute each part of this structure.

Regarding the definition of the exogenous energy services demand, it is important to note, as shown in Fig. 1, that a top-down approach is followed. The exogenous demand is derived from Macro Data (MD), such as population (passengers) in different environments (e.g., rural or urban), weight of freight to be transported, dwellings and commercial area categorised by climate zone, and demand for materials. Based on these values, representative parameters called Demand Characterization (DC) and Activity Factor (AF) are applied for each sector to define the final demand for energy services.

For the residential and commercial sectors, the DC parameter represents the quotas of dwellings and commercial area classified by efficiency, while the AF parameter indicates the typical energy services demanded per dwelling and commercial space. In the case of transportation, the DC parameter captures the typical mobility demand based on distance for freight and passengers according to their residential environment. The AF parameter corresponds to the passenger vehicle occupancy rate (passengers per vehicle) and the freight vehicle load factor (tons per vehicle).

This structure has two main goals. Firstly, it aims to provide a transparent and reproducible data framework for application in different countries and contexts. Secondly, it allows for the endogenous inclusion of behavioural changes. Further details about the definition of the exogenous energy services demand can be found in Section 2 of the Supplementary Material.

Finally, it is important to note that Section 1 of the Supplementary Material also provides comprehensive information on the configuration of the openMASTER model, including the input, output, and *visualiser* modules. These modules serve to streamline and standardise tasks related to input data preparation and result extraction, including the representation of decision variables in intuitive formats. Designed with a user-friendly approach, these modules ensure that individuals with varying levels of technical expertise in optimisation can easily utilise the model. Alongside the model code, users have access to these modules, which play a vital role in guaranteeing interoperability, accessibility, and adaptability.

3.2. Main equations

This section describes the main equations that form the basis of the model, providing the reader with an understanding of its fundamental principles. A current stable version of openMASTER can be found in an open repository on GitHub [34]. The detailed mathematical formulation can be found in Section 4 of the Supplementary Material.

3.2.1. Objective function

The model aims to minimise the objective function, which represents the costs of the energy sector. These costs include (i) the domestic consumption and import of primary energy (PE); (ii) fixed and variable O&M costs of conversion technologies (CE); (iii) the cost of raw materials (RM) consumed by industrial supply technologies (ST); (iv) fixed and variable O&M costs of supply technologies (ST); (v) the investment cost of new conversion technology capacity (CE); (vi) the cost of reactivating hibernated capacity of conversion technologies (CE); (vii) the investment cost of new supply technology capacity (ST); (viii) the penalty cost of slack variables, which include unsupplied energy services (ESNS), as well as exceeding emission caps and carbon budget constraints; and (ix) the cost of agents' behavioural measures, including both economic costs (such as housing insulation) and intangible costs (such as discomfort).

3.2.2. Balance equations

The balance equations are employed to guarantee the conservation of energy (and material within the industrial sector) across all the processes involved. Consequently, the energy transformations taking place in the CE, ST and TE processes are subject to ensuring that the energy output corresponds to the input, accounting for efficiency losses. These balances must be met in all the time slices defined by the model.

An important consideration is the treatment of technologies capable of producing multiple outputs, such as refineries in CE technologies or vehicles in ST technologies. To provide a realistic modelling approach for these processes, minimum and maximum quotas are defined for each technology to determine the range of outputs they can produce. From this perspective, the model can simulate the behaviour of these processes in a more accurate and reliable manner. For instance, a refinery may vary its production of diesel, gasoline, or kerosene from crude oil within specified operational boundaries. Similarly, a vehicle can provide different energy services (e.g., metropolitan and inter-city mobility demands) within realistic ranges. These constraints enable the model to optimise the operation of these technologies while ensuring that the generated outputs align with practical considerations and limitations.

3.2.3. Storage equations

In the particular case of storage technologies, which store and release energy, the energy balance is not conducted on a per-time-slice basis. Rather, it is modelled daily, seasonally or annually. Furthermore, in order to ensure proper performance, storage technologies must adhere to a capacity restriction that limits their physical ability to store a specific amount of energy. This restriction must be considered when conducting the energy balance.

3.2.4. Capacity constraints

Capacity constraints are imposed to ensure that sufficient capacity is installed to enable operational functionality. Consequently, Conversion Energy technologies (CE) and Supply Technologies (ST) cannot exceed their respective installed capacity when conducting energy transformation processes.

The dynamic approach of openMASTER enables investment decisions to be made over the entire time horizon under consideration. This is achieved by considering the existing installed capacity and the decommissioning of technologies at the end of their operational lifespan on an annual basis. It is important to highlight that openMASTER incorporates the pre-existing installed capacity in the initial year of calibration, referred to as *brownfield*.

However, openMASTER treats the capacity installation of CE and ST technologies differently:

- **Conversion Energy (CE) technologies** are decommissioned at the end of their lifespan. Additionally, there is the possibility of decommissioning earlier if the model determines that the technology will no longer be required. Moreover, CE technologies can be hibernated and reactivated, which means that if a technology is not in use, it can be hibernated to save O&M costs. However, it cannot be utilised during this hibernation period. If the technology needs to be operational again, it can be reactivated.
- **Supply Technologies (ST)** are modelled considering their vintage. This means that their technical characteristics, such as efficiency and emission factors, are subject to the year of manufacture. For instance, a diesel car manufactured before 2009, following European emission standards, should meet Euro 4 standards, while in later years, the standard to be met would be higher, such as Euro 5. In addition, modelling these technologies based on vintages allows for probabilistic decommissioning. In this manner, the entire vehicle fleet is not decommissioned at the end of its lifespan, but rather decommissioned over the considered period based on the probability of decommissioning.

Furthermore, maximum capacity constraints can be imposed to align the model's decisions with technical and policy considerations. For instance, the installation of new hydropower capacity may be restricted by the country's topography and water availability, whereas the introduction of new nuclear or coal capacity might be constrained by policy decisions.

On the other hand, a capacity constraint exists regarding the domestic consumption and import of primary energy. In this context, the energy resources available to the represented country or region are modelled, taking into account factors such as the absence of specific resources (e.g., Spain lacking oil resources) and the capacity for imports (e.g., the presence of gas pipelines or regasification plants for natural gas importation).

Finally, the availability of renewable energy resources is determined by CE technologies' availability factor. This factor enables the definition of operating profiles for these technologies across all time slices. For instance, solar photovoltaic plants operate according to solar irradiation availability. Additionally, the availability factor allows for considering levels below 100 % for technologies not reliant on variable renewable sources, accommodating scheduled maintenance outages, among other factors.

3.2.5. Electricity generation reliability constraints

In the operation of large power systems, meeting certain reliability conditions at every time slice is essential to ensure smooth and secure functioning. For this reason, reserve and adequacy constraints on the electricity generation capacity are imposed.

The **reserve constraint** recognises that there is always uncertainty in the load that generators need to supply, such as imprecise demand forecasting, power plant failures, and the variability of power generation from renewable sources. Therefore, this constraint imposes that certain power plants must be capable of rapidly increasing their output in the event of a sudden imbalance.

The **adequacy constraint** ensures enough capacity to meet peak demand and maintain a reserve margin in power systems. The firmness concept quantifies the reliable capacity of technology. It stipulates that the firm capacity must exceed the peak demand multiplied by the required reserve margin (e.g., 10 % excess capacity).

As previously stated, openMASTER presents a unique approach to defining exogenous demand in terms of energy services, where final energy consumption is a decision variable representing end-use technology consumption. This approach is particularly relevant for electricity generation reliability constraints as it requires treating the annual peak electricity demand as a decision variable instead of an input parameter. Although this introduces potential non-linearity, openMASTER addresses it by developing an auxiliary equation and using an additional variable.

By incorporating the annual peak electricity demand as a decision variable, openMASTER can provide a coherent and realistic reserve margin based on optimisation results, effectively capturing the intricate dynamics of electricity demand and supply. This feature enhances the accuracy and realism of strategic energy planning by accommodating evolving consumer preferences and industry trends, such as the growing adoption of electric vehicles and household electrification.

3.2.6. Technological and modal choice constraints

By integrating all exogenous demand as energy services in the model, informed decisions on supply technology investment and operation can be made, leading to technological competitiveness that allows to improve energy efficiency and emissions reduction.

In the particular context of the transport sector, supply technologies correspond to vehicles that supply passenger and freight mobility demands based on distance. Various options, such as electric cars, diesel cars, buses, metro, or bicycles, can be employed to meet the demand for metropolitan mobility. However, optimising the model to minimise costs would naturally favour lower marginal cost modes like walking or cycling, potentially overshadowing other modes. To address this, constraints are introduced to regulate the rate of modal shift, controlling changes in how mobility demand is met across different modes (e.g., car, bus, motorbike, bicycle, metro). Taking advantage of the dynamic approach of openMASTER, the model allows for annual limitations on the rate of change (e.g., a maximum of 2 % annual change), preventing drastic shifts. It is important to note that within each mode, there may still be technological competition. For instance, if the electric car proves more competitive, it may replace traditional gasoline or diesel cars. Moreover, these constraints account for changes in mobility demand from year to year, ensuring that the imposed quota is not solely based on the previous year's demand, but adjusted for overall mobility growth or decline.

3.2.7. Endogenous behavioural measures equations

The openMASTER model introduces a formulation that incorporates behavioural changes of agents in a linear and endogenous manner. This is achieved by including additional variables and equations, as detailed in Section 3 of the Supplementary Material.

This comprehensive approach allows decision-makers to gain valuable insights into the impacts of specific measures across the energy value chain. The model considers four groups of behavioural measures:

- **Passenger vehicle occupancy rate (passengers per vehicle) and Freight vehicle load factor (tons per vehicle)**, allowing to include phenomena such as car-sharing or car-pooling.
- **Typical mobility demand by distance and passenger type,** which could accommodate trends such as remote working, 15-min cities, or changing delivery patterns.
- **Typical demand for energy services by household type and commercial area,** considering behaviours such as adjusting thermostat temperature, using cold water cycles for laundry, or increased remote work.
- **Proportion of dwellings according to efficiency level**, primarily representing improvements in building thermal insulation.

It should be noted that the scope of these behavioural change measures can be limited. However, by considering the interactions between different measures, the model enables optimal implementation strategies for behavioural changes. For instance, it allows for trade-off

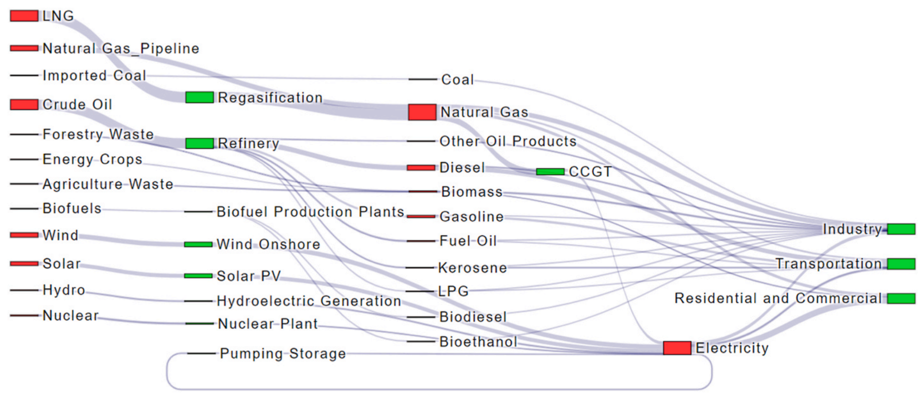

Fig. 2. openMASTER results' visualizer: Energy Sankey diagram for 2030.

analysis of measures like remote work, which reduces mobility demand but increases energy services demand at home. The model facilitates determining the optimal level of remote work, considering investment and operational requirements in transportation and households, as well as the consumption of energy carriers and associated emissions throughout the energy supply chain.

These behavioural changes significantly impact the objective function, introducing both tangible (e.g., investment in housing insulation) and intangible costs (e.g., discomfort from reducing space heating temperature). Future advancements could incorporate income-based modelling to represent intangible costs experienced by different social groups in terms of passenger and household behaviours.

3.2.8. *Emissions accounting equations*

The openMASTER model considers emissions of CO2, as well as pollutants such as NOx, SOx, and PM. By employing a bottom-up approach, openMASTER enables the calculation of emissions in the energy sector's processes with a high level of technological detail. This includes energy conversion (CE), energy transportation (TE), and final use in supply technologies (ST), ensuring a comprehensive and specific analysis of emissions. In the case of energy transportation (TE), special attention is given to emissions associated with methane leakages, which can be accounted for as equivalent CO2.

Emissions are quantified by applying emission factors to the involved processes. Both conversion energy (CE) and supply technologies (ST) consider the fuel consumed when determining emission factors. For example, a hybrid plug-in gasoline car that can utilise either electricity or gasoline will have different emissions associated with the consumption of each fuel. Similarly, a combined cycle power plant may blend natural gas and biomethane.

Moreover, supply technologies (ST) not only consider emissions related to energy consumption but also take into account process emissions. These process emissions result from the use of these technologies regardless of the fuel source. Examples include emissions from tire wear in cars or chemical reactions in cement production. Consequently, the process emission factor of ST technologies depends on the energy service (ES) generated, meaning that emissions are calculated per vehicle-kilometre or tonne of cement. This allows for distinguishing between emissions generated by the same technology in different uses, such as a car emitting more when driving at higher speeds, resulting in higher emissions factors for inter-city distances than metropolitan ones.

3.2.9. *Emission caps and carbon budget constraints*

After accounting for emissions, it becomes feasible to establish global and sector-specific limits on emissions, including CO2, NOx, SOx, and PM. In this regard, the dynamic approach of openMASTER enables the implementation of annual caps on key sectors, including transportation, industry, residential and commercial activities, power generation, and refining. Moreover, additional constraints can be readily established, such as pollution restrictions from the transportation sector could be implemented within urban areas to enhance air quality.

Moreover, this dynamic approach facilitates the effective implementation of a carbon budget constraint, which involves tracking the cumulative CO2 emissions over a specific timeframe.

4. Applications

The MASTER model, known as such prior to the creation of openMASTER, has been utilised for over a decade to conduct several research projects across different fields of study. On one hand, the MASTER model has contributed to the publication of scientific papers in high-impact journals. These papers explore a range of topics, including a comparative analysis of energy efficiency measures versus renewable energy implementation [3], the integration of water considerations into long-term energy planning models [35], the effects of water constraints on power generation in the face of climate change scenarios [36], the

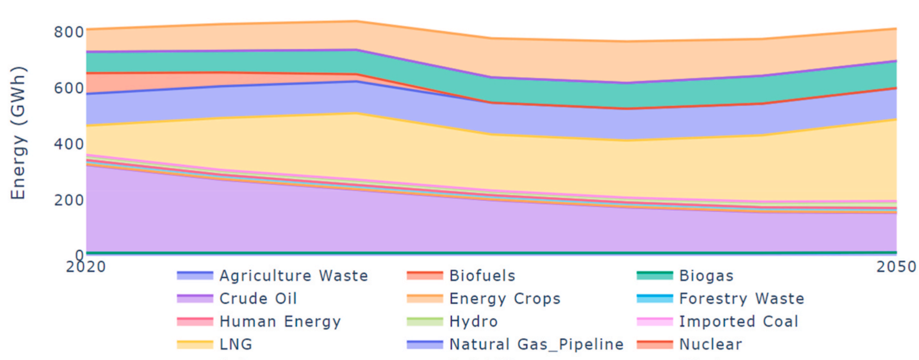

Fig. 3. openMASTER results' visualizer: Evolution of primary energy consumption (2020–2050).

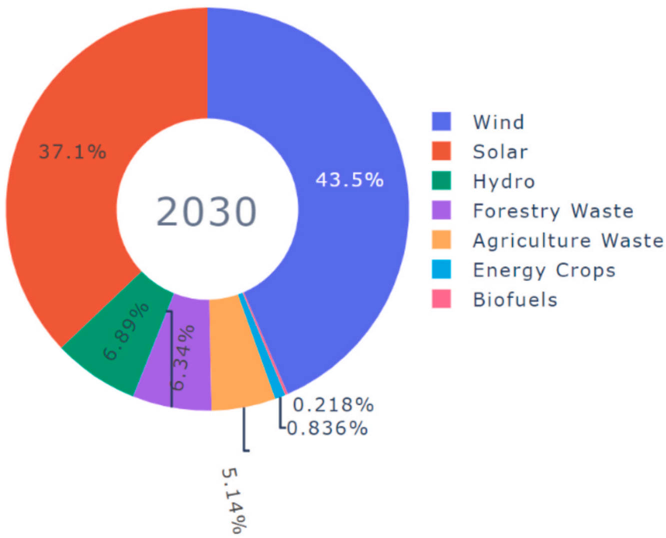

Fig. 4. openMASTER results' visualizer: Renewable energy mix for 2030.

utilization of multicriteria decision-making to address sustainability indicators [37], the implications of the decarbonization on energy poverty [38], and the treatment of epistemic uncertainties through robust techniques [33].

In addition, it has been employed in the preparation of public reports, with the objective of providing decision-makers with insights into the economic, environmental, and technological consequences of different potential pathways for the energy sector. This analytical tool enables informed discussions among stakeholders, facilitating the necessary consensus for the energy transition. Notably, these public reports includes an analysis of long-term (2030–2050) scenarios in the Spanish energy sector [39], strategies for decarbonising land transport in Spain [40], and the impact of climate change in water resource availability for electricity generation [41]. This highlights that openMASTER is a flexible and adaptable model, making it a valuable tool for a wide range of research applications in the field of energy planning.

It is important to introduce the openMASTER results' *visualiser*, which is publicly accessible along with the model's entire code, and provides a user-friendly interface displaying comprehensive information on the energy system and its emissions. The *visualiser* allows users to access intuitive data, presented through graphs that can be customised for specific scenarios and years of interest.

In Figs. 2, 3, 4 and 5, we showcase some graphs generated by the *visualiser*, including the Sankey diagram illustrating energy flows within the processes of the energy system, tracing them to their final consumption across various sectors through end-use technologies. Moreover, the *visualiser* offers the ability to track the evolution of primary energy consumption, assess the composition of renewable energy sources, and examine emission-related indicators such as their temporal changes and technological sources. These graphs are generated using Plotly, making them interactive and capable of being modified to represent different scenarios and years via selectors.

A feature of this visualisation tool is the *comparator*, which facilitates intuitive comparisons between different years or scenarios, as shown in Fig. 6. This empowers decision-makers to gain valuable insights through easily interpretable visualisations. Notably, the model offers comprehensive information related to the decision variables outlined in Section 3. This encompasses a wide range of details, including the evolution of the capacity of both energy conversion technologies and end-use technologies, the emissions sources, and the operational characteristics of technologies on a time-slice basis, among others.

Regarding the computational load, the model exhibits the features illustrated in Table 2. The optimisation is performed using Gurobi Optimizer version 10.0.1 on a PC equipped with a 64-bit Windows Operating System, an Intel(R) Xeon(R) Silver 4116 CPU @ 2.10 GHz processor, and 128 GB RAM. The findings clearly indicate that the computational load and solving time are highly reasonable for strategic energy planning, and comparable to other similar models. In this context, it's essential to consider the computational load associated with the temporal resolution of the model. Most common openMASTER applications use configurations of 96 and 672 time slices per year, corresponding to hours in a typical day or week for each season. It's important to note that these temporal resolution scale up due to the time horizon in years, reflecting the dynamic character of openMASTER. Table 2 presents the computational results for utilising 96 time slices per year within a time horizon spanning from 2020 to 2070, with a representation of 5-year gaps.

5. Illustrative case study

This section presents a brief illustrative case study to demonstrate how openMASTER can be used to address real-world energy decision-making problems, and showing some of the results achievable with it. It is essential to emphasize that the interpretation of the results is not

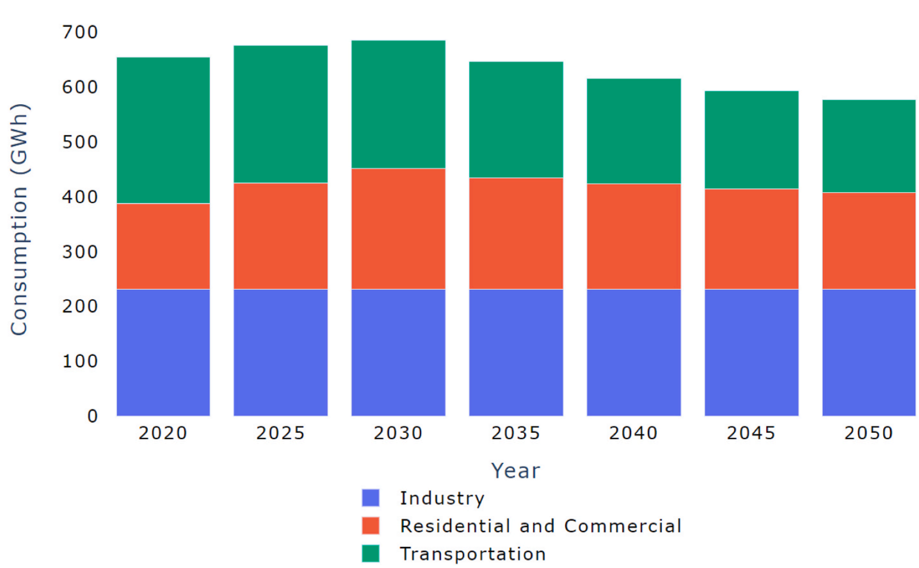

Fig. 5. openMASTER results' visualizer: Evolution of final energy consumption (2020–2050).

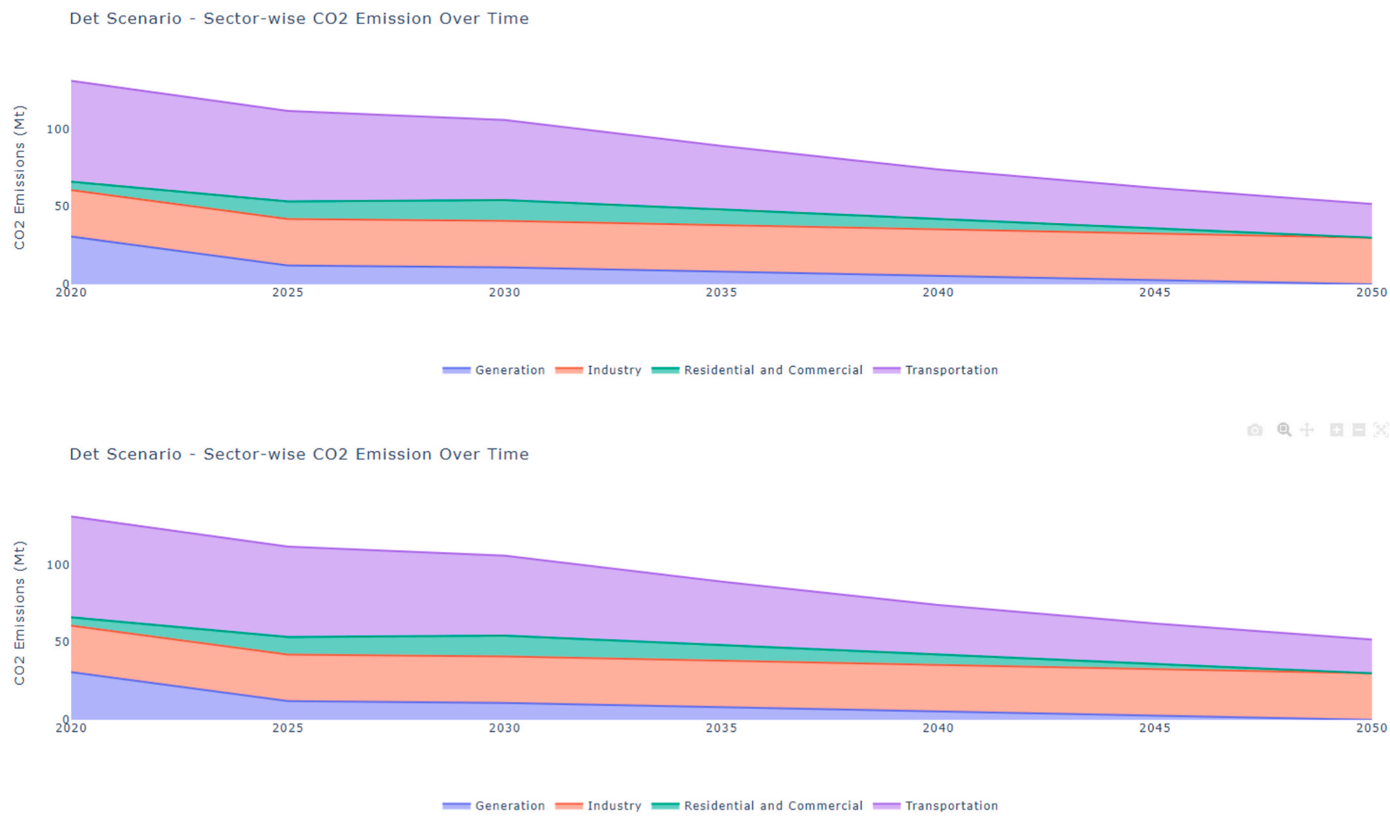

Fig. 6. openMASTER results' comparator: Sector-wise CO2 emissions. BAU vs Decarbonization scenarios.

Table 2
Computational characteristics.

Type	Variables	Equations	Solver time
LP	2,087,907	3,042,005	131.31 s

discussed here, but rather the model's capability to generate them.

This illustrative case study is calibrated for the Spanish energy system in the year 2020, representing a decarbonization scenario conducted under the constraint of annual emissions formulated by the Spanish government to achieve climate goals outlined in the Integrated National Energy and Climate Plan. Consequently, sectorial carbon cap constraints were imposed on all emissions during the 2020–2030 period. Detailed information regarding the calibration of this illustrative case study can be found in section 5 of the Supplementary Material, including data on fuel prices, energy technology investment costs, technology efficiencies, and installed capacity for the 2020 calibration year.

Table 3
Installed capacity of conversion energy technologies.

[GW]	2020	2030
Nuclear	7.4	3.2
Coal	10.2	0.0
CCGT	26.6	16.3
CCGT + CCS	0.0	14.6
OCGT	0.0	12.5
OCGT + CCS	0.0	0.0
Fuel Oil	3.7	0.0
Hydro	14.0	20.9
Wind Onshore	26.8	67.7
Wind Offshore	0.0	3.0
Solar PV	11.0	79.0
Solar Th	2.3	2.3
Biomass PP	1.4	0.0
Storage	6.4	16.3
CHP	5.3	2.6
TOTAL ELECT	115.0	238.4
Oil Refinery	47.9	26.1
Biofuel	56.2	51.0
Regasification	43.8	83.4

Table 4
Car fleet.

[Million vehicles]	2020	2030
Gasoline	10.67	9.095
Diesel	8.0063	2.563
CNG	0.0018	0.001
LPG	0.0091	0.003
Hybrid Gasoline	0.0077	4.363
Hybrid Diesel	0.0063	0.002
EV	0.01	1.512
TOTAL	18.711	17.539

Table 3 presents the installed capacity of conversion energy technologies for the year 2030 compared to the calibration year of 2020. It illustrates how the model resolves the investment planning of energy technologies for the years within the study horizon, not only for the electricity sector but for all energy vectors.

In addition to investment planning in conversion energy technologies, openMASTER also operates and invests in end-use energy technologies, referred to as supply technologies. In this regard, openMASTER considers three demand sectors (residential & services, industry, and transportation), where demand is defined as energy services (e.g., passenger and freight mobility, quantity of materials, or energy services in buildings such as heating, appliances, or lighting).

As an example of the installation of supply technologies, the results in Table 4 show the evolution of car fleet capacity. Similarly, it is worth noting that the model also provides this capacity for supply technologies

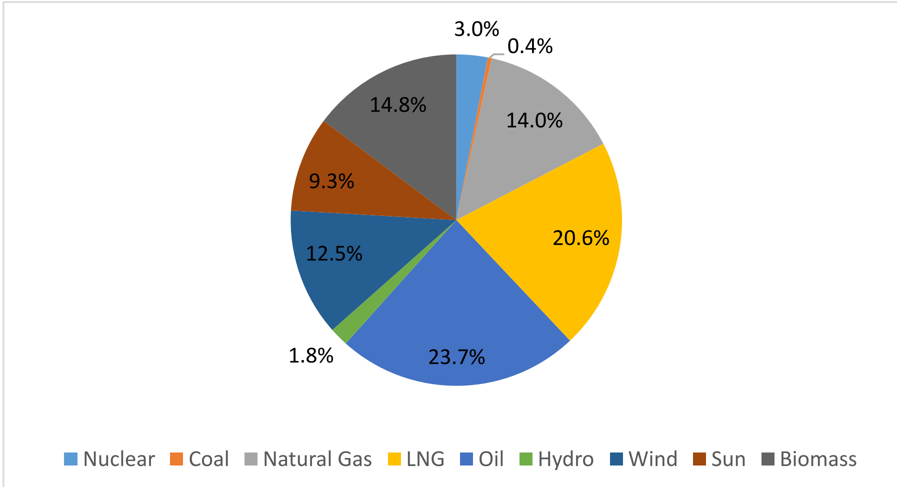

Fig. 7. Primary energy mix for 2030.

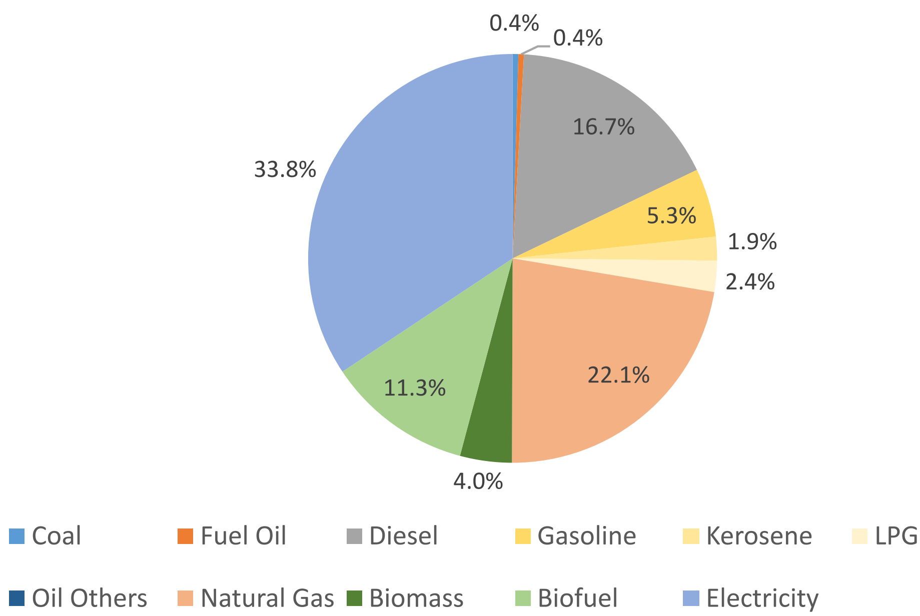

Fig. 8. Final energy mix for 2030.

of other mobility options (e.g., airplanes, trucks, buses, etc.) and sectors (e.g., gas boilers, heat pumps, or high and low-efficiency washing machines in residential areas, or various industrial processes such as Hall Heroult aluminum factories).

Furthermore, regarding Tables 4 and it is important to note that this car fleet corresponds to the total aggregate of each technology for the years 2020 and 2030, although the model disaggregates these technologies by vintage. Therefore, the number of each type of vehicle is disaggregated by its age, influencing its energy efficiency and emission factor. This allows for the inclusion of the learning curve, decommissioning after the end of their useful life, and compliance with environmental regulations of the supply technologies.

On the other hand, the operation of these technologies to meet the demand for energy services is another crucial aspect of openMASTER. In this regard, Figs. 7 and 8 display the primary energy mix and final energy mix, respectively. It is noteworthy that the information in these figures is aggregated for the year 2030 but is available for all time slices that configure the model.

As shown above, these results serve as a sample of the outcomes achievable through the utilization of openMASTER. Naturally, openMASTER can yield a diverse range of other results, including but not limited to CO2 emissions, atmospheric pollutants (such as NOx, SOx, and PM2.5), and behavioural measures, among others.

This comprehensive suite of outputs enables a holistic understanding of the impacts and implications of energy policies and scenarios analyzed using the openMASTER model.

6. Conclusions

Over the span of more than a decade, the MASTER model has demonstrated its reliability and adaptability across various research domains. In this context, we now introduce openMASTER, a valuable open-source tool for both public discussions about the energy transition and cutting-edge research.

Through an extensive review of the literature, we have shown how openMASTER offers several advantages over similar models. The publication of the model as an open-source tool serves as an exercise in promoting transparency and replicability within the scientific community engaged in long-term energy system modelling.

Considerable efforts have been devoted to developing an accessible and modular tool, designed with user-friendly data treatment and visualisation modules. Additionally, the model offers a visualisation tool that proves instrumental for decision-makers. Importantly, all auxiliary modules associated with the model are also publicly available, further enhancing its usability and transparency.

Despite its strengths, the model does have limitations, as addressed in Section 2.1. It lacks spatial modelling for electricity and gas grids, crucial for representing regional or global models with energy interconnections. This could increase computational complexity. Additionally, the model's bottom-up approach and high level of detail entail a significant number of equations and variables, necessitating a trade-off between detail and computational complexity. While openMASTER has been applied to real-world case studies like the Spanish national energy system, expanding its scope to continent-wide or global applications remains unexplored and may require adjustments to temporal detail. Hence, improvement in these areas represents a potential avenue for enhancing the model's performance.

Ongoing research involving the openMASTER model is advancing in various directions, such as the consolidation of robust planning techniques for dealing with epistemic uncertainties, improving the representation of the transportation sector, integrating indicators of a just transition, and enhancing the level of detail in production processes and the circular economy within the industrial sector. These potential avenues hold promise for further leveraging the capabilities of the openMASTER model.

Credit author statement

Antonio F. Rodriguez-Matas: Conceptualization, Methodology, Software, Writing – original draft, Visualisation, Validation. Pedro Linares: Conceptualization, Methodology, Supervision, Writing-Reviewing. Manuel Perez-Bravo: Conceptualization, Methodology, Software, Visualisation, Validation. Jose C. Romero: Conceptualization, Supervision, Writing- Reviewing.

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

All data and source code can be found on GitHub (link in Manuscript)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2024.101456.

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