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Tsani Stella, Kozlova Mariia

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Energy modelling for sustainable policy making: State of the art and future challenges

Stella Tsani[1,*] Mariia Kozlova[2]

[1] Department of Economics, University of Ioannina, Ioannina, Greece

[2] School of Business and Management, Lappeenranta – Lahti University of Technology LUT

[*] Corresponding author, University of Ioannina, 451 10, Greece stellatsani@uoi.gr

Abstract

Green energy and sustainability transition pose new challenges and questions for policy making. Uncertainties with regards to future uninterrupted and affordable access to energy, sectoral and technology developments, demand, supply and behavioral aspects, to name a few, drive methodological developments in the energy modelling sphere. The development of energy models and design alternatives allow scientists, and through expert analysis policy makers, to assess current and future developments, to examine alternative technology, policy and socio-economic development paths of the future and to lay ground for optimal policy options for current and future energy systems and markets. This chapter discusses the recent developments in energy modelling and the necessity to come with new methodological approaches to address pressing issues of policy relevance. Some popular models that have provided useful insights for policy design and future directions of interest are examined. This is undertaken keeping in mind the historic perspectives of energy modelling that indicate the omnipresent influence of policy needs on the methodological developments in energy modeling. Current policy needs and methods indicate the potential usefulness, possibility and relevance of bridging behavioral characteristics to sectoral, economy, energy and environmental models.

Keywords: Energy modelling, energy policy, energy transition, real option, energy-economy-environment

Introduction

Energy remains important for all modern economic activities, for socio-economic development and for human wellbeing. Access to energy sources, to energy markets and transit routes have shaped economies and societies for many decades. Abundance of energy sources has been an input to growth for countries like the USA, Canada and Norway. For other countries security of energy supply has been a constant issue of concern in the policy agendas and a major driver of socio-economic and technological changes (see for instance developments in the European Union, European attempts to diversify away from its energy suppliers, i.e. Russia and Middle East, and the European green energy agenda as a stimulus to European research and development). Technological progress in the energy system has enabled front-runners to benefit from first-mover advantages and dominant market positions, for conventional and/or renewable energy alike. Energy markets, both in terms of demand and supply developments, are subject to high volatility and unpredictability. Sources of uncertain developments are related to the availability of inputs to energy production, technological progress, socio-economic developments, and geopolitical tensions.

In the presence of such uncertainties and given the importance of uninterrupted and affordable access to energy, energy policy has been always faced with the need to grasp the trends and the developments lying ahead and to have valid visions of alternative energy futures. This need has driven the development of a diverse set of energy modelling methods and tools since the second half of the twentieth century. The development of energy models and design alternatives allow scientists, and through expert analysis policy makers, to assess current and future developments, to examine alternative technology, policy and socio-economic development paths of the future and to lay ground for optimal policy options for current and future energy systems and markets. The development of energy models in the scientific domain has been driven by the main policy challenges and questions to be addressed at different periods in time. The progress and abundance of works in energy modelling has also been supported by advancements in other scientific fields (e.g. IT, economics, finance), which have supported the deployment of alternative modelling approaches (e.g. computational modelling) and scope (e.g. micro-, fuel-, technology- level and/or macro-level).

In the era of the first and the second oil price shocks policy questions where related mainly to the security of supply, price developments of oil and their impact on the sectoral and economic outlook of the countries and regions in the world (Rath-Nagel and Voss, 1981). In times of high price volatility in the energy markets, policy concerns where mainly focused on the impact of price changes in the macro- and the micro-economy and the potential of energy supply diversification of sources. As the environmental impact of energy production and of the use of conventional sources has been identified, and the calls for shifts to more environmentally friendly energy sources are intensifying, policy making and the energy sector are concerned with questions of optimal renewables share in the input mix to energy production, socio-economic cost-benefit analysis of alternative energy production technologies and fuels, sectoral, macroeconomic and environmental effects of shifts to new energy technologies.

Both policy making and scientific analysis have come to realize that the energy sector cannot be studied in isolation. The interconnections between the energy sector and the rest of the economy have been identified and mapped since the very early energy modelling exercises. As energy modelling evolves over time the explicit reference to the energy-economy-environment relationships becomes even more prominent and accepted as a standard practice. Approaches in modelling the energy-economy interaction have been developed with the utilization of two distinct approaches. The first, consists of a bottom-up approach where rich technological characterization of the energy system plays a key role. In the other end stand top-down approaches where the focus lies on the macro-economic representation of the energy system interactions with the rest of the economy. In these distinct approaches, energy-economy interactions with the environment have been introduced through environmental analysis and use of appropriate environmental variables to account for the links between human activity and the environment.

Following landmark global and regional actions to address climate change (e.g. Kyoto Protocol, Paris Agreement, European Green Deal), energy transition and shift to green energy has accelerated (particularly in Europe) and is being embraced even in countries (see for instance China's pledge in 2020 to be carbon neutral by 2060) and regions (e.g. oil-rich Gulf countries like Saudi Arabia investing in renewable energy projects domestically and abroad) that have been resistant to agree on actions at various scales (whether global and/or regional). Economies and societies have entered a new technological revolution era, with green energy technologies developing fast with ever decreasing production costs. The development of these technologies will inevitably transform the energy sector at an unprecedented level. At the same time such development introduces significant uncertainty and poses several challenging questions for policy making related to energy.

The questions are related to the optimal renewable energy mix for energy production, socio-economic and employment effects of alternative energy forms (at sectoral level, regional and global level), competitiveness impacts of green energy transition (i.e. optimal timing of phasing out traditional energy sources and introducing new energy forms in the energy mix). As the economies enter this new technological and energy systems race, consumer attitude and investors' preferences and decisions will play a crucial role in the future developments. Questions related to investors' attitude and decision making under uncertainty, to the effects of retroactive policy changes and technology learning emerge as of primary importance for energy modelling and energy policy making at the present and in the near future.

Such behavioral aspects and changes cannot be captured adequately by the energy-economy models developed so far, as no possibility like that is inbuilt in their design. Methodological and conceptual developments to address these limitations look at the usefulness of real options models. Real option models, developed first in the financial domain, are often criticized on the grounds of being limited to a single investor's perspective and failing to capture market-level phenomena. These symmetrical drawbacks of energy-economy models, which fail to capture so far micro- behavioral characteristics, and real option analysis that are limited to the microeconomic perspective, indicate potential benefits from merging the two modeling approaches and their comparative advantages. This can lead to the delivery of integrated energy-economy-environment models that adequately represent the macro- and the micro- economic aspects of relevance to energy systems and policy making.

Hourcade et al. (2006) define an ideal energy-economy model as the one addressing three key dimensions: Technological explicitness, Macroeconomic completeness, and Microeconomic realism. Keeping this definition in mind this chapter discusses the recent developments in energy modelling and the necessity to come with new methodological approaches to addressing pressing current issues of policy relevance. Some popular models that have provided useful insights for policy design and future directions of interest are examined. This is undertaken keeping in mind the historic perspectives of energy modelling that indicate the omnipresent influence of policy needs on the methodological developments in energy modeling. Current policy needs and methods indicate the potential usefulness, possibility and relevance of bridging microeconomic/behavioral effects to sector/economy-energy models.

The remainder of the chapter develops as follows: Section two reviews from a historical perspective the impact of policy needs on energy modelling developments. Section three discusses the theoretical background of the conventional modeling frameworks and possible merging real options behavioral finesse with the width of energy-economy models in the context of renewable energy policy analysis. Last section concludes with useful insights on the policy priority questions that methodological merging should address.

Policy drivers in energy modelling

Energy modelling dates back in the 1970's and the first oil crisis. While until then the need for an integrated assessment of the energy future was understood, it was only after the first energy and economic shock that this necessity became an urgency (Rath-Nagel and Voss, 1981). While policy proactive stance to future developments has been a main concern and impetus to developing energy models, several other policy relevant reasons have also impacted overtime on the development of the energy models. Energy models of the 1960s and 1970s focused mainly on the single fuel markets and sectors (e.g. demand and supply for oil or electricity) and where addressing mainly policy issues of optimal allocation and transport alternatives (Deam et al., 1973). At the same time have also been developed models looking at the supply side focused many on the optimal supply planning to address demand needs, which has been in large treated as an exogenous variable to the models. These models have been developed with focus mainly on sole sectors and fuels. What has been early understood for these single-sided models was the inability to capture the complex relationships between the single sector and fuel source to the rest of the economy. Isolation from the energy and the economy system ignored in large the interaction playing role in the macro-economic environment but also the ability to substitute fuels or optimize the energy supply with the utilization of alternative energy technologies and sources. Also, it became apparent that any single sector and fuel approach neglects in large the substitution that may result from price, technology and preference changes. These are particularly important if current energy developments related to environmental considerations are taken into account.

In historical perspectives, this recognition of the necessity to look for the wider macroeconomic and inter- and intra-sectoral links led to the development of energy system models that introduced for the first-time multi-sector and multi-fuel simultaneous demand and supply analysis (e.g. Hoffman, 1973; Agnew et al., 1979). In terms of assistance to policy making the system approach to the energy sector was important as it allowed for the first time to consider the integrated relationships between the energy sector with the rest of the economy but also to account for the dynamic changes taking place over time. In an energy-system approach the dynamic changes are taken into consideration and policy making can be based on evidence coming from "closer-to-reality" simplified models of energy-economy (Rath-Nagel and Voss, 1981). The integrated approach to energy systems introduced for the first time in the energy modelling work the need to focus on the technological features of the different fuels and energy production options. The issue of technological state and progress, and how this related to policy making, has been critical for the development of the energy models. Moving beyond linking the energy sector to the economy, technological modeling is important both in methodological but also in empirical terms.

In terms of methodology and climate change study, modelling of technological change remains important for policy analysis (Gillingham et al., 2007). While early approaches have treated technological change as exogenous, recent approaches have aimed for the endogenous representation of technological change (Karkatsoulis et al., 2016). Endogenous technological change implies the incorporation of feedback mechanism that captures the policy impact on the direction and potentially the level of technological change. As Karkatsoulis et al (2016) note, studies mostly use R&D-induced and learning-induced technological change. In the first case, innovation is treated as the result of explicit investment in R&D where pathways include a stock of knowledge and a flow of R&D investment into that stock of knowledge. The stock of knowledge directly and/or indirectly affects technological change and knowledge is treated as rival or non-rival and appropriable or non-excludable good. Endogenous technological change induced by R&D builds on the work of Kamien and Schwartz (1968), Binswanger and Ruttan (1978), Aghion and Howitt (1998) and Romer, (1990). Knowledge generates free spillovers to other firms, that are the primary driver of economic growth (Clarke and Weyant, 2002; Jaffe et al., 2005). Following the endogenous growth theory, common approaches to endogenous technological change include a knowledge stock directly in the economy-wide production function (Kakrkatsoulis et al., 2016).

The recent waves of energy-economy-environment modelling have been facilitated by the improvements and innovations in other related fields of research like economics and econometrics, statistics, IT, and operations research. Nevertheless, the improvement of the energy models and the development of new integrated tools is not an end goal per se. It is rather the challenging policy and sectoral development decisions that need to be taken for sectoral and macroeconomic development that the model construction and progress should address. Societies, economies and policy makers have long been concerned with the energy security, cost of energy production and sectoral forecasts as energy inputs are core to the social wellbeing and economic activities. While the progress to date with energy models has looked mainly at the sectoral and economy interaction, recent global initiatives in support of green energy deployment and sustainability transition, and scientific calls which urge for the need to take action and transform the energy system (see for instance the IPCC 2018 report on limiting global warming to 1.5 degrees Celsius), call for new directions in energy modelling. These new directions should go beyond single fuel, single sector or merely energy economy interactions. New modelling developments need to consider the environmental dimension of energy, uncertainty with regards to alternative energy inputs, technology innovation and investment returns and socio-economic and environmental sustainability. Of particular importance for policy making remains the adequate modelling of behavioral aspects of green energy. This include investors' attitude to green technologies, uncertainty with regards to decarbonization efforts and targets, consumers acceptance of new energy forms, transport routes, and energy communities, rise of prosumers and relevant economic analysis, and response to different policy tools that are used for the green energy deployment (e.g. subsidies, taxation).

State of the art in energy modelling

The literature on energy modelling offers a plethora of reviews and classification approaches (for a recent comprehensive review see Müller et al. 2018, and Herbs et al., 2020). A non-exhaustive summary of reviews of energy-economy models is presented in Table 21. In general terms classification looks at the sectoral level of detail and technology representation and distinction is made between: i) technology-rich bottom up models, where the level of detail of the energy sector and the different energy forms and technologies plays a key part, and ii) models with an economy-wide, macroeconomic view of the energy-economy interactions. In each of these two broad categories of modelling and simulation different methodological approaches have been developed over time, addressing different end-point goals. These range from optimization and simulation to input-output analysis and general equilibrium. A graphic representation of the different approaches and the general categorization of the energy models is summarized in Figure 1. In addition to the methodological differences, models vary by the spatial scale and resolution, policymaking reference point (e.g., global CO2 abatement vs. national renewable energy policy), policy timeframe (Hourcade et al., 2006), and the ways models can assist policymaking (Capros et al., 2014).

Table 1. Summary of selected review studies of energy-economy models

Study authors	**Focus / highlights**	**Models reviewed/used**	**Parameters of review**
(Berglund & Söderholm, 2006)	Technology learning curve	MESSAGE, GENIE, MARKAL, POLES, ERIS	(i) model features (ii) details of learning curve modeling (factors, endogenous/exogenous) (iii) main findings and implications
(Capros et al., 2014)	European decarbonization pathways	PRIMES, GEM-E3, TIMES-PanEu, NEMESIS, WorldScan, Green-X, and GAMES	(i) application (ii) model type (iii) microeconomic element (iv) policy instruments (v) technology variety (vi) emissions analysis extent
(Hilpert et al., 2018)	Open science	WASP IV, EnergyPlan v12, MARKAL/TIMES, MESSAGE-III, oemof v0.2, urbs v0.7, calliope v.0.5.3, PyPSA v 0.12, and OSeMOSYS	(i) open science (free of charge; open license) (ii) concept (high-level language, generic data model, flexible level of accuracy, multi-purpose toolbox) (iii) functionality (economic dispatch, investment planning, power flow, unit commitment, sector coupling)
(Brouwer et al., 2018)	Nexus concept	E3ME-FIT, MAGNET, CAPRI, IMAGE, OSeMOSYS, MAgPIE-LPJmL	(i) model type (ii) main topics (iii) geographic coverage (iv) energy dimension (v) Nexus components (vi) key gaps in addressing the Nexus
(Siala & Mahfouz, 2019)	Choice of spatial clustering	urbs	-
(Bolwig et al., 2019)	Inclusion of socio-technical perspective	system dynamics modeling	-

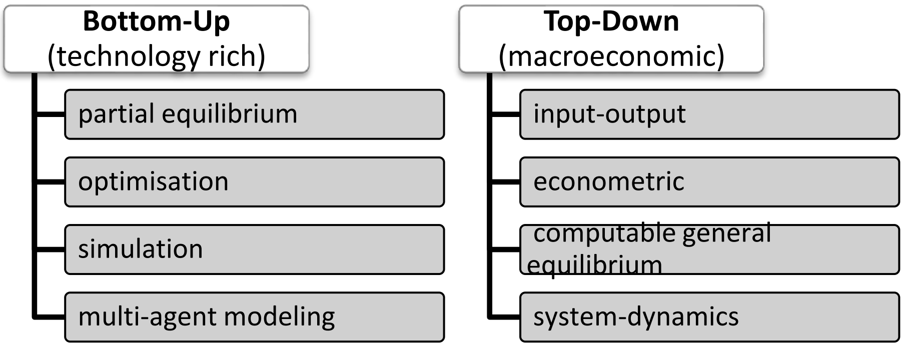

Figure 1. Methodological classification of energy-economy models

An increasing number of researchers make selective reviews of energy models and propose improvements in different directions. Berglund and Söderholm (2006) examine bottom-up energy models concerning the inclusion of technological development or so-called learning-by-doing effect. They outline the importance of incorporating the learning curves of new technologies into energy models to reflect reality better and properly assist policymaking. However, because of computational problems caused by the non-convexity of the learning curve, its introduction to the models is hindered, and only few models include endogenous (adoption driven) technology development, such as MESSAGE, MARKAL, POLES, and ERIS.

Capros et al. (2014) review and compare the set of models used for European decarbonization pathways analysis. The PRIMES model is highlighted for its microeconomic details. The profit maximization navigates the dynamic behavior of economic agents. "… investment behavior consists of building … new energy equipment…". PRIMES incorporates different policy instruments, e.g., tradable certificates, that affect agents' behavior and, consequently, the market equilibrium of energy supply and demand. The GEM-E3 model is a computable general equilibrium model that can capture the effects of different environmental and energy policy instruments, including auctioning and taxes. The NEMESIS model is econometric that, *inter alia*, can be used to analyze the impact of different policies on research and innovation. The TIMES-PanEu model is technologically oriented and characterized by a thorough industrial subdivision and a great degree of detail and, therefore, it is used for emission-reduction potential analysis across individual sectors and subsectors. Another technology-oriented model is GAINS that is a bottom-up integrated assessment model which has been used for, among other, policy design and planning processes. The Green-X model specifically focuses on the analysis of renewable energy diffusion and its costs. The effect of different support policy instruments can be evaluated with this model. Finally, the WorldScan, computable general equilibrium model is designed to evaluate the economic impacts of climate policy. The study (Capros et al., 2014) further reviews European decarbonization scenarios and introduces a methodology for the decomposition of emission reductions.

Hilpert et al. (2018) discuss energy system modeling practices in the context of open science. A review of selected models showed that some of them are free of charge, only a handful have an open license, and a single modeling framework, suggested by the authors themselves allows public collaborative development of the model. Brouwer et al. (2018) urge to embed the Nexus concept into energy modeling. This concept considers, apart from energy, also the flows of natural resources, such as water and food, allowing accounting for their interrelations and better fit such paradigms as circular economy and sustainable development. The models that to some extent include the Nexus concept are: i) E3ME-FIT model used for EU policy assessment, ii) MAGNET model that assesses the impact of climate change on agriculture in the globe; it also serves as a part of an integrated model IMAGE of long-term interactions of economy, society, and biosphere, iii) CAPRI is another agricultural-economic model used for EU policy assessment, iv) OSsMOSYS, an open-source model that combines the assessment of energy, climate, land use and water resources, and v) MAgPIE-LPjmL model that optimizes land-use.

Siala and Mahfouz (2019) demonstrate that the choice of spatial clustering in energy modeling, e.g., administrative divisions vs. clustering based on resource availability, impacts on the shares of renewable energy technology in the future electricity mix, as well as on the geographical distribution of power plants. Since many energy models are designed to work with country-level input data, their results may be distorted for policymaking. Bolwig et al. (2019) call for including socio-technical perspective into energy transition modeling by enriching it with such system dynamics elements as reinforcement feedback loops, learning processes, and inertia. In their complex interlinked model, technological development is affected not only by R&D and policy regime but also by environmental awareness in society.

Hourcade et al. (2006) argue that an ideal energy-economy model should have technological explicitness, complete representation of the macroeconomy and simultaneous realistic representation of the microeconomy. Under these preconditions both conventional bottom-up and top-down models are found to fall short. Several hybrid approaches attempt to address the issue of complete energy models proposing alternative methodological advancements that aim mainly at the better representation of behavioral effects under uncertainty (microeconomic realism). With the energy transition posing new policy and modelling challenges, recent developments have been looking at inputs from other disciplines, like finance, that could enrich the behavioral representation in energy models. Pfenninger et al. (2014) outline the importance of including behavioral aspects into energy models. Indeed, many energy-economy models are built under the assumption of perfect foresight and no uncertainty concerning policy, technological change, or market conditions (Berglund & Söderholm, 2006). In contrast, developments in other disciplines, like finance, offer promising methodological alternatives. A prominent example is the real options framework.

Although some hybrid models are claimed to be improved in terms of microeconomic realism (Hourcade et al., 2006; Pfenninger et al., 2014), the effects observed in real options modeling are typically overlooked in energy-economic models. A summary of the existing reviews of real options studies applied to energy field is presented in Table 2. Real options analysis originates from the finance, in particular from the corporate finance domain, with its practice of investment valuation. The traditional Net Present Value (NPV) investment analysis has proven to be too simplistic and limited, not being able to capture uncertainty surrounding large and complex investment projects. Addressing this shortfall, a more sophisticated real options analysis started to spread into academia (Amram & Kulatilaka, 1998; Trigeorgis, 1995) and the corporate world (Block, 2007; Graham & Harvey, 2001; Ryan & Ryan, 2002). In contrast to the traditional NPV analysis, the real options approach incorporates uncertainty and recognizes the value of managerial flexibility or, in other words, the ability to steer a project in the stream of unfolding uncertainty. These flexibilities could generally apply to any investment project, like to postpone investment, to stage it, and abandon it or could be, e.g., technology-specific, for example, switching inputs in flex-fuel cars (Trigeorgis, 1995).

There are a variety of methods in real options valuation, which choice depends on the aim of the analysis, the real options available (Kozlova, 2017), and the type of uncertainty faced by the problem (Collan, Haahtela, & Kyläheiko, 2016). Inherited from the financial options valuation, real options are often modeled by systems of partial differential equations (Dixit & Pindyck, 1994). Such an analysis, when allows for an analytical solution, reveals all the system's interdependencies and enables making generalized conclusions on investor's behavior, for instance, whether there is an incentive to postpone the investment and how it depends on different parameters, see, e.g. (Bøckman, Fleten, Juliussen, Langhammer, & Revdal, 2008; Boomsma & Linnerud, 2015; Kozlova, Fleten, & Hagspiel, 2019). However, such models have to be kept fairly simple to enable an analytical solution. Therefore, they are limited by a rather simplified representation of reality that includes a single or few uncertainty sources and real options. These limitations are overcome in simulation-based modeling that can include such techniques as Monte Carlo simulation (Mathews, Datar, & Johnson, 2007), optimization (Bashiri, Davison, & Lawryshyn, 2018), and system dynamics (Jeon, Lee, & Shin, 2015). Other methodological approaches exist in real options analysis; however, they are outside the scope of this chapter and can be familiarized with, for example, in (Kozlova, 2017).

Table 2. Summary of selected real options papers

Study	**Focus / highlights**	**Scope**	**Number of studies reviewed**	**Parameters of review**
(Martínez Ceseña, Mutale, & Rivas-Dávalos, 2013)	Technology-specific custom real options	Electricity generation projects	41	(i) technology type (ii) stage of project at which real option is recognized (planning, operation) (iii) sources of uncertainty (iv) mathematical tool
(Fleten, Linnerud, Molnár, & Nygaard, 2016; Linnerud, Andersson, & Fleten, 2014)	Empirical studies confirming that real-world investors' behavior follows the real options logic	Small hydro-power plants in Norway	-	-
(Kim, Park, & Kim, 2017)	Emerging economies	Renewable energy	22	(i) case country (ii) technology type (iii) uncertainty type
(Kozlova, 2017)	Flexibility in project and policy design	Renewable energy power projects and policy	101	(i) case country (ii) analysis focus (project, policy) (iii) technology type (iv) real option type (v) mathematical tool (vi) sources of uncertainty (vii) uncertainty modeling approach
(Trigeorgis & Tsekrekos, 2018)	Coverage and theory expansion of real options approach	operations research, all application areas	164	(i) model context (single firm, game-theoretic setting) (ii) journal (iii) application area (generic, R&D, manufacturing, logistics, energy etc.) (iv) theory advancement

				(v) empirical or applied (vi) information (complete, incomplete)

Most of the real options studies, due to the nature of the method – investment valuation, take a single investor perspective. Although conclusions from such studies can be generalized, such models cannot reflect the development of the entire market or a sector. Nevertheless, some real options studies opt to game-theoretic approaches to study investment behavior in a multi-agent setting (Trigeorgis & Tsekrekos, 2018). However, Trigeorgis and Tsekrekos's review (2018) identified only six studies in the category “Energy, Natural Resources & Environment” that approached the problem with multi-agent game-theoretical modeling concept. The “multi-agent” term in these works is exhaustively limited to two-firm-setting or duopoly and is employed to study the effects of the competitive environment.

The review of operations research literature that utilizes real options approach (Trigeorgis & Tsekrekos, 2018) outlines ongoing intensive work on expanding the theoretical framework, invites researchers to develop further and use more extensively numerical tools such as Monte Carlo simulation for more realistic applications and encourages more empirical work. Concerning the latter, a series of empirical studies has been done in the energy field (Fleten et al., 2016; Linnerud et al., 2014) that demonstrate that the real options framework reflects the observed investment behavior. Cesena et al. (2013), in their review of the real options approach applied to electricity generation projects, urge business experts to collaborate with engineers to create technology-specific custom real options to enable flexibility in the very design of projects. Kim, Park, and Kim, (2017) focus on emerging economies emphasizing high volatility and risk of energy investments, what makes these projects perfect candidates for the real option framework. Kozlova (2017), in her review of renewable energy studies that used real options as methodological framework, highlights that this approach, being able to shed light on investment behavior, is often used to analyze and optimize renewable energy support policies. The tradeoff between policy effectiveness (in terms of technology promotion) and cost efficiency (a burden to rate payers) is commonly discussed in such studies. The feed-in tariff scheme has shown to be more effective, while auctions and renewable energy certificate trading perform better in the cost-efficiency. Comprehensive development in the renewable energy support policy domain goes beyond its analysis into its design. It is the introduction of real options in the design of the support policy that allows investors to gain extra flexibility and, consequently, value for their projects (Balibrea-Iniesta, Sánchez-Soliño, & Lara-Galera, 2015; Yu, Sheblé, Lopes, & Matos, 2006).

Rios et al. (2019) attempt to integrate real options logic into energy-economy models. Their research focuses on the phenomena of construction cycles in generation capacity after power market liberalization. Such a cyclical behavior of power markets, despite been proven empirically, has not been captured by energy-economy models. The authors build a system dynamics model, where investors have the freedom to delay the investment. The timing of the decision is based on the comparison of the investment value if exercised now and the continuation value if it is postponed. The simulation starts at market equilibrium in zero-profit conditions. Such a situation proclaims the continuation value is greater than the exercise value, so the investors choose to wait. Several years later, the reserve margin (available capacity minus peak demand) drops, prices spike, the inequality of values flips, and immediate investment becomes more attractive than waiting. New growing generating capacity increases the reserve margin, this leads to the electricity price decline, and the continuation value is again exceeding the exercise value putting the wave of new investment on hold. Thus, the market cycles arise as a natural model output when the real options theory is imbedded into the investment behavior of an energy-economy model. The model of Rios et al. (2019) is only a start in this important direction and has many limitations. Nevertheless, it is of crucial importance in the energy systems modeling realm, and it can provide a basis for delivering new insights in renewable energy policy analysis as well.

As discussed above, in the Green-X model investment decisions are influenced by external factors only through the discount rate. That is, e.g., investment timing is defined solely by when a particular technology becomes profitable, considering a risk premium entering through the discount rate. In this model, investors are not able to wait if a project is profitable now, even though it might be expected to be more profitable in the future. The real option element of the hybrid model by Rios et al. (2019) would be of use in Green-X to simulate proper investment behavior and reactions to policy. The Green-X model also incorporates a possibility to change a policy type along the simulation run by a user. However, again the regulatory risk enters investment behavior through discount rate premium. If the real options -based behavior is implemented, it might lead to a more realistic investors reaction with major delays to get better information and gain confidence in a new regulatory regime.

Separate attention in renewable energy context deserves a technological development phenomenon. Berglund and Söderholm (2006) conduct a comprehensive review in that respect and highlight the importance of modeling technology change as an endogenous process. The authors also emphasize that neither top-down nor bottom-up models can adequately and fully capture technology diffusion processes. The models that undergo detailed scrutiny of these authors include MESSAGE, GENIE, MARKAL, POLES, and ERIS. Another model that incorporates technology learning and specifically focuses on renewable energy is Green-X (Capros et al., 2014). Nevertheless, all these models lack the effect that is further induced by technological development. All real options studies that incorporate technology learning into their models unanimously conclude that the anticipation of the future cost drop creates an incentive to postpone investments (Fuss and Szolgayová, 2010; Kumbaroğlu et al., 2008; Torani et al., 2016; Welling, 2016). Indeed, from a single investor point of view, why would one buy solar panels today if tomorrow their price is expected to drop. This postponing effect has not been studied systematically to enable a full understanding of how different renewable energy support mechanisms shape it (Kozlova, 2017). However, it is reasonable to speculate that, for example, fixed feed-in tariffs would intensify this effect, providing the same absolute revenues to the projects built in different years and so at different capital costs, therefore, creating an incentive for investors to wait and jeopardizing the efficiency of the policy. Since bottom-up energy models are often used to assess the effects of different public policies (Berglund and Söderholm, 2006), missing this effect out would generate overestimated policy effectiveness results in terms of new investments and technology diffusion.

Concluding remarks

The overview of the developments with energy modelling shows the richness in methodology and policy questions of relevance addressed. Models have been able to assist policy making with regards to long lasting issues of concern like, security of energy supply, energy demand and production, transport, distribution, end-user technology, macroeconomic and environmental effects. In the light of sustainability and green energy transition these policy issues remain still relevant. Traditionally the issue of security of energy supplied was linked with oil and gas import dependence, depletion of conventional sources (hydrocarbons) and geo-political factors that could impact on the transition of fuels. With increasing climate change concerns, socio-demographic shocks (like migration or climate change refugees) and green investment shifts, energy supply assessment through modelling exercises needs to be updated with focus on the uncertainty surrounding these developments. With regards to energy production, transport, distribution, and end-user technology there is a range of features, advantages and shortcomings that should be included in the energy models to be developed. These relate to inclusion in the mix of diverse and new energy forms (offshore wind, ocean wave etc.), development of new energy grids and communities (e.g. energy communities, small independent interconnections), and technologies (smart metering, batteries and storage options). The introduction and large-scale commercialization deployment of these new technologies, their costs and technical parameters and characteristics can be introduced in the modelling exercise. Yet this introduction is related to considerable uncertainty streaming from micro-economic and behavioral characteristics. The price determinants, reflecting the marginal cost for producers and marginal benefit for the consumer, of these technologies may be complex and yet not well-known to fully capture them in the modelling process. This is another challenge that requires appropriate updating of the energy models with detailed micro-economic and behavioral parameters.

In the presence of scientific calls for urgent climate action and regional and global policy initiatives for green energy deployment and sustainability transition, the development of appropriate modelling approaches that can address the particularities and uncertainties related to renewable energy forms and new technologies should become a methodological priority. In this push forward to energy-economy-environment modelling core traditional energy policy concerns, such as security of supply, employment and macroeconomic effects, remain relevant, even under the scope of green transition. Surely for renewable energy policymaking assistance, a model should incorporate details in renewable energy technologies and different support mechanisms, as well as investors' behavior, to appropriately capture policy effects. What appears as a demanding development in this regard is the introduction of behavioral analysis that better characterize risk and uncertainty attitude towards new technologies. If the modelling developments can provide a better characterization and representation of these matters will significantly address policy needs related to the acceptance and time-deployment/fulfillment of the energy transition and sustainable operations at sectoral (energy), economy (micro- and macro-economy) and environmental level.

Ongoing work in the energy-economy-environment modelling are considering these extensions. What the review conducted indicates as still missing in the field, is the introduction of the sustainability parameters and alternative financing options i.e. extensions in the representation of the financial sector and the novel financing tools that can be used for the sustainability and green energy transition. Future work in energy modelling could also consider the questions on the definition and measures of welfare, economic growth and development. Moving beyond GDP and economic growth, other social and environmental parameters may need to enter the models. These can include for instance biodiversity or health indices. Considerable uncertainty exists with the future impact of energy efficiency and green energy production to such measures and indices and future work in the field could enrich scientific knowledge and the insights offered by modelling.

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