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A review of current challenges and trends in energy systems modeling

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ABSTRACT

The requirements made on energy system models have changed during the last few decades. New challenges have arisen with the implementation of high shares of Renewable Energies. Along with the climate goals of the Paris Agreement, the national greenhouse gas strategies of industrialized countries involve the total restructuring of their energy systems. In order to archive these climate goals, fitted and customized models are required. For that reason, this paper focuses on national energy system models that incorporate all energy sectors and can support governmental decision making processes. The reviewed models are evaluated in terms of their characteristics, like their underlying methodology, analytical approach, time horizon and transformation path analysis, spatial and temporal resolution, licensing and modeling language. These attributes are set in the context of the region and time in which they were developed in order to identify trends in modeling. Furthermore, the revealed trends are set in the context of current challenges in energy systems modeling. Combining specified research questions and specific greenhouse gas reduction strategies, this paper will help researchers and decision makers find appropriate energy system models.

1. Introduction

In order to achieve the climate goals of the Paris Agreement of 2015 [1], established structures of national energy supply systems will be subject to comprehensive changes in future [2,3]. These efforts are vital to limit global warming to 'well below 2 °C above pre-industrial levels' [1]. The extension of Renewable Energies represents a crucial factor for the reduction of greenhouse gas emissions [4,5]. In addition, the share of alternative, carbon-free technologies and energy efficiency must be increased in end use sectors [6–10]. Due to the interconnection between these sectors and the different technologies, the development of a national decarbonization strategy becomes very complex [11]. Moreover, the projection of future energy demand and supply is bound to uncertainties based on the influence of climate and weather, socio-economic variables, technological developments and potentials, etc. [12–14]. For this reason, forecasting is always related to a scenario tree of potential future developments [13,15].

The analysis of existing national energy systems, as well as the prediction of potential future scenarios, is usually performed with the aid of an energy system model [16,17]. First, systematic approaches are presented by Barnett (1950) [17,18]. Along with an increase in computing power, as computer-aided modeling grew in importance, the first notable energy system models were developed in the 1970s and 1980s [19–22]. Till the end of 1970s, national energy supply was generally a governmental monopoly, or at least strictly regulated by the government [23]. This situation is also reflected in the purpose of energy system models from this period. Governmental mismanagement and the demand for security of supply were key drivers for the need of strategic reserves and long-term planning in the energy sector [23,24]. As a consequence, model frameworks like the Brookhaven Energy System Optimization Model (BESOM) were designed to evaluate energy technologies and policies [20]. Its derivatives, the 'Market Allocation' (MARKAL) model and the 'Time-stepped Energy System Optimization Model' (TESOM) were developed with the objective of investigating long-term scenarios in the context of new technologies in the energy system [21,22]. Driven by the 1973 Oil Crisis and the liberalization of energy markets in the 1980s and 1990s, new needs arose alongside a new generation of energy system models [25–28]. During this time period, there was an additional shift in the research focus from environmental pollution, like acidification, towards climate protection and the assessment of greenhouse gas strategies [29,30]. The emergence of greenhouse gas reduction as a major research theme was later fostered by the adoption of the Kyoto Protocol in 1997 [31–33]. As a result, the first models appeared that had a focus on greenhouse gases [34,35]. However, the common focus of models developed in this period was still on the economy, market behavior, technological issues

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and environmental pollution [30]. In the 2000s and 2010s, however, this purpose changed in favor of the assessment of the implementation of Renewable Energies and the associated demand for flexibility within the energy system [30]. Consequently, greenhouse gas reduction became a major objective of energy system analysis and modeling. Moreover, computing power reached a level that enabled some energy system models to be run on desktop computers. Thus, a significant expansion of the modeling community can be registered since 2000 (see results section). However, fluctuating renewable energy technologies, such as solar and wind power, are highly dependent on weather conditions. This dependency led to the need for high temporal and spatial resolutions in energy system models for the appropriate implementation of these technologies [36–39]. Correspondingly, the demand for computing power is increasing in accordance with the degree of detail needed for the modeling renewable energy systems [40–42].

Given the complexity and variety of energy system models with diverging purposes, reviews are a tool for researchers and decision makers for gaining an overview of the existing model landscape and to help them find suitable models for a corresponding research question. Due to the small amount of modeling approaches in the 1970s and 1980s, the first noteworthy model reviews were published by Beaver (1993) [43] and Grubb et al. [44]. They gave a summary of the most important models of this period, which were predominantly economic in focus. Along with an increasing amount of different models, there was a need for the categorization and classification of energy system models [44]. The first model review that tried to meet this demand was published by van Beeck [45]. He systematically classified existing models and generalized his approach to apply it to other models. Jebaraj and Iniyan [46] gave a general review on energy models based on a different classification approach that focused on the model's purpose. An application-related review of energy models was published by Sahir and Qureshi [47]. As a result of the increasing number of models, Connolly et al. [48] investigated 68 tools/models and gave a detailed analysis and description for 37 of these. A year later, Bhattacharyya and Timilsina [49] published a general model overview with a focus on the utilization of the reviewed energy system models. They investigated computing and data requirements or gave a qualitative evaluation of the needed skills to use and run each model. In contrast, Nakata et al. [50] reviewed energy models based on their specific application. Moreover, a small and very specific review was conducted by Zeng et al. [51], in which they analyzed optimization models for energy system planning and greenhouse gas emission mitigation under uncertainty. In 2012, another short overview about optimization models was given by Weijermars et al. [52]. Pfenninger et al. [30] noted diverse energy models addressing the challenges in energy modeling, which they tried to overcome. Another comprehensive model review was published by Hall and Buckley [53], who performed a meta-analysis for models in the UK and identified nearly 100 that they then categorized. The latest methodological review also introduces and compares energy models from Collins et al. [54].

Most previous reviews of energy system models tried to give a general overview of the whole model landscape and to classify them in a second step based on their functionality. This approach helps to register the status quo of modeling, but cannot give advice or support finding suitable models for a specific purpose. Jebaraj and Iniyan [46] published a review based on the model's objective. However, their applied classification approach is not applicable to the current challenges and research questions of energy systems modeling. With the aim of answering recurring questions and the emerging requirements of modeling relating to the Paris Agreement, this paper will highlight trends, challenges and needs for future developments in energy systems modeling. Furthermore, appropriate models are determined, evaluated and compared in order to enable researchers and decision makers to choose an appropriate model for their purposes.

For this reason, the method section of this paper explains which models are investigated and how they were chosen. Moreover, categories for the classification and later comparison of the models are described. The following results show the identified trends and challenges of energy systems modeling. The six major criteria are analyzed in the subchapters. Afterwards, a table with an overview of the investigated models is given, followed by a presentation of conclusions and a discussion of the results.

2. Method

A basic idea for the selection of models and model generators is their ability to support governments with strategic decisions on the future of their countries' energy supply and to accomplish climate goals based on the Paris Agreement of 2015. In a first step, it is necessary to filter appropriate models which are able to handle this task [42]. In a second step, criteria for the evaluation of the models must be determined [52].

In order to find models that can answer the initial question of finding the best strategy to accomplish climate goals, a set of minimum requirements must be defined. For that reason, the models analyzed in chapter 3 are reduced to a set of models that are:

- Calculated on a national geographic horizon;
- Applicable to all energy sectors of a country; and
- Supportive of governmental decision making processes.

The kind of support is not specified and could manifest in various ways depending on the model's purpose and corresponding research questions. In the literature, the purpose of an energy system model is often used for differentiation between the modeling approaches [30,46,55]. Van Beeck (2000) presents a scheme to categorize different purposes in forecasting, exploring and back-casting [45]. This was refined by Hall and Buckley [56], who defined the mentioned purposes as a general category and added a more specific classification. As possible examination aims, they mention the interactions within the energy system and its sectors, decarbonization pathways, the impacts of policy and climate goals, as well as the associated costs of energy scenarios [56].

Applying these eligibility criteria, 24 models and model generators are suitable and part of the following evaluation. The appropriate selected models are: Balmorel, BESOM, Calliope, CIMS, DynEMo, E4Cast, EnergyPLAN, ENPEP-BALANCE, ESME, IKARUS, LEAP, MARKAL (derivative of BESOM), MESSAGE, NEMS, OEMOF, OSeMOSYS, PRIMES, REMIND-D, REMix, REMod-D, SCOPE, Temoa, TIMES (derivative of MARKAL and EFOM), TESOM (derivative of BESOM).[1]

For the general characterization and later assessment of energy system models, there are diverse possibilities. Van Beeck (2000) suggested a classification approach that consists of nine criteria that can be described with qualitative attributes (see Table 1) [45]. Connolly et al. (2010) applied most of these and added the research question of whether models are able to calculate a scenario with a share of 100% of Renewable Energy in the electricity supply and energy supply in general [48]. Furthermore, Bhattacharyya and Timilsina (2010) added some categories concerning the model's internal structures and scope, as well as application-oriented criteria like the required skill and computing effort to run the model [49]. Hall and Buckley (2016) decided for 14 categories and listed possible attributes for each category, which can describe all reviewed energy system models [56].

Like van Beeck (2000), they decided for the same characterization pattern and added four criteria for the implementation of specific technologies and model aspects. In this case, their focus is on renewable and storage technologies, as well as the implementation of demand characteristics and costs [56]. However, the published results only answered what kinds of technologies are implemented in the models

[1] Detailed description in the appendix A.