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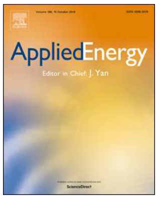

Review of models for integrating renewable energy in the generation expansion planning

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HIGHLIGHTS

- The paper provides review of models integrating RES in Generation Expansion Planning.
- It classifies models based on the applied theoretical approach in three categories.
- Optimization, general/partial equilibrium and alternative models.
- It compares their characteristics, advantages/disadvantages and their suitability.
- It contributes in better understanding on the expected outcomes of each methodology.

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ABSTRACT

The Generation Expansion Planning (GEP) stands as one as one of the most discussed topics within the academia and decision makers in the energy sector, especially related to meeting deep emission reduction targets. Every country, aiming at decarbonizing its economy, focuses on the application of policies that could enhance the penetration of Renewable Energy Sources (RES) in its power capacity mix. GEP is a complex task, combining techno-economic, financial, spatial and environmental characteristics. Several models are developed to model GEP, applying different methodological approaches. The underlying theory is very important as it might inherit bias in the resulted outcomes. The debate on the appropriateness of each methodology is increased, especially as projected outlooks deviate from reality. The paper aims to provide a review of the models employed to integrate RES in the GEP. The paper classifies models in three generic categories: optimisation models, general/partial equilibrium models and alternative models, not adopting the optimum integration of RES in the GEP. It provides insights on the characteristics, advantages and disadvantages of the theoretical approaches implemented, as well on their suitability for different aspects of the problem, contributing in the better understanding on the expected outcomes of each methodology.

Abbreviations: AEO, Annual Energy Outlook; AHP, Analytical Hierarchical Process; AIM, Asian-Pacific Integrated Model; CBA, Cost Benefit Analysis; CCS, Carbon Capture and Sequestration; CGE, Computable General Equilibrium; CIMS, Canadian Integrated Modelling System; DICE, Dynamic Integrated Climate-Economy; DSM, Demand Side Management; E3, Economy Energy Environment; E3ME, Economy Energy Environment Model Global economy; E3MG, Economy Energy Environment Model Europe; EFOM, Energy Flow Optimisation Model; EGEAS, Electricity Generation Expansion Analysis System; ENPEP, Energy and Power Evaluation Program; EPPA, Emission Prediction and Policy Analysis; ETM, Energy Technology subModel; ETSAP, Energy Technology Systems Analysis Program; EU, European Union; GAINS, Greenhouse Gas - Air Pollution Interactions and Synergies; GDP, Gross Domestic Prod; GEP, Generation Expansion Planning; GEM-E3, General Equilibrium Model for Energy-Economy-Environment; GHG, GreenHouse Gases; GREEN, GeneRal Equilibrium ENvironmental; GTAP, Global Trade Analysis Project; HOMER, Hybrid Optimization of Multiple Energy Resources; IAEA, International Atomic Energy Agency; IEA, International Energy Agency; IIASA, International Institute for Applied System Analysis; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; LEAP, Long-range Energy Alternative Planning; MARKAL, Market Allocation Model; MAC, Marginal Abatement Curves; MAUT, Multiple Attribute Utility Theory; MCDA, Multi-Criteria Decision Analysis; MCS, Monte Carlo simulation; MDM-E3, Multisectoral Dynamic Model– Energy, Environment, Economy; MERGE, Model for Evaluating the Regional and Global Effects of GHG Reduction Policies; MILP, Mixed Integer Linear Programming; MVP, Mean-Variance Portfolio; NEMS, National Energy Modelling System; NEMESIS, New Econometric Model of Evaluation by Sectoral Interdependency and Supply; NEWAGE, National European Worldwide Applied General Equilibrium; POLES, Prospective Outlook on Long-term Energy Systems; PRIMES, Price-Induced Market Equilibrium System; RES, Renewable Energy Sources; RESC, Renewable Energy Supply Chain; RETScreen, Renewable Energy Technologies Screen; ROA, Real Options Analysis; SD, Systems Dynamics; TEP, Transmission Expansion Planning; TIMES, The Integrated MARKAL-EFOM System; TIAM, TIMES Integrated Assessment Model; UK, United Kingdom; USA, United States of America; WASP, Wien Automatic System Planning

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1. Introduction

The Generation Expansion Planning (GEP) is one of the most discussed topics within the academia and decision makers in the energy sector. The carbon pathway of a country's power system strongly affects the country's capability to meet deep emission reduction targets. Moreover, the penetration of Renewable Energy Sources (RES) in the whole energy mix is strongly related to the RES penetration in the power sector, as RES applications in other energy subsectors are currently not so competitive. RES contribute to the sustainable development of the economy, providing environmental, social, and economic benefits. The transition to a low or zero carbon economy is strongly related to the integration of RES into the GEP, resulting not only from the growing environmental concerns, but as well from market reasons, due to the rapid reduction of the levelized cost of energy from the renewables technologies. The penetration of RES leads to sharp reductions of marginal cost in power markets, that could provide considerable benefits for the final consumers [1,2]. The integration of RES with other technologies in the power systems, such as demand-response, storage and electric vehicles, enables the considerable improvement of public health and of elimination of environmental degradation, leading to a sustainable society.

Although the share of renewables in the power mix is unanimously accepted to be increased in the medium and long-term, there exist different models on examining the RES penetration capability and the RES technologies pathways, as well as the associated influence on the total energy system cost and the carbon footprint of a power system. This paper aims at providing a review on the models related to the integration of RES in the GEP problem, with special focus on the applied methodological framework, as it strongly affects the model outputs. The applied methodology might inherit bias in the outcomes. There exist several studies predicting the evolution of power systems dominated by a technology or an energy carrier, resulting even from a negligible cost advantage compared to competitive options. This fact creates the need to focus more on the methodology rather than on the different technical and economic characteristics of each power generation option.

The manuscript considered numerous papers, including review papers cited in this section [3–7] or in the upcoming sections, that tackle the issue of integration of RES in the generation expansion problem. Lopion et al. [3] analyse the historical trends in the development of energy system models, identifying that recent models are more flexible in terms of spatial or temporal resolution. Bazmi and Zahedi [4] provide a review on the role of optimization modeling techniques in power generation and supply. Moreover, the paper explores the future prospective of optimization modeling as a tool for sustainable energy systems. Lund et al. [5] provide a review of different approaches, technologies, and strategies to manage large-scale schemes of variable renewable electricity, such as wind and solar power. It presents energy system flexibility measures to enable high levels penetration of variable renewable energy. Banos et al. [6] provide a review of computational optimization methods applied for design, planning and control problems in the field of renewable and sustainable energy applied. The paper concludes that the use of heuristic approaches, Pareto-based multi-objective optimization and parallel processing are promising research areas in the field of renewable and sustainable energy. del Granado et al. [7] provide a nexus of energy system and economic models concerning modelling energy transition. The paper proposes a new modelling framework to represent a broader scope of the energy-economic system.

Those review papers either focus on specific methodological framework, i.e. optimization models, energy system models, decision making methods, or on specific aspects of the integration process of RES, namely technical issues, environmental performance, and uncertainty. These models, although tackling the integration of RES problem, focus in general on different aspects of the GEP problem. Those review papers present the characteristics, as well as the advantages and disadvantages of each specific methodological framework; however they do not provide comparison with other methodological approaches, concerning their strengths/limitations and their suitability for different aspects of the problem. The aim of the paper is not to judge the superiority of any method, as this would require their application on the same specific problem and the adoption of competence criteria, such as computing time, iterations to converge etc. The contribution and the novelty of our work concerns the consideration of all (to the best of our knowledge and based on research undertaken) models that have been applied, with the aim to classify them and to highlight their related advantages and disadvantages, as well as to suggest their suitability for different aspects of the GEP problem.

There are several methodologies that have been applied to tackle the GEP problem, where most of them are considered as optimization models. Although there exist several differences among the developed models, our research focuses on the generic methodological framework, organizing models in few generic categories. The selection of the different categories has been based on a top-down approach, to allow modellers and decision makers to have an overall understanding of the different methodological approaches, their advantages/disadvantages and their suitability on tackling different aspects of the RES integration in the GEP problem. Implementing a bottom-up approach on classifying the models would lead to a more detailed disaggregation; however without notable characteristics on methodological issues among different categories. Moreover, this paper does not aim to provide a comprehensive review, which could amount to numerous research papers, but its main contribution is to present the methodological approach of representative papers and applications of each category. Thus, the present work, focusing on the theoretical and methodological framework, classifies the models in three distinct categories:

- Optimization models, applying different methods such as non-linear programming, mixed integer programming, dynamic programming and decomposition techniques for modelling the GEP problem. The optimization models, concerning the integration of RES, are organized in two sub-categories:
  i. with a simple objective function, i.e. minimizing the total energy system cost considering environmental constraints, such as emissions reduction and/or RES penetration targets.
  ii. with a multiple-objective function, whereby the environmental targets are not considered as constraints, but as objective of the multi-objective model.
- Computable general or partial equilibrium models, where the GEP problem is part of an optimum equilibrium solution of the whole economy or the energy system respectively. Those models in general principle are also considered as optimization models, as they incorporate a cost-minimizing behaviour by representative agents. However, they usually deviate from that principle to simulate real economic and energy systems, i.e. by considering imperfect competition, non-market clearing for unemployment or for commodities (inventories). RES technologies are considered as supplementary options, penetrating in the mix based on the competitiveness and the overall environmental targets applied.
  i. Partial equilibrium models are formed as complementarity problems, namely through the formation of a square system of equations/inequalities and unknown variables, which creates problem in the model specification, as complementarity requires explicit representation of primal and dual optimality conditions [8]. Thus, partial equilibrium models are differentiated from the more compact representation of the energy system implemented by the single or multiple objective constrained optimization models.
- Alternative models. Those models are deviating from the optimum integration of RES in the generation and capacity mix. This category incorporates different models such as probabilistic, simulation, life

cycle assessment, cost-benefit analysis, econometric, multi-criteria, system dynamics and modern portfolio theory models. Those models aim to capture critical aspects of RES, providing a simplified -but less robust- approach or simulating energy and RES systems in a more realistic manner, compared to the myopic behaviour of optimization models.

The paper is organized with the following way: Optimization models, computable general or partial equilibrium models and alternative models are presented in Sections 2–4 respectively. Section 5 provides a comparison of the different methodologies, while Section 6 provides the concluding remarks.

2. Optimization models

There exist some recent review papers, organizing the models belonging in this category. Oree et al. [10] provide a review of GEP optimization models with renewable energy integration. In this context, the paper classifies the different methodologies into four distinct groups: (a) traditional methods that integrate environmental considerations as external costs or constraints in the GEP, (b) formulation of the GEP as a multiple-objective optimization problem, with the ecological footprint being one of the objectives, (c) techniques used to tackle variable RES-related uncertainties in the GEP process, and (d) new dynamics and challenges introduced in the power systems by the increased integration of intermittent RES. Koltsaklis and Dagoumas [11] provide a review on the state of the art of the GEP problem. More specifically, it organizes GEP into the following categories, concerning different issues that the GEP has to tackle: the transmission expansion planning, interdependence with the natural gas system, short-term operation of power markets, electric vehicles' penetration, demand-side management and storage, risk-based decision-making, as well as with applied energy policy including security of supply. In addition, Sadeghi et al. [12] provide a comprehensive review on the GEP problem. The manuscript examines papers from the perspective of various factors, including the electricity market liberalization, climate change and environmental issues, the revolution in RES technologies, regulatory policies, and emerging techniques in the optimization and modelling fields. A recent paper by Lund et al. [5], reviews different technologies, approaches and strategies in order to manage variable electricity generation from RES, considering both supply and demand-side measures. Although the above review papers provide comprehensive review of optimization models used for the integration of RES in the GEP, they focus on optimization models and/or specific aspects of the GEP problem, without providing insights on the advantages and disadvantages of the optimization models compared to the other model types.

Optimization models have numerous applications on national/regional power systems, providing realistic and robust simulations for regional decision makers. Developing a cost optimization planning model for the power system of USA, Frew et al. [13] aims at evaluating the trade-offs and benefits of different flexibility mechanisms, as well as comparing pathways towards a zero-carbon power system with only renewables. By comparing four mechanisms, the work concludes that geographic aggregation is the optimum flexibility mechanism. Developing a dynamic multi-regional optimal generation expansion model, Komiyama and Fujii [14] examine the massive integration of variable RES into the Japan's power-generation and capacity mix. Kwon et al. [15] examine the GEP problem of South Korea, considering the transition of renewable and nuclear policy. Through the formulation of a Mixed Integer Linear Programming (MILP) model, Muis et al. [16] deal with the optimal planning of RES electricity generation schemes, under CO_2 reduction target, in case of Malaysia. Building an optimization model, Noorollahi et al. [17] study the power generation expansion planning of Iran, considering different renewable energy technologies. Through the application of a genetic algorithm, Oscan et al. [18] cope with the integration of RES in Turkey's long-term GEP. By creating an optimization model, Sharifzadeh et al. [19] explore the integration of uncertain RES in the UK, towards meeting a 50% target in the power generation mix by 2050, from wind and solar energy. In addition, Pean et al. [20] use the PLEXOS optimization tool to investigate the relationship between electricity interconnections (France and Great Britain), the penetration of variable renewable energy sources and the reduction in overall operational costs. Moreover, Deane et al. [21] utilize the PLEXOS modelling tool to calculate the impacts of integrating renewable energy targets in national policies in North-West Europe.

The list for national/regional optimization models is extensive, as transmission system operators and other decision makers consider that those models provide robust results. Using multi-objective optimization, Prebeg et al. [22] investigate the long-term energy planning of the Croatian power system, focusing on the integration of RES and electric vehicles in the power system. Furthermore, Pereira and Saraiva [23] present a long-term generation expansion planning model, which uses system dynamics to capture the interrelations between different parameters and variables. The model is applied for a realistic simulation of the Portuguese/Spanish power generation system, identifying the most adequate expansion plans towards the increased RES penetration in the power mix. By constructing a goal programming model, San Cristóbal [24] identify the optimal locational and mix of renewable energy power units in north Spain. Aryandoust and Lilliestam [25] conduct research into the German future power system consisted only of RES, investigating the complementary potential of demand response. Employing a bi-level optimization framework, Zhou et al. [26] investigate the impacts of different incentive policies for the enhancement of RES investments in the US, including subsidies to renewable technologies, tax policies, and mandatory renewable targets. Through the utilization of a linear programming model, Chang and Li [27] determine the optimal GEP of the countries belonging to the Association of Southeast Asian Nations (ASEAN), showing that the promotion of RES development enhances electricity trading. Applying a column generation approach and novel Dantzig–Wolfe decomposition, Flores-Quiroz et al. [28] address the GEP with high renewable energy penetration in case of the Chilean power system. The paper demonstrates that the proposed approach outperforms applications from commercial solvers, as it significantly reduces the computational burden and overcomes intractability.

There is also an extensive list of models addressing the GEP problem as a multi-objective problem. This is attributed to the rising influence of crucial parameters such as renewable energy targets, climate change mitigation and energy security. Iqbal et al. [29] conduct a review of optimization classifications, algorithms and tools for RES, while Aghaei et al. [30] focus on the integration of renewables in the GEP, using a multi-objective framework. Also, Luz et al. [31] present a multi-objective power generation expansion planning with high penetration of RES, applying it for the Brazilian power system. The model considers three objective functions: minimizing the total cost, maximizing the contribution of non-hydro RES and maximizing generation at the peak load. A popular multi-objective generation expansion model is EGEAS, having two objective functions: minimizing total costs and minimizing levelized annual customer rates. EGEAS software is used by utility planners to develop integrated resource plans, evaluate independent power producers' plans, estimate avoided costs, develop environmental compliance plans and to analyse life extension alternatives [32]. Making use of a two objective-functions model, Chedid et al. [33] assess the wind and solar penetration in an isolated system, with diesel generators and backup batteries. Moura and de Almeida [34] developed a multi-objective model of the GEP in Portugal, investigating the penetration of RES, considering several objectives: total cost minimization, intermittences' minimization, maximization of the contribution of RES to the winter peak load and the summer peak load. Zhang et al. [35] study the problem of RES generation curtailment, requiring co-optimization of the GEP and TEP to optimize energy usage and to improve investment profitability. Moreira et al. [36] examine the co-optimization of power system's resources, towards meeting RES targets. It aims at capturing not only the cost-optimality, but also the reliability related to the integration of RES generation in the integrated GEP and TEP problem.

Another subcategory of optimization models in bilevel programming, where one problem is embedded within another. This approach is usually applied for operational problems rather than for energy planning, however there are some applications for power system expansion. Zolfaghari and Akbari [37] propose a bilevel model for transmission expansion planning considering wind investment, as well as Garcia-Herreros et al. [38] suggest a mixed-integer bilevel optimization model for capacity planning with rational markets.

2.1. Technical and operational aspects

Several researchers focus on operational issues related to the penetration of variable RES, such as flexibility or the integration of RES together with demand response and storage facilities. Fig. 1 presents the technical/operational phases of a thermal power plant, which is important to be considered for the robust operation of power systems, as the integration of RES strongly affects the flexibility and ramping requirements of power systems. Collins et al. [39] carry out a methodological review on the integration of short-term variations of the power system into integrated energy system models. Alizadeh et al. [40] present a comprehensive literature study, defining, classifying and discussing the latest flexibility mechanisms in power systems. More specifically, it includes the barriers, abilities and inherent attributes of future power systems' potential to deal with the high penetration of variable RES. Papaefthymiou and Dragoon [41] outline the necessary steps towards building power systems, with the required flexibility to maintain reliability and stability, while relying primarily on variable RES. The paper provides a comprehensive overview of the technical changes, policies and institutional systems, towards the transition to zero carbon power systems with 100% renewables. Through the formulation of an optimization model, Mikkola and Lund [42] find cost-optimal ways for the management of the energy system with large-scale intermittent RES. It identifies the crucial role of the optimum use of the power system's flexibility. By handling both thermal and electric loads, the model also allows the identification and quantification of the penetration capability of power-to-heat conversion systems.

The list for optimization models, tackling the RES impact on operational and technical aspects of the power system, is also numerous. Within that context, Palmintier and Webster [43] examine the impact of operational flexibility on the GEP, incorporating RES and emission reduction targets. Pina et al. [44] assess the impact of demand-side management strategies in supporting the integration of RES, providing insights on their supplementary role for load shedding and flexibility management. Batalla-Bejerano and Trujillo-Baute [45] provide an estimation of the evolution of balancing market costs and requirements, due to the variable RES evolution. Examining the Spanish electricity system, the paper concludes that costs for integrating RES depend on the predictability and variability of RES generation, as well as on each power system's flexibility. Developing a mid-term generation expansion planning model, which incorporates a unit commitment model, Koltsaklis and Georgiadis [46] capture technical and operational aspects from the RES integration. The model identifies the power mix, the RES evolution and the day-ahead prices of the Greek interconnected system. Examining mathematical modelling studies for the generation expansion planning for a candidate power system, Rajesh et al. [47] identify the impact from the supplementary integration of intermittent RES and storage facilities. Developing a multi-stage mixed integer non-linear programming model for the optimal GEP of a power system, Hemmati et al. [48] investigate the linkage between energy storage capacities with variable renewable and thermal generating capacity

The variable nature of RES is a major concern for power systems, affecting not only short-term operation, but also long-term planning. Utilising a stochastic optimization model for the GEP, Ji et al. [49] study a power system with different renewable portfolio standards levels and load demand scenarios. Also, Stiphout et al. [50] present a GEP model, incorporating storage and reserve requirements, to capture the uncertainty characterizing the renewable energy sources and to enhance the power system's operational flexibility. Employing an optimization model for the GEP model, which incorporates short-term

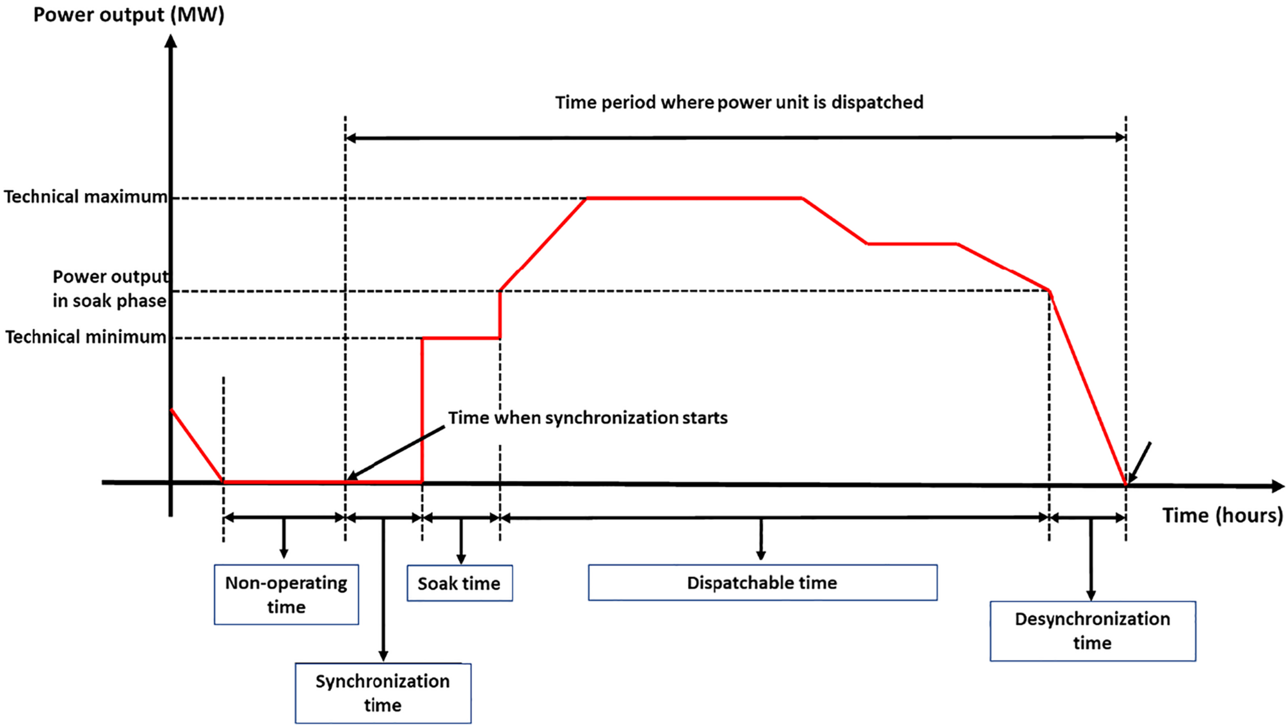

Fig. 1. Operational phases of a thermal power plant.

dynamics of the power system operation, Wierzbowski et al. [51] and Lyzwa et al. [52] investigate the integration of enhanced RES penetration together with variable load. Besides those works, Lyzwa and Wierzbowski [53] quantify the impacts of variable and intermittent RES on the long-term power generation mix optimization. By making use of a linear programming model, Krishnan and Cole [54] assess the impacts of spatial resolution of the power systems, concerning the investment planning decisions at a national level. The paper highlights the regional temporal aspects that affect the relative competitiveness of RES technologies. Finally, Poncelet et al. [55] focus on the selection of representative days to capture the implications of integrating intermittent RES in the GEP problem, providing evidence for more robust results but with higher computational cost.

The list of works in the literature to deal with the variable nature of RES is extensive. Pereira et al. [56] developed an optimization-based GEP model to quantify the effects of variable RES on the thermal power plants efficiency. This model, compared with a previous one [57], results in more robust results, regarding the cost and even the structure of the optimal generation mix for long-term GEP, in case of complex power systems that combine thermal and renewables' power plants. However, it requires considerably more time for running a scenario, identifying the off-setting among robustness and computational burden. Developing a new power system planning model that incorporates technical operational constraints, Belderbos and Delarue [58] determine the optimal generation and capacity mix of different power generation technologies. The paper demonstrates that the power plants' operational constraints, especially related to the volatile nature of RES, have an important impact on the generation and capacity mix. Constructing a dynamic model for the GEP, based on Conditional Value-at-Risk (CVR) theory, Lu et al. [59] analyse the RES investment decisions taking into account different risk scenarios, applying it at a provincial grid in China. Formulating a multi-year stochastic GEP model, Park and Baldick [60] investigate changes in the generation mix under environmental and energy policies, including the application of carbon tax and of a renewable portfolio standard, where correlated wind and load samples are generated via Gaussian copula.

2.2. Integrated generation and network expansion planning

The integrated generation and transmission expansion planning is also tackled by several researchers, revealing the role of transmission networks for the penetration of RES. Hemmati et al. [61] provide a review of works that deal with the coordinated generation and transmission expansion problems, in terms of penetration of distributed RES, uncertainties, reliability, environmental impacts and line congestion. Aghaei et al. [62] present an integrated model for the optimal generation and transmission expansion planning, considering reliability criteria, resulting from variable RES, as well as from random generation or line outages. By applying an MILP model for the integrated generation, transmission and storage planning, Go et al. [63] investigate the economic interactions among the energy investments in these three distinct power system sectors, considering high renewable penetrations. Wiernes and Moser [64] make use of an optimization model for the integrated GEP and TEP of a future European power system, considering energy storage, renewable energy and demand-side management programs. Developing an MILP model for the optimal energy management of an (electricity and gas) hub, Haghifam et al. [65] examine the supplementary role of energy storage, RES and demand response programs, while Hemmati et al. [66] suggest an optimization framework to incorporate the optimal planning on RES and energy storage systems of the studied energy hub. Richardson and Harvey [67] present a methodology to optimally determine the dimensioning of energy storage resources, RES and demand response, aiming at replacing conventional power generation in Ontario's power and private transportation sectors.

The growing need for models integrating generation and transmission expansion planning is attributed to the fact that RES integration requires considerable investments in the transmission system. Presenting an optimization framework for the integrated GEP and TEP, Guerra et al. [68] examine a case of interconnected power systems, considering Carbon Capture and Sequestration (CCS) technologies, Demand-Side Management (DSM), RES technologies, as well as reserve and CO_2 emission constraints. Lumbreras et al. [69] present an optimal transmission network expansion planning model, which is applied for real-sized power systems with high RES penetration. Using a modified version of Benders' decomposition, the model performs optimal TEP in a stochastic optimization context, by applying a double architecture for Benders cuts as well as a progressive contingency incorporation algorithm. In addition, the model identifies the potential of candidate transmission lines automatically, which is very useful in case of large-scale problems. Madrigal and Stoft [70] conclude that efficient and effective expanding networks, constitutes a key task for the achievement of renewable energy objectives. Utilizing a stochastic two-stage optimization model, Weijde and Hobbs [71] capture the multi-stage nature of transmission planning under uncertainty. The model is used for the evaluation of inter-regional grid reinforcements in Great Britain, identifying the cost of uncertainty and the value of flexibility. The work points out that integrated GEP and TEP without the consideration of the risk from variable RES has considerable quantifiable economic consequences. Using a mixed integer optimization framework, You et al. [72] consider the coordinated GEP and TEP, under high wind penetration rate. Wind and demand variation is tackled through scenario analysis.

To summarize, the list of models and applications using single or multi-objective optimization models is considerable, resulting from their robust nature, as a result of considering detailed techno-economic, spatial and environmental characteristics of the power system, as well as from the needs of researchers to assess national energy and climate policies. Optimization models for the integration of RES into the GEP, usually aim to capture some of the critical challenges arising from the variable nature of RES, multi-objective nature of energy policy formulation, operational issues arising from the integration of RES, demand-side management and storage in the power systems, as well as the considerable role of spatial network characteristics. However, their optimum nature create bias, which must be considered in the interpretation of modelling results.

3. Computable general or partial equilibrium models

The theoretical framework of this category is the adoption of the Walrasian general equilibrium [9] across all the interconnected markets in the economy. Computable General Equilibrium (CGE) models are simulations that combine the abstract general equilibrium structure, formalized by Arrow and Debreu [73] with realistic economic data to numerically solve for the levels of demand, supply and price that support equilibrium in the interconnected markets, including the energy markets. CGE models are a standard tool of empirical analysis and are widely used to analyse the aggregate welfare and distributional impacts of policies, including energy and climate policies. In case the equilibrium theory is applied for a specific sector of an economy and not for the whole economy, then we have a partial equilibrium model, i.e. for the energy system. General and partial equilibrium models have been extensively used for the assessment of climate change policies, as those required global models to provide valuable results. They require a considerable amount of data and assumptions, which eliminates the wider use of them by several researchers, as it happens in case of optimization models presented above. CGE models have been very useful in international organizations. However, they face critique, due to their theoretical “equilibrium” assumption. Blanchard [74] provides a discussion on the future evolution of macro-economic models, with special focus on the CGE models. Moreover, the top-down representation of the energy and power systems is simplified, leading the results to be "sensitive" on the magnitude of substitution elasticity among energy carriers and RES technologies. Fig. 2 provides a generic representation of the way RES are incorporated in the production structure in general equilibrium models.

A review of models that belong in this category, is incorporated in a paper by Dagoumas et al. [75], which provides an economic assessment of the Kyoto Protocol application, using the GTAP-E model, standing for the Global Trade Analysis Project – Energy. GTAP-E is a general equilibrium model for quantitative analysis of international policy issues. This paper provides a review of the different classifications of models for examining climate and energy policies, organizing them in the following sub-categories: computable general equilibrium models, energy system models, integrated assessment models and emission trading models. More specifically, CGE models *"are also called "top-down" models and are either static or dynamic. The main characteristic of these models is their ability to capture the influence of energy policy on international trade and the economy and the fact that the construction of the economic system is based on the assumption of perfect markets"* [75]. Representatives of this category are GTAP-E, GREEN, EPPA, GEM-E3, G-CUBED, WORLDSCAN and NEWAGE models. Energy system models "*represent the energy sector in much more detail than the CGE models. They are referred as bottom-up models because they represent the energy sector by using a disaggregated data of existing and emerging technologies. Their main disadvantage is the fact that they represent only the energy system and do not take into account linkages of the energy sector with the rest economy".* [75]. Typical in this category are MARKAL, WASP-IV, POLES, PRIMES, LEAP and ENPEP models. Integrated assessment models *consider human activities, atmospheric composition, climate change and ecosystems and can be described as environmental models. They are very useful when conducting studies that address the problem of climate change because of the detailed representation of this change mechanism. Their economic structure belongs to one of the above categories* [75]. Representatives of this category are the AIM, MERGE, DICE and GAINS models, the latter developed by IIASA. The latter category, namely emission trading models, concerns models that use marginal abatement curves (MAC) to analyse international emission trading. MAC curves are usually produced by energy system models, CGE models or are estimated econometrically [75].

Energy systems models are reviewed by Bhattacharyya S.C. [76]. However, the models within this suggested category do not fit all together in one of the three categories proposed in our paper. Some of the energy system models are considered as optimization models, as they select the mix of technologies/options minimizing the total discounted system cost or surplus over the examined planning horizon, within the limits of imposed physical and policy constraints. Some of the energy system models are considered as partial equilibrium models, as the equilibrium theory is applied for the energy sector. A generic representation of an energy system model, within the partial equilibrium category, is provided in Fig. 3, depicting the interactions of the power sector with other producing or consuming energy-related sectors. There exist also energy system models that belong in the alternative models' category, as they do no adopt optimization in the integration of RES in the GEP. Popular energy system models are the WASP-IV model, belonging in the "optimization models" category, and the non-linear equilibrium ENPEP/BALANCE model, belonging in the "partial equilibrium models" category, both developed at the IAEA. Dagoumas et al. [77] provide a post-Kyoto analysis of the Hellenic electricity sector, using the WASP-IV platform for the simulation of the Hellenic electric power system expansion and the ENPEP/BALANCE platform for the evolution of all other energy related sectors. Després et al. [78] present a new electricity module of the simulation POLES model, belonging in the alternative models' category, to examine the role of electricity storage for the integration of high shares of variable RES. The integrated simulation model examines several flexibility options, demand response, within-day storage and grid interconnections, concluding that electricity storage can benefit from high carbon values and from surplus energy from RES.

The most popular energy system model is the Market Allocation Model (MARKAL) model, belonging in the partial equilibrium models' category, as GEP problem is part of an optimum equilibrium solution of the energy system expansion. The MARKAL model, or its successor The Integrated MARKAL-EFOM System (TIMES) model, are supporting a rich technology detail. Partial equilibrium models are popular among research and decision-making institutions, especially the MARKAL/TIMES family of models which are used by several modelling teams in the world. Jaskólski [79] using the MARKAL model, examine the long-term technological transition of the Polish power system, focusing on the impact of emission trading due to coal dominance in the Polish power system. The model results show that nuclear, wind and biomass

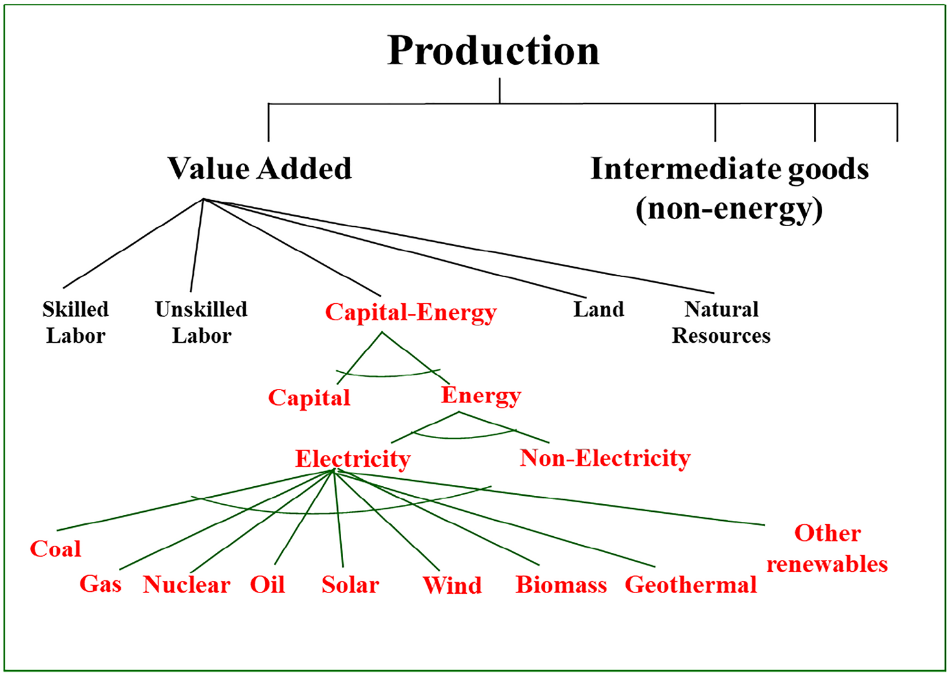

Fig. 2. Generic representation of incorporating energy substitution in the production structure in general equilibrium models.

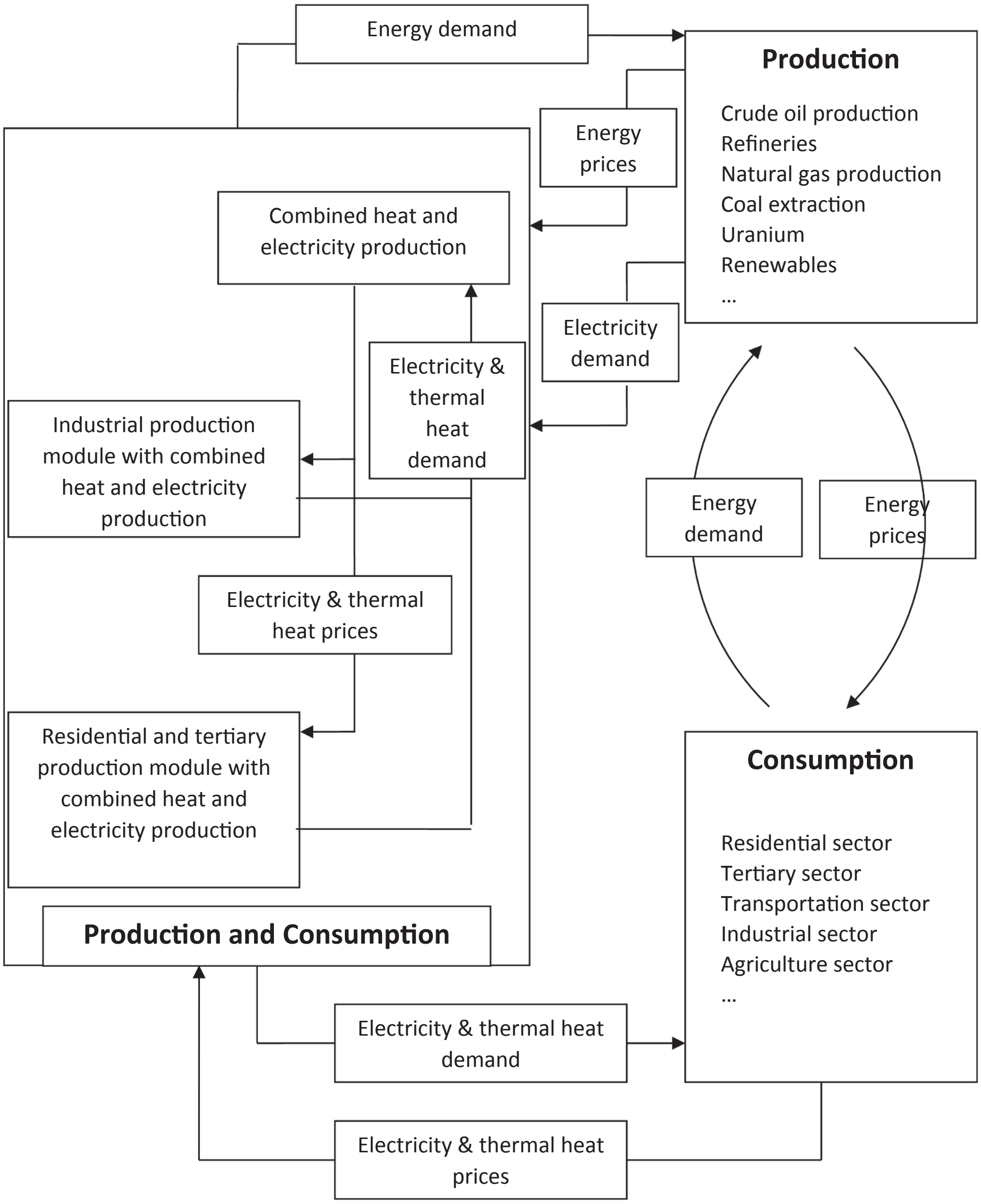

Fig. 3. Generic representation of an energy system model, within the partial equilibrium sub-category.

will replace coal base-load plants, while the potential of carbon capture and storage and emission trading should be considered. Using the MARKAL model, Tsai and Chang [80] evaluate the Taiwan's GHG mitigation strategies, presenting results on the simulations of different technology development scenarios, evaluating emissions reduction on Taiwan's electricity, tertiary, industry, and transportation sectors, identifying the potential of RES in all sectors. Agoris et al. [81] provide an analysis of the Greek energy system, in view of the country's Kyoto commitments, using the MARKAL and the WASP-IV models, while Føyn et al. [82] examine the evolution of a global renewable energy system, using the ETSAP/TIAM equilibrium model. The paper identifies the barriers towards zero carbon energy system with 100% renewables. Developing and applying a temporal MARKAL energy system model, Kannan [83] develops a flexible time slicing feature to enhance representation of seasonal and diurnal electricity demand curves, through the disaggregation of resource availability and energy service demands.

There exist several other applications of partial equilibrium models, examining the evolution of RES as part of national energy system expansion pathways. Anandarajah and Strachan [84], report implications and interactions and of climate change and renewable policy on the UK, using the MARKAL model. The paper quantifies a range of policies, carbon pathways and sectoral trade-offs, when combining mid-term and long-term renewable targets with CO_2 reduction policies. Using a partial equilibrium bottom-up model, namely the TIMES model, Amorim et al. [85] present electricity decarbonisation pathways for Portugal by 2050. The model accounts for the short-term dynamics of demand and supply, enabling a better match and optimization of energy resources complementarities. Tigas et al. [86] examine the wide-scale penetration of RES in the Greek electricity sector in view of the European decarbonization targets for 2050, by using a multi-regional TIMES model. The "optimum" nature of the energy system models is a known drawback, usually leads to non-realistic pathways of the energy system expansion. This myopic behaviour is tackled by several researchers, aiming at providing more reliable solutions and partly offset their neoclassical theoretical nature. Nerini et al. [87] provide insights on the myopic decision-making concerning the energy system decarbonisation pathways, examining the UK energy system using the UK TIMES model, which is an upgrade of the MARKAL model. The paper demonstrates that using a perfect foresight, technology-rich, bottom-up and cost-optimization energy system model, in tandem with its myopic equivalents, can provide valuable insights for policy design.

Besides the popular MARKAL family of models, there are several other equilibrium models. PRIMES and the GEM-E3 models are partial and general equilibrium models respectively, which are used for the official forecasts of the European Commission [88]. The PRIMES model involves non-linear formulation for the power system optimization, where non-linear cost-curves represent fuel supply, renewable potentials and limitations on the power plants' installation. GEM-E3 aims at covering the interactions between the Economy, the Energy system and the Environment (E3). The model computes simultaneously the competitive market equilibrium among all sectors, determining the optimum balance for energy supply/demand and emissions abatement. Rasouli and Teneketzis [89] present a methodology tying GEP to spot markets, employing a forward moving approach that achieves social welfare maximizing expansion. Utilizing a comprehensive partial equilibrium model, Tveten et al. [90] incorporates a high spatial and temporal resolution to examine the benefits of interconnecting hydropower and thermal regions, towards integrating variable RES.

A supplementary category to general/partial equilibrium models, towards capturing energy-economy-environment (E3) interactions, is the development of hybrid models by linking energy system and macro models, such as the MARKAL-MACRO model. A representative model of this category is the NEMS model, used by the US Department of Energy in the USA, for preparing the Annual Energy Outlook (AEO), as well as the CIMS model used for the Canadian economic and energy systems. NEMS model is used to analyse the functioning of the energy market, under alternative growth and policy scenarios. The model employs a technologically rich representation of the energy sector, covering the spatial patterns in energy use in the USA. The supply-side of the model contains four modules: coal supply, oil and gas supply, gas transportation/distribution, and renewable fuels. Welsch et al. [91] compare the performance of an extended version of an open source energy system model (OSeMOSYS), which incorporates operation constraints by integrating a long-term energy system model (TIMES) with a unit commitment and dispatch model (PLEXOS), for the case the Irish power system. The paper undermines the importance of considering the uncertainty of RES, concluding that omitting the intermittence of RES may underestimate the overall energy system costs, affecting also the costs for meeting energy security or climate change targets.

To summarize, general and partial equilibrium modelling capability to integrate the economic-energy-environment (E3) systems, enable the examination of inter-sectoral or interregional policies. They provide insights on the carbon pathways towards the decarbonization of the electricity sector and the transition to low carbon economies. Their "equilibrium" nature leads to a myopic behaviour, as in case of the optimization models. The top-down representation of the power system is simplified, leading the results to be "sensitive" on the magnitude of substitution elasticity among energy carriers and RES technologies.

4. Alternative models

This category gathers all models that do not employ optimization approach for the integration of RES in the GEP. It incorporates different models such as probabilistic, simulation, life cycle assessment, cost-benefit analysis, econometric, multi-criteria, system dynamics and modern portfolio theory models. Fig. 4 shows the different methodologies applied for developing models, being classified in the category "alternative models". Models of this category, deviating from optimum-restricted theoretical considerations, have higher flexibility. They enable focusing in more detail on specific aspects of the RES integration, such as its contribution to sustainable development, especially as related to life-cycle analysis. However, they are more simplified and less robust, as they do not consider technical characteristics of the power system and the interaction with the whole economic and energy systems.

One sub-category is the models that use econometrics, namely applying statistical techniques in dealing with problems of an econometric nature, towards deriving statistical relationships from past behaviour to model future behaviour. Dagoumas and Barker [92] present pathways to a low-carbon economy for the UK using the macro-econometric E3MG model, which stands for Energy–Economy–Environment Model at the Global level. The model incorporates a bottom-up approach (Energy Technology subModel, ETM) for simulating the power sector, which then provides feedback to the energy demand econometric equations and the whole economy. The ETM submodel uses a probabilistic approach and historical data for estimating the penetration levels of the different technologies, considering their economic, technical and environmental characteristics. The paper provides modelling evidence that deep reduction targets can be met through different carbon pathways, while also assessing the macroeconomic effects of the pathways on the Gross Domestic Product (GDP) and investment. The macro-econometric E3MG model belongs to the same family of models, E3ME and MDM-E3 developed at the University of Cambridge. E3ME, started as a European model, is a global, macro-econometric model designed to address major economic and economy-environment policy challenges. Its econometric specification addresses concerns about conventional macroeconomic models and provides a strong empirical basis for analysis. It can fully assess both short and long-term impacts

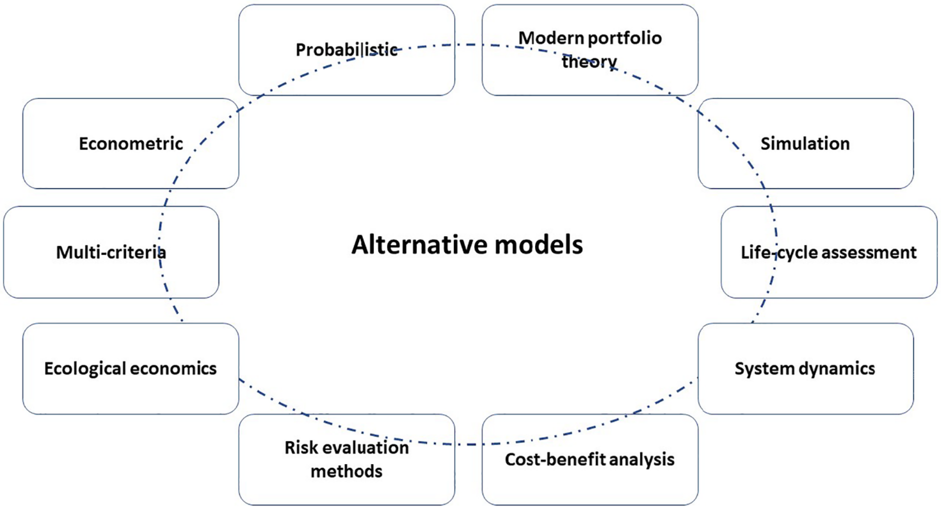

Fig. 4. Methodologies applied for developing models, classified in the category "alternative models".

and is not limited by many of the restrictive assumptions common to Computable General Equilibrium (CGE) models. MDM-E3 is a Multi-sectoral Dynamic Model of the UK economy, analysing changes in economic structure and assessing energy-environment-economy (E3) issues and other policies. Another econometric model is NEMESIS model, which is a macro-sectoral econometric model aimed at developing tools for decision making in the fields of energy, environment and economic policies.

Another sub-category is simulation models, which simulate the behaviour of energy producers and consumers in response to prices, income, and other signals. Their solution is more robust –usually in the short and medium term- than the optimization models, as they provide a logical representation of an energy/power system. The Long-range Energy Alternative and Planning (LEAP) is a bottom-up accounting model belonging to this category, as it allows its users to simulate the energy system, incorporating a set of available functions in the demand and supply side. Saeed et al. [93] provide an assessment of sustainability in energy of Iraq in the long-run, through the application of the LEAP model. Applying the LEAP model, Kumar [94] assesses the renewable energy potential in the energy mix in two Southeast Asian countries, i.e. Indonesia and Thailand. Tozzi and Jo [95] provide a comparative analysis of renewable energy simulation tools. Performance models simulate energy outputs with system configurations specified by the user, while optimization models can help plan appropriate system sizes to meet energy goals, such as maximizing carbon reduction or minimizing life-cycle system costs. The paper classifies RES tools into three groups: multi-scale RES tools, district level RES tools, including more detailed models, and regional level RES tools, including higher scale project tools that can be applied at a national level. RETScreen is a representative model from the multi-scale category sub-category, comparing a "baseline case", typically being the conventional technology or measure, to an alternative "proposed case", being the clean energy technology. HOMER, a representative tool from the district level tools sub-category, is used for designing and deploying microgrids and distributed power systems combining RES, electricity storage and fossil fuel-based generation. EnergyPLAN is a representative model of the regional level RES tools sub-category, simulating the operation of national energy systems on an hourly basis, including electricity, heating, cooling, industry, and transportation sectors. Using EnergyPLAN, Dominković et al. [96] present the transition pathways towards a 100% renewable energy system, to achieve a zero-carbon energy system by 2050. However, those RES simulation models are case specific, developed for a specific power system under specific circumstances, i.e. region, district, market participants. Moreover, they cannot easily be applied/adjusted to other energy/power systems.

Another sub-category is the multi-criteria models, where the evolution of an energy/power system include a wide set of measures/criteria, considering other criteria besides economic, as the optimization models do. Strantzali and Aravossis [97] provide a review of decision-making methods in renewable energy investments. The reviewed papers are classified by their year of publication, energy carrier type, decision -technique, criteria used, geographic distribution, and the application areas. It organizes papers in those that apply life cycle assessment (LCA), cost benefit analysis (CBA) and multicriteria decision aid (MCDA) methodologies. Cost benefit analysis is not considered as an optimization approach, as it comprises a systematic approach to compare alternative options, aiming to identify the most appropriate option through scenario analysis. Lund and Biwsas [98] review the application of life-cycle analysis for RES, aiming to assess their environmental performance for electricity generation. LCA method has considerable advantages, concerning the holistic environmental assessment of RES technologies, as it considers the entire life cycle of the product, namely extraction of raw materials, transformation, manufacturing, transportation, distribution, use, maintenance, recycling, re-use and final disposal. However, it provides an examination of a RES power generating technology, irrespective of the power system characteristics and the other GEP problem characteristics. Kaldellis et al. [99] conduct a cost benefit analysis of a hybrid photovoltaics and electricity storage solution for remote islands, while Kennedy [100] provide a cost benefit analysis on the construction of a new nuclear power generation in the UK. However, CBA is a restricted method concerning the GEP problem, as it only monetizes aspects such as capital, maintenance and operation costs of the examined RES technology.

The rapid penetration of multi-criteria methodology on examining the integration of RES is revealed in a paper by Huang et al. [101], which provides a review of decision analysis in energy and environmental modelling. An update of this review [102] shows that relevant research papers have almost tripled within a decade. The paper concludes that, given the shift of problems from energy issues to energy-related environmental issues, decision analysis methods, particularly Multiple Attribute Utility Theory (MAUT), Analytic Hierarchy Orocess (AHP) and the outranking methods, are likely to play a considerable role in energy and environmental modelling problems in the future. The multi-criteria approach is a very popular method for environmental and energy policy decision-making, leading to a rapidly growing number of multi-criteria studies over the last years. Examples are the application of an AHP approach for maintenance strategy selection in hydroelectric power plants in Turkey by Özcan et al. [103], of a multi-criteria optimization analysis for Jordan's energy mix by Malkawi et al. [104], of a multi-criteria analysis of policy options for hydropower surplus utilization in Paraguay by Blanco et al. [105] and of an optimal diversity of renewable energy alternatives in the UK under multiple criteria by Shmelev and van den Bergh [106]. Multi-criteria methods can present supportive tools in policy and decision-making process, ranking the alternative options. Applying multi-criteria decision making (MCDM) methods in energy planning problems, enables handling complex issues with low requirements, but as well their applications to power systems with poor data, such as those of the developing countries. Therefore, it provides a "top-down" simplified approach to tackle the penetration of RES in the GEP problem. However, MCDM is not historically widely used by system operators, concerning the GEP problem, as it does not capture in detail technical and operational aspects of the power system.

Another mathematical modeling technique to tackle integration of RES into GEP is System Dynamics (SD) approach, which contributes to understanding the nonlinear behaviour of complex systems. A recent paper [107] provides a review of applications of the SD approach in Renewable Energy Supply Chain (RESC), identifying the need for further research papers, as the literature is rather scarce. Mutingi et al. [108] present a taxonomic analysis of SD approaches to energy policy modelling and simulation, while Gravelsins et al. [109] explore how SD Modelling (SDM) approach could be used in modelling the energy transition towards low carbon energy system, by combining the techno-economic and socio-technical analysis. Mutingi et al. [110] examine SD archetypes for capacity management of energy systems, identifying two archetypes based on causal loop analysis: (i) limit to growth, and (ii) growth and underinvestment.

Other methodologies, such as the Modern Portfolio Theory (MPT) tackle energy planning as an investment selection problem. DeLlano-Paz et al. [111] provide a review on energy planning and modern portfolio theory. The portfolio approach is based on minimizing either the cost or the risk of the portfolio, subject to different constraints as well as considering the economic risk arising from each alternative technology. MPT is characterized as having a wider capacity and conceptual richness, compared to the other methodologies, such as the individual least cost alternative. However, MPT models are not classified as optimization models, as MPT does not determine an optimum GEP pathway but the efficient cost-risk frontier. The paper concludes that "*the application of modern portfolio theory (MPT) to energy planning has been widely accepted and confirmed by numerous studies. However, its limitations in terms of the different nature of the assets analyzed (financial vs. real) are accepted by the authors. The contributions of the studies have* *attempted to improve their adaptation to the field of energy through demand-side models and simulation techniques. Likewise, the inclusion of externality costs and portfolio emission factors favor the correct characterization of the technologies in the models and approaches with a social dimension. The studies generally consider that the inclusion of RES technologies favor the reduction of the portfolio risk.*" [112].

The consideration of the variable RES nature, as well as other risks, is very important in the decision-making process on the RES investments. Ioannou et al. [112] provide a review of the risk-based methods, used for sustainable energy system planning. Initially, it identifies several aspects of risk in the renewable energy investment sector: political, social, technology, economic, legal and environmental. Consequently, it classifies the methodologies in two generic categories: quantitative and semi-quantitative. Quantitative risk-based evaluation methods, such as Mean-variance portfolio (MVP) theory, Real options analysis (ROA), stochastic optimization methods and Monte Carlo Simulation (MCS) deal with statistical risk factors. Semi-quantitative methods, such as MCDA and scenario analysis, take into consideration both statistical and non-statistical risks. Those approaches aim to capture the probabilistic nature of RES, as well as other randomly-evolved factors. They can be considered as alternative -to optimization and equilibrium- methodologies, as their focus is a more probabilistic representation of RES technologies and their investment decision making, being closer to the real nature of RES and real problems of their integration. However, some of those approaches, such as the Monte Carlo simulations, are very popular risk assessment options integrated within the optimization models. Santen and Anadon [113] provide a comprehensive framework for managing technological innovation uncertainty, concerning the GEP investment planning. The paper develops a bottom-up stochastic GEP model, incorporating uncertain endogenous research and development-based technical change, with focus on solar photovoltaics deployment. Nowak et al. [114] present a probabilistic model for assessing the risk related to the implementation of national RES targets. The model is applied in case of the UK [115], concluding with recommendations for further issues that are crucial to be incorporated in the model to enhance its robustness. Careri et al. [116] study the impacts of incentive mechanisms, i.e., quota obligation, feed-in tariffs, emission trade and carbon tax on GEP towards supporting the enhanced power generation from RES. A scenario analysis approach is used by Promjiraprawat and Limmeechokchai [117] to assess Thailand's energy policies and CO_2 emissions, focusing on the penetration of RES and the application of energy efficiency measures. Saiah and Stambouli [118] provide a prospective scenario analysis for the long-term energy mix planning in Algeria, towards supporting RES penetration and enhancing energy security.

Finally, this category includes models adopting ecological economics theoretical considerations. It is important to highlight the difference among ecological and environmental economics, as the first school of economic thought emphasizes on sustainability and preservation of natural capital, rejecting the environmental economics' assumption that natural capital can be substituted by human-made capital. The first school of thought adopts mainly policies regulating or banning the use of natural resources, while the latter school of thought mainly focuses on policies that endogenize the environmental cost in the economic and energy system. Ecological economics focus on issues related to nature, justice and time, concerning the use of natural energy resources. They raise the importance of ethical values such as irreversibility of environmental changes and inter-generational equity. Their focus is on criticizing/off-setting the capability of some models to tackle sustainable development issues, such as the cost benefit analysis and the cost-optimization methods. However, those approaches have also started developing mathematical methodologies, aiming to provide comprehensive evidence on those important arguments. Mathematical models are therefore used in ecological economic analysis, including various methodologies and techniques [119,120], such as models adopting evolutionary, physical and biological principles [121] or linkages among biodiversity and the environmental Kuznets curve [122], besides multi-criteria and agent-based modelling techniques described above. To sup up, there are an extensive number of sub-methodologies belonging in this alternative models' category, based on their common characteristic of non-biased and non-myopic nature. Deviating from optimum-restricted theoretical considerations, they have higher flexibility. Those models are also simplified and easy to use, but usually applied to national/regional or technology-restricted applications, not capturing interactions with the whole energy system and the economy. Moreover, they are less robust, as they do not take into consideration technical characteristics of the power system in detail.

The "alternative models" category is rapidly expanding its applications besides the criticism it faces for the simplified representation of the power system. A major reason for this is the capability of linking/integrating different model types. Multi-criteria methods are very popular, based also on their capability to be linked with other model types, therefore offsetting the criticism on the problem formulation. Using outputs from more comprehensive and detailed approaches, such as simulation/energy system models enable a more robust quantification on weighting the importance of each factor. Probabilistic models are also very flexible in being incorporated in other methodologies, such as energy system and econometric models aiming to capture crucial uncertainties of the energy system. Cost-benefit analysis and LCA methodology can also offset their case-specific approach, through broadening its applications by being incorporated/linked with investment selection problems, such as those tackled by MPT methodology of risk evaluation models. Econometric approaches challenge their history dependent forecasting credibility, through linkage/comparison with simulation models or models using artificial intelligence such as neural networks and genetic algorithms. System Dynamics (SD) approach can be better used and explained should they consider the detailed representation offered by energy system models. Ecological economics' methodologies, besides its different approach in evaluating natural resources, including RES, can provide outputs to other model types towards complementary representation of sustainable development.

5. Comparison of different models

This section provides a comparison among the different models' categories. The optimization models' category stands as the dominant one, as the majority of GEP models belong in this category. This fact is not deriving from its superiority compared to other categories, but mainly by the modellers' needs and capabilities. The applications of other approaches, such as the multi-criteria and life cycle assessment approaches belonging in the third category, are also popular as they are simplified and convenient to use. Researchers are usually developing GEP models at a national and/or regional level, due to their better understanding and access in more information on those power systems. Moreover, energy policies, such as those related to the penetration of RES, are usually applied at national and regional level, creating need for locally-focused research. Therefore, although there also exists evolution of global models, such as the general equilibrium models, for the examination of international treaties, such as the Kyoto protocol and the Paris agreement, it is usually easier to develop a robust and detailed optimization model or a multi-criteria model at a national level. The development of the model at national level is a challenging task. However, it has some advantages such as: the availability/access to data, the understanding of national energy system in detail by modellers, the need for addressing policies at national level and the availability of relevant funding by national sources.

The optimization models are based on the minimization/maximization of an objective function, while the equilibrium models adopt the general equilibrium theory [9]. The alternative models' category is a more "generic" category, incorporating models not adopting optimum integration of RES in the GEP, but consider probabilistic, simplified and other approaches to analyze the power system. The integration of RES in both optimization and equilibrium models is optimum, based on techno-economic and environmental characteristics of the power system or on the substitution elasticity with other energy carriers and generation technologies respectively.

GEP incorporates several uncertainties, which are further enhanced and multiplied by the integration of RES. Table 1 provides the risk/uncertainty components in the GEP problem, organizing them in four generic categories: socio-economic, policy/regulation, technical/operational, and climate/environmental uncertainties. RES-related uncertainties are evident in all these categories of uncertainties, as the integration of RES affects directly or indirectly several risk aspects of the GEP problem. All categories of models incorporate the capability to conduct risk assessment, aiming to capture some of those uncertainties, while most of them focusing on the variability of RES. All categories of models tackle climate/environmental aspects as they are strongly related to the integration of RES in the GEP, but depending on the nature and the level of detail of the model, different aspects of uncertainty are tackled, i.e. optimization model focus more on technical/operational uncertainties, general equilibrium models focus more on socio-economic risks, while alternative models focus more on policy/regulatory aspects. The techniques for quantifying the risk in the GEP problem include mainly scenario, sensitivity and Monte Carlo analysis. Alternative models, which in several cases already inherit probabilistic approaches, can conduct Monte Carlo, sensitivity and scenario analyses. Optimization models tackle their "optimum" myopic behavior, by incorporating all the above-mentioned risk assessment models to provide not just a single optimum solution, but also a distribution of solutions concerning the capacity and power mix of RES technologies. The new generation of general equilibrium models is dynamic and stochastic, enabling also undertaking risk assessment, offsetting in some extent their initial static and myopic nature. The perfect foresight and myopic nature of optimization and equilibrium models, although considered as a disadvantage, has also strengths, especially related to providing optimum solutions, that could be used as benchmark outputs.

All models have considerable advantages and disadvantages. Optimization models are considered as robust models, incorporating in detail the techno-economic characteristics of the power system. The term robust for the characterization of the models concerns their capability to provide technically robust solutions. Optimization models that incorporate technical/operational characteristics provide solutions that are technically realistic, while less technical models provide solutions that might not be realistic i.e. from the perspective of a power system operator. However, optimization models are considered myopic, due to their "optimum" nature with no or limited interaction with the whole economy. The latter is tackled by developing hybrid modelling approaches, coupling optimization or energy systems with macro-economic models. Optimization models are also applied at national/regional level due to the level of detail and the needs of researchers/decision makers to examine national/regional policies.

General and partial equilibrium models have faced considerable critique over the last years, resulting mainly from the global 2008 economic crisis and the climate change. However, they have considerable advantages, such as the representation of the global energy system, as well as its interaction with the global economy. The incorporation of environmental and socio-economic considerations enables the examination of intersectoral or interregional policies, while the evolution of the new generation of dynamic and stochastic general equilibrium models enables the capture of critical uncertainties. On the other hand, their "equilibrium" nature leads to a myopic behavior, as in case of the optimization models. Moreover, the top-down representation of the power system is simplified, as there is no consideration, or at least no detailed consideration, of the technical characteristics in case of general or partial equilibrium models, respectively. This leads the results to be "sensitive" on the magnitude of substitution elasticity, which represents the comparative penetration capability of the different technologies. The rational agents, within Computable General Equilibrium (CGE) models, imply that markets lack uncertainty, imperfect knowledge or innovation. However, some of those elements are being (partially) tackled by the new generation of CGE models.

The alternative models' category represents different sub-methodologies, so each approach has different advantages and disadvantages. The common advantage of this category is its non-biased and non-myopic nature, deviating from the "optimum" nature of the other categories. Moreover, with few exceptions, they are more simplified, making them easier to use, which leads to a considerable number of applications. However, those applications are national/regional and/or RES technology oriented, lacking the capability for more holistic representation of the power and the economic system. Finally, the consideration of non-rational and more realistic representation of economic agents in several models enables a higher research flexibility, compared to the other optimum-restricted models. Table 2 provides the basic characteristics of the different categories of models applied for the integration of RES in the GEP problem, as well as their advantages and disadvantages.

Table 1
Generic risk categories in the GEP problem.

Socio-economic	Policy/regulatory
✓ (RES) technologies generating costs (capital, financial, operational and maintenance)	✓ Renewables energy targets
✓ Fuel prices and carbon prices evolution	✓ Renewable supporting schemes
✓ Demand and consumption pattern evolution	✓ Taxation regime
✓ Demand-side, storage and electric vehicles costs	✓ National energy and industrial policies
✓ Electricity prices' variability and affordability	✓ International climate agreements
✓ Social acceptance, behavioral shift	✓ Energy security, access to energy resources
✓ Public health and other externalities	✓ Electricity and carbon markets design
	✓ Environmental regulation
	✓ Competition regulation
	✓ Bureaucracy problems
Technical/operational	*Climate/environmental*
✓ Integration of different technologies (renewables, storage, demand response, electric vehicles)	✓ Renewables availability
✓ Learning rate evolution for (renewable) energy technologies	✓ Renewables variability
✓ Flexibility, ancillary services, ramping capacity and reliability needs	✓ Renewables and emissions reduction targets
✓ Ageing infrastructure, outages	✓ Water inflows/management
✓ Renewables and grid curtailment	✓ Rainfalls and precipitation issues
✓ Increasing interdependence with other energy sectors (transmission, gas system)	✓ Climate change, embodied energy and life-cycle assessment
	✓ Extreme climatic events
	✓ Nuclear and carbon concerns
	✓ Natural disasters

Table 2
Comparison of the different categories of models, applied for the integration of RES in the GEP.

	Optimization models	General/partial equilibrium models	Alternative models
Basic theoretical assumption	Minimization/maximization of an objective function	General equilibrium theory	Probabilistic or simplified simulation of energy system
Integration of RES	Optimum integration based on techno-economic and environmental characteristics of the power system	Optimum integration based on substitution elasticity with other energy carriers and generation technologies	Non-optimum integration, based on probabilistic, life cycle, Cost-benefit, Multi-criteria and financial analysis
Risk assessment	Besides RES variability, they mainly focus on technical/operational aspects using Monte Carlo analysis, Scenario analysis, and Sensitivity analysis	Besides RES variability, they mainly focus on socio-economic aspects using Scenario analysis and Sensitivity analysis	Besides RES variability, they mainly focus on policy/regulatory aspects using Monte Carlo analysis, Scenario analysis, and Sensitivity analysis
Advantages	Technically robust, consideration of detailed technical characteristics	Global, interactions with the economy, environmental and socio-economic considerations, capable of examining intersectoral policies, new generation of models are dynamic and stochastic	Non-biased and non-myopic, simplified, easy to use & be linked with other models, flexibility due to non-rational and more realistic representation of economic agents
Disadvantages	Myopic, national/regional applications, no interaction with the whole economy	Equilibrium, myopic, results “sensitive” on an elasticity figure, markets lack uncertainty, imperfect knowledge or innovation, no (detailed) consideration of technical characteristics	Simplified, less technically robust, no consideration of technical characteristics and interactions with the whole economy

From Table 2, it can be derived that all models have considerable advantages and disadvantages. We can also derive some generic conclusions on their suitability. Optimizations models are more suitable for consideration of technical and operational aspects of the integration of RES in the GEP problem; therefore, they are more useful when employed by entities such as energy system operators. Equilibrium models are more appropriate for consideration of Economy-Energy- Environment (E3) interactions at an international level; therefore, they comprise a proper option for institutions such as international energy agencies or energy departments of big countries/unions. Alternative models are ideal for fast assessing the financial and environmental performance of RES investments, therefore they can satisfy the requirements of entities such as regulatory authorities and banking institutions at national/regional level. Optimization and equilibrium models have the disadvantage of their optimum myopic nature; however, their outputs can be utilized as benchmark outputs, while the alternative models are more simplified and less technically robust approaches. The existence of considerable advantages and disadvantages for all models, as reported in Table 2, lead us to recommend the use of different and supplementary methodological approaches. This enables the elimination of the impact of the inherited bias in each applied methodology in the outcomes, as well as the development of integrated and holistic approaches tailored to each specific problem.

5.1. Need for integrated approaches to tackle sustainability issues

The review analysis that has been undertaken reveals that the RES integration in the GEP is a complex task with several aspects, leading to the development of relevant models to focus on some of those aspects. It highlights also the importance for integrated approaches in order to examine interlinkages among the economic, energy and environmental systems, as the RES does not contribute just do a change in the capacity and generation mix in the power system but is an important pillar of the sustainable development of the whole economy. Economic and power systems should not be tackled as closed systems, but as modules/components of integrated approaches that endogenize the external environmental cost from the energy technologies and the energy-using sectors. This approach is popular in the alternative modellers' group, as mentioned in the previous section.

A common element of all approaches is that they recognize sustainable development as a priority for our human or nature-based economic system and society. The integration of RES in the GEP, as well as the general transition to sustainable low or zero carbon societies, can be met through several policies/strategies, which also contribute to broader environmental targets. The main policies usually applied by countries towards the promotion of RES in their power system and the sustainable development of their economy are:

- Introducing maximum limits on environmental pollution, supplemented with emission trading systems (cap and trade system). This framework partially covers the lack of ownership rights in environmental resources.
- Adopting green taxation (e.g. environmental/energy taxes or carbon tax), which strengthens the competitiveness of cleaner forms of energy.
- Adopting green legislation (e.g. Kyoto protocol, Montreal protocol, green and white certificates, energy certificates, energy labelling on devices, prohibition of technologies, etc), which strengthens the competitiveness of new technologies and prohibits the use of energy carriers/technologies.
- Adopting Green incentives (e.g. grants, research and development funding, feed in tariff system, transfer of technology/know-how in developing countries, tax exemptions, etc), which strengthens the competitiveness of new clean technologies.

Those policies, or combinations among them, are the usual practices/measures adopted by countries towards the promotion of renewables in their energy mix, the enhancement of energy security and the sustainable development of their economy. Those policies are strongly related the progress in the development of new RES and other technologies or the rapid reduction of their cost, which is usually a result of the combined effect from learning by research and learning by doing. The outcome is that RES are now considered as competitive options, having low levelized cost of energy, providing considerable benefits for the final consumers. Moreover, the integration of RES with other technologies such as demand-response, electricity storage and electric vehicles, enables the considerable improvement of public health and of elimination of environmental degradation, leading to a sustainable society.

6. Conclusions

The penetration of RES in the GEP is a crucial factor towards tackling critical challenges of the power systems, namely the decarbonization of the economy, the enhancement of climate change mitigation and energy security. GEP is a complex task, as it combines different aspects: techno-economic, financial, policy/regulatory, spatial and environmental. Several models are developed to model GEP, including the integration of RES, applying different methodological approaches. The adopted methodology is important as it affects the results, conclusions and policy recommendations. The paper aims to provide a review of the models employed to integrate RES in the GEP, classifying them in three generic categories based on their generic methodological framework: optimization models, general/partial equilibrium models and alternative models. It provides insights on the characteristics, advantages and disadvantages of the theoretical approaches implemented, as well on their suitability for different aspects of the problem.

The dominant category is that of the optimization models, which aim at the minimization/maximization of an objective function, by applying different methods such as non-linear programming, mixed integer programming, dynamic programming, bilevel programming and decomposition techniques for modelling the GEP problem. RES integration into GEP is based on their competitiveness compared to other options, considering the technical, economic and environmental characteristics of the power system. Computable general or partial equilibrium models, adopting the general equilibrium theory, are -in general principle- also considered as optimization models, as they incorporate a cost-minimizing behaviour by representative agents. However, equilibrium models usually deviate from that principle to simulate actual economic and energy systems. RES technologies are penetrating in the energy mix based on their competitiveness compared to conventional technologies, considering any environmental/social policy applied. Alternative models are a generic category incorporating models not adopting the optimum integration of RES, but consider probabilistic, multi-criteria, simplified and other approaches to analyze the power system. Those models aim to model power systems in a simplified but more realistic manner, compared to the myopic behaviour of optimization models.

Perfect foresight of optimization and equilibrium models, although theoretically is considered as a disadvantage, is very useful as optimum planning scenarios could be used as benchmark scenarios. Moreover, models have been dynamically evolved over years, incorporating methodological elements and assumptions to tackle their disadvantages. Optimization models and energy systems models try to offset their myopic nature by introducing stochastic modelling, restricted foresight time-period, time-dependent discounting and flexible planning elements. Those developments might challenge the methodological boundaries among different models. However, we argue that the classification proposed is meaningful and useful, as it concerns the original nature of the models, accompanied with generic characteristics and (dis)advantages. Those characteristics and/or developments that aim to improve deficiencies should be aware by model users/developers, as it enables better interpretation of forecasting outputs.

All categories of models incorporate the capability to conduct risk assessment, usually through Monte Carlo, sensitivity and scenario analysis, aiming to capture some of the numerous uncertainties reported in the paper. The vast majority of models focus on elaborating the variable nature of RES. Depending on the methodological nature and the level of detail of the model, different aspects of uncertainty are tackled, i.e. optimization models focus more on technical/operational uncertainties, general equilibrium models focus more on socio-economic risks, while alternative models focus more on policy/regulatory aspects.

All models have considerable advantages and disadvantages. The aim of the paper is not to identify which is the superior model, but to classify models identifying their basic characteristics and differences. Optimization models are considered as robust models, as they incorporate in detail the techno-economic characteristics of the power system. They are usually applied at national/regional level due to the level of detail and the needs of researchers/decision makers to examine national/regional policies. Those models are commonly used by system operators and national regulators to form national energy regulation. General/partial equilibrium models have considerable advantages, such as the representation of the global Economy-Energy-Environment (E3) systems, which enables the examination of intersectoral and interregional policies. They provide insights on the carbon pathways towards the decarbonization of the power sector and the transition to low carbon economies. Their “equilibrium” myopic nature is partially tackled in the new generation of dynamic and stochastic general equilibrium models. However, the top-down representation of the power system is simplified, not considering detailed technical characteristics, leading results to be “sensitive” on an elasticity value, which represents the substitution elasticity among the different technologies and energy carriers. Those models are commonly used by international institutions, ministerial departments and national regulators to form regional/national energy and climate policy. The common advantage of the alternative models’ category is its non-biased and non-myopic nature, deviating from the “optimum” nature of the other two categories. However, those models are usually more simplified, making them easier to use, which leads to big number of applications. The simplified representation of the power system, omitting considerable amount of information and detail, leads to less robust models. Those models are commonly used by banking institutions to assess energy projects. However, the consideration of non-rational and more realistic representation of economic agents in several models enables a higher research flexibility. This flexibility, as mentioned above, is incorporated in other models’ categories to enhance their robustness and to offset their drawbacks.

The paper contributes in the better understanding on the expected outcomes of each models’ category. Each model and its outputs should be tackled, considering the underlying theory, as well as the level of detail of the technical, economic and environmental characteristics of the power systems they incorporate. Model results should not be taken as granted, but should always be seen from a critical perspective, as there are cases where even a negligible cost advantage of a technology or an energy carrier can affect considerably the capacity and power mix. The economic and energy systems should not be considered as closed systems, as they are strongly interconnected with the environment, where the integration of RES in the GEP is part of the overall process towards the transition to a sustainable society, preserving the natural capital. Several policies are available for decision makers towards this procedure, considering the rapid developments in the RES and other technologies. The integration of RES with other technologies such as demand-response, electricity storage and electric vehicles, enables the considerable improvement of public health and of elimination of environmental degradation, leading to a sustainable society.

The paper identifies the characteristics of each category, but it also highlights the needs for integrated approaches, to strengthen the robustness of the applied methodological framework. Energy system expansion is a complex task that should encompass the strengths of different approaches. The rapid technological developments in renewables but also in other technologies, such as electric vehicles and storage, as well as the evolution of smart energy systems, through the implementation of internet of things that enable active demand participation and peer to peer trading via blockchain technology, enquiry the consideration of operational aspects in long-term energy planning. The societal needs, as depicted through enhanced environmental awareness and demand for jobs creation, should incorporate input-output elements in the analysis, in order to capture the added value of renewables in local communities. Renewables penetration in the energy and capacity mix should also capture the dynamic evolution of final consumers to active prosumers that follow market developments. Those needs can be tackled through integrated approaches, that pave the way for further research in this challenging issue. Moreover, resent development in economic theory, related to the challenging of neoclassical economics and the evolution of alternative economic thinking, such as behavioral economics and institutional economics, create research challenges for the energy system as well. The incorporation of elements, that tackle technological developments and market participants as representative agents with bounded -and not optimum- rationality, is expected to improve the forecasting capability of models.

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