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Modelling the energy transition: A nexus of energy system and economic models

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ABSTRACT

Climate change induced policies impose wide-ranging implications throughout the whole energy system and influence various sectors of the economy. To analyse different decarbonization pathways for the energy system, existing models have traditionally focused on specific energy sectors, adopted specific research perspectives, assessed only certain technologies, or studied isolated components and factors of the energy system. However, few efforts have been undertaken to successfully model a broader picture of the energy-economic system. In this conceptual paper, we propose linking top-down and bottom-up models to represent: distributed generation and demand, operations of electricity grids, infrastructure investments and generation dispatch, and macroeconomic interactions. We review existing work on modelling the different dimensions of the energy transition to understand why models tend to focus on certain features or parts of the energy system. We then discuss methodologies for linking different type of models. We describe our integrated modelling framework, and the challenges and opportunities on linking models based on their capabilities and limitations.

1. Introduction

The energy transition is pushing the frontiers in energy modelling towards the development of modelling frameworks capable of representing the interdependencies between policy making, energy infrastructure expansion, market behaviour, environmental impact and security of supply. Analysing these interdependencies requires modelling tools capable to determine, for example, the backup capacity and reserves required to accommodate increasing shares of renewables (i.e. wind and solar), to assess investments in infrastructure to exchange power with neighbouring regions, to investigate issues of energy and climate policy, and to propose regulatory frameworks for the design of energy markets. In addition to these dimensions, the assessment of the energy transition requires a broader modelling scope to consider the impact of short-term operational aspects of grid stability and energy markets on long term decarbonisation strategies while considering implications to other domestic and foreign non-energy markets. Individual components, sectors and layers of the energy system should therefore not be analysed in isolation but should be looked at with a broad cross-disciplinary approach capable of capturing system-wide interdependencies.

Existing energy modelling practices — while manifold — share two main limitations that prevent a more comprehensive representation of the energy system. First, they tend to focus on only one or a few layers and/or sectors of the energy system (Fig. 1), choosing to ignore the interconnectedness with all other components of the energy system. One reason for such a choice is that research groups are frequently composed of researchers from similar areas of expertise (e.g., a focus on gas from an economic perspective, or an emphasis on power grids engineering features) or due to the particular research circumstances (i.e., project objectives). In many cases, this is due to the prevalent infrastructure, available resources or strategic orientation in the specific research institutions. Such a narrow focus confines many research projects to the boundaries of

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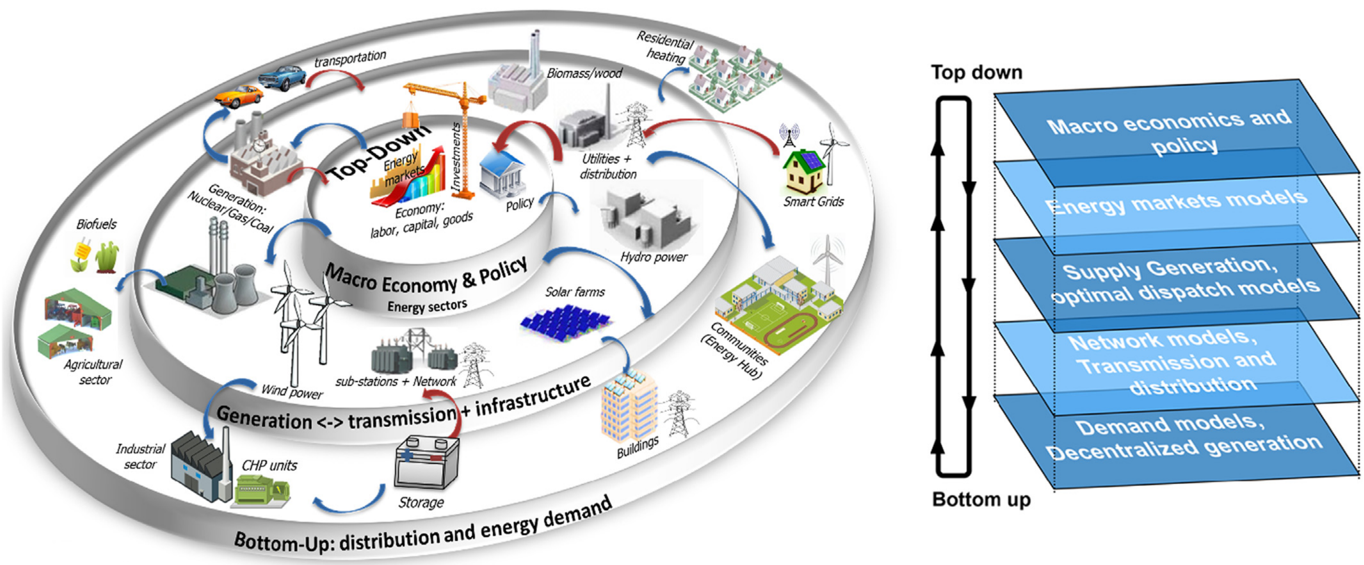

Fig. 1. Vision of linking energy sectors and layers of the energy system.

a particular area of expertise and can lead to limitations in modelling other features or parts of the energy system. For instance, bound to the specific problem setting in which the research is conducted, each study defines its own modelling assumptions, boundaries, variables' characteristics or parameters of choice, and has a large number of ceteris paribus assumptions, in which certain variables of interest are allowed to vary while keeping others constant. Such modelling practices limit the scope of the analyses and result in different implications when applied in distinct contexts which might lead to inconclusive policy recommendations. Second, model-based analysis is further hampered by a lack of transparency in the documentation of research procedures and models development often turning the analysis into a 'black box' [1]. This impedes the transfer of knowledge, limits cross-disciplinary cooperation and thus prevents a collective learning process within the energy modelling community [2]. In summary, current modelling practices do not account for the complexity inherent in energy system configurations and are thus of limited use in identifying and analysing effective decarbonisation strategies.

The next challenge lies in linking models by integrating knowledge across disciplines such as economics, system engineering, power system modelling, risk assessment, etc. [3,4]. The ETH Zurich has set out the ambitious goal to develop such a well-documented framework of linked models that will: 1) harmonize data and modelling assumptions, 2) jointly represent (Fig. 1) various layers, sectors, and components of the energy system, 3) integrate existing knowledge to facilitate trans-disciplinary research, and 4) link tools related to technical and economic aspects of the energy system (bridging the gap between engineering and economic energy models). As first step, in this paper, the proposed modelling framework focuses on the electricity sector. Future work will expand to other sectors and energy carriers.

In this conceptual paper, we discuss the opportunities and challenges of developing a methodology capable of creating a nexus between different energy models. Fig. 1 shows the overall structure of the energy system, and provides a schematic sketch of the concept: the demand for energy services (e.g., heat, electricity) is driven by the economy, implemented via a top-down (economic) perspective that captures the interactions of domestic and international markets (including energy markets) and other economic sectors. The demand then drives bottom-up technology choices adopted in the different energy sectors (i.e., the energy infrastructure), which then again act as input to the economic top-down decisions. This representation of the energy-economic system raises the question of what tools are capable of modelling this integrated system of layers and sectors, and whether existing models can complement each other in such a system and represent a broader scope of the energy system (Fig. 1).

The answers to these questions lie in understanding the capabilities of different modelling approaches and why they incorporate or avoid modelling certain features of the energy system. In the next section (Sec. 2), we review the ongoing challenges in linking technology-rich engineering models with economic models and discuss their strength and weaknesses. Then, in Section 3, we propose and discuss the possibility of going one step further by linking 1) macroeconomic and energy markets, 2) the energy infrastructure (i.e. the wider power system), and 3) demand sectors and decentralized generation systems. Section 4 concludes with some remarks about the importance of developing a comprehensive modelling approach that is in line with the challenges posed by the energy transition.

2. Modelling approaches and existing work

There are three main modelling approaches to represent the interactions between the technological details of the energy systems, the economy and the environment: Top-down macroeconomic modelling emphasizes the aggregated economic-wide view and incorporates the energy production technologies with less detail through aggregated functions within a large macroeconomic system. The second, bottom-up, approach, uses models with a technology-rich and detailed representation of the energy system but does not include the interactions between the energy system and the broader economic system. The third, hybrid, approach integrates the detailed energy technology representation of bottom-up models into a top-down macroeconomic model (for a recent review and categorization, see Ref. [5]).

2.1. Top-down approaches

A well established top-down method to model a consistent