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

Pedro Crespo del Granado [a, **], Renger H. van Nieuwkoop [b, *], Evangelos G. Kardakos [d], Christian Schaffner [c]

[a] Dept. of Industrial Economics and Technology Management, NTNU, Trondheim, Norway
[b] CER, Zurichbergstrasse 18, 8032, ETH Zurich, Switzerland
[c] Energy Science Center, ETH Zurich, Switzerland
[d] Power System Lab, ETH Zurich, Switzerland

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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

* Corresponding author.
** Corresponding author.
E-mail addresses: pedro@ntnu.no, pedro@gwu.edu (P. Crespo del Granado), rengerv@ethz.ch (R.H. van Nieuwkoop).

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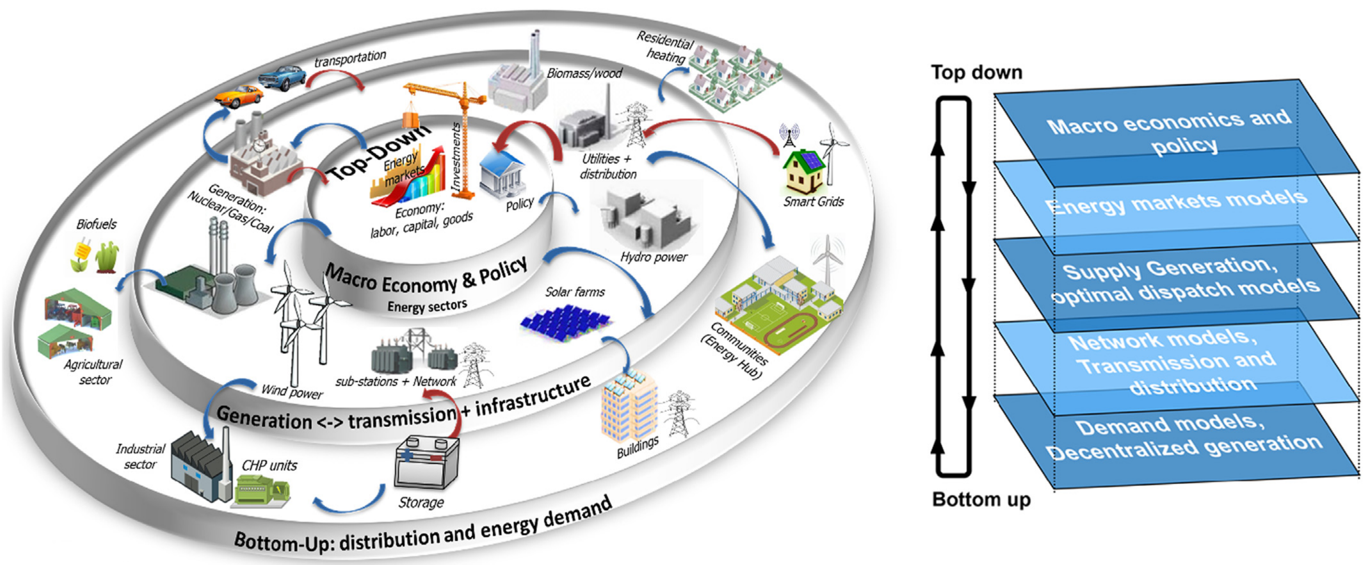

Fig. 1. Vision of linking energy sectors and layers of the energy system.

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 macro- and microeconomic behaviour is the application of computable general equilibrium (CGE) models. CGE models are top-down models firmly grounded in neoclassical, microeconomic theory and consist of the agents in an economy (households, producers/firms, government), and the markets for goods and factors.[1] Households and government maximize their welfare, and the producers maximize their profits. The agents interact in the markets by either supplying or demanding goods or factors. Market equilibrium is reached by a price mechanism. Prices can adjust to find an equilibrium between supply and demand. Distortions of the price building like taxes can also be incorporated. The strength of CGE models is that they incorporate the interactions between the different agents as well as the feedbacks through the whole economy. The interaction with other economies can either be done using multi-regional models, in which each economy is formulated in full detail or a single-regional model in which the interactions with the rest-of-the-world are formulated using a closing rule that relates the exports, imports, and the current-account balance. CGE models can be solved for one time period (usually one year) or solved for several linked time periods. Dynamic CGE models can be of the recursive-dynamic type, in which a static version of the model is solved for one period and outputs of that period (e.g., savings and investments) are used as inputs for the next period. This means that agents do not take into account the past and the foreseeable future. In a Ramsey-setting, it is assumed that economic agents have complete information over the complete time horizon, and the model is solved for all periods simultaneously. The optimisation assumptions of CGE are consistent with most energy systems models.

Another approach is the use of econometric models. Econometric models specifiy the statistical relationship between the model variables (prices, quantities) and estimate the relevant model parameters. These models are often more aggregated than CGE models and can, contrary to CGE models, be used for estimating the future trajectory of the variables. CGE models are typically used for scenario analysis, where different policies are being compared. An example of an econometric model which includes a bottom-up model of the electricity supply industry, being otherwise top-down in approach, is the E3ME model [6].

Weaknesses of the pure CGE and econometric approaches with respect to the energy-economic system are the high level of aggregation and therefore an unrealistic view of the energy sector as well as the high level of time aggregation (usually one-year steps; a finer resolution would be possible at the cost of aggregating the overall structure of the model). Although some CGE models take into account a stylized representation of the energy network structure (see Ref. [7]), CGE models usually refrain from modelling a more technological detailed power system. Moreover, stochastic elements and imperfect competition,[2] essential features of the energy market, are hard to implement in these models and are usually only implemented in partial models (for examples and discussion see Ref. [8]). Another weakness is that CGE models are not very well suited to represent the financial markets [9].

2.2. Bottom-up approaches

A well-known example of a bottom-up approach which uses a detailed and technology-rich model without interactions with the rest of the energy system, is the MARKAL model (**MARK**et **AL**location, [10]). It is a popular model for analysing the supply side of the energy system. The most simple version is a bottom-up linear programming model, where a multiple of energy supplies and demands are depicted based on technology costs and technical characteristics (e.g., investments, operating costs, capacity utilization, efficiency of fuel use). The technology mix is the result of minimizing total system cost of energy supply based on a given energy demand, costs of running these technologies as well as costs of investments in additional capacities or new technologies. In its basic form, MARKAL has a number of limitations [11]. For example, the demand for energy is exogenously given and does not adjust if energy prices change. Other important drivers like the impact of GDP or income growth on energy consumption are missing. For these reasons, the MARKAL model has been extended in many directions. Examples include the MARKAL Stochastic, the MARKAL-ED (Elastic Demand), and others [12].

A next step in the development of bottom-up optimization models is the TIMES model (**T**he **I**ntegrated **M**ARKAL-**E**FOM[3] **S**ystem, [13]). The TIMES model extends the MARKAL system in several directions [11]: It is scalable from local to global, and it allows for vintaging of technologies, flexible time slices (daily load curves), variable forecast horizons, and the distinction between service life and economic life of technologies. Although the MARKAL/TIMES models show a good level of detail and contain many features of the energy-economic system, they mostly lack an explicit treatment of the energy networks and decentralized generation sources, endogenous microeconomic behaviour, feedbacks of the energy system to the macro economy, and detailed system security assessments. Furthermore, several authors (e.g. Refs. [14,15]) have questioned the quality of the results because of the simplifications made when representing the high temporal resolution of supply-demand operations, Ref. [16] address this issue by using a combination of the TIMES and EnergyPLAN [17] model to implement an hourly time resolution in the presence of high shares of renewables in the system. However, these extensions might still fall short on analysing the power systems operations, a strength of optimal power flow (OPF) models.[4] In fact, most of existing energy system models (e.g., TIMES, US-REGEN by Ref. [18]; Calliope by Ref. [19]; OSeMOSYS by Ref. [20] and others[5]) use a stylized grid representation (transportation model) that overlooks the insights OPF models offer. For instance, Ref. [21] demonstrate that using a TIMES model compared to an OPF undervalues flexibility resources, underestimates wind curtailment and overestimate base-load operation. In contrast, OPF models have a very limited long-term outlook due to the computational tractability of its non-linear optimization. Therefore, generation capacity planning and other long-term decisions have to be exogenously calculated. Meaning that power system models typically provide a more accurate assessment of system operations in terms of reliability and stability conditions while energy system models strengths are on capacity expansion planning [20,22]. This is further addressed in a hybrid approach by Ref. [22] where a power system model is soft linked to PRIMES [23]. Results show that the detailed dispatch model better captures power system flexibility in terms of curtailments, levels of system inertia, and congestions. A similar study by Ref. [24] shows the importance of complementing long-term planning perspective with a unit commitment model.

[1] For an extensive introduction in CGE, see Ref. [52].

[2] Note that optimization based energy system models also typically pursue a system cost minimization that assumes perfect competition.

[3] The Energy Flow Optimization Model (EFOM) is the supply part of the energy model complex of the Commission of the European Communities, see Ref. [53].

[4] OPF models analyses the power balance in the electricity grid at each node considering voltage and line limits. Grid topology and physical components are represented in high detail.

[5] Artelys is an important example of dispatch type model, https://www.artelys.com.

Another class of bottom-up models focus on the analysis of the distribution system and its demand sectors. For example, the assessment of smart grids, decentralized generation technologies (e.g. PV systems), demand response and energy efficiency measures (e.g. Ref. [25]). However, these consumer or demand-side based models do not represent upper layers of the energy system. Also, established supply based approaches usually do not integrate decentralized supply options on their national supply assessments (only under aggregation assumptions or by deriving exogenous inputs of demand sectors, e.g. Ref. [26] or PRIMES).

2.3. Frontiers in energy modelling: linking models and hybrid approaches

Recently, there has been a tendency towards developing more comprehensive energy and economic modelling approaches.[6] The literature describes several approaches for linking existing top-down models with bottom-up models or for having a more multi-model/sector perspective [22,27–29]. A typical example is the MESSAGE-MACRO model [30] that links the MACRO model to the MESSAGE energy supply model. Other examples are developed by Ref. [31] who couple the Swiss MARKAL residential model to GEMINI-E3, a global CGE model, or, with a more detailed implementation of the energy sector, the **E**missions **P**rediction, and **P**olicy **A**nalysis (EPPA) model developed at the MIT [32]. The EPPA model is a recursive-dynamic multi-regional general equilibrium model of the world economy designed to develop projections of economic growth. The model includes a wide range of energy supply technologies and is linked to a climate-land ecosystems model.

A major drawback of top-down-bottom-up linkage can be the inconsistency in the behavioural assumptions in the used models. To resolve these inconsistencies, Ref. [33] calibrate the top-down model to the results of the bottom-up model. They adapt the transport sector representation in the EPPA CGE model to be consistent with the technological specification of MARKAL. Alternatively, Ref. [34] proposes to adjust the elasticities in the CGE model to the ones used in the bottom-up model. Ref. [35] propose a method to include behavioural aspects in environmental policy analysis based on complexity dynamics and agent heterogeneity. The use of CGE models with an integrated aggregated bottom-up energy system is discussed in Ref. [36].

Another approach for linking top-down with bottom-up models aims at incorporating either a reduced bottom-up model within an existing top-down model or adding some equations coming from a top-down model inside an existing bottom-up model. Ref. [37] is an example in which the top-down and bottom-up model are completely integrated using the same modelling format. An example of the integration of a reduced top-down model in a bottom-up model can be found in Ref. [38]; who incorporates a bottom-up specification of the electricity sector in a CGE model for the US economy. Ref. [12] integrate the macroeconomic model ETAMACRO [39] into the MARKAL model. All in all, these model linkage approaches have opened new possibilities to analyse multi-sector coupling [40]. For instance, Ref. [28] soft-links a TIMES model to a power system and a housing stock model to analyse the electrification of residential heating. Other multi-sector bottom-up examples are; Ref. [41] who model the interdependencies between gas and electricity networks, Ref. [42] who study decentralized multi-carrier energy systems and the role of storage technologies, and [43] who look into reciprocal effects between energy demand and the evolution of the transport sector.

[6] For an overview of approaches of the last 10–20 years, see Refs. [11] and [54].

Summarizing, bottom-up and top-down methodologies differ in the treatment of temporal resolution, technological detail, aggregation or consideration of energy sectors, regional coverage, and energy system interactions with other external factors and the economy. All in all, existing modelling approaches tend to fall short in at least one of the following features: representing interactions with decentralized generation systems, modelling the details of the power system and the grid, providing a secure and adequacy assessment of the grid, and studying long-term outlooks along with macroeconomic implications.

3. Nexus modelling framework: an alliance of models

To address the modelling limitations described in the previous section, we propose a modelling framework of interconnected top-down and bottom-up models representing the central layers and sectors of the energy system. This framework derives its name "Nexus" from the vision to develop a linkage methodology capable of creating the *nexus* between several energy models and being able to answer research questions beyond the boundaries or assumptions typically established in each model individually. Fig. 2 illustrates the Nexus framework consisting of the four interconnected main modules as there are the top-down CGE model, the generation expansion model, the energy networks, and the decentralized generation. The energy networks and generation expansion-dispatch module are linked with a system security analysis module.

One of Nexus' main features is that it is open to other modelling approaches: It should be possible to easily replace the module to study differences depending on choice of modelling approaches. The choice of the models for the initial set up of the Nexus modelling framework is to represent the main layers of the power system. The scope and capabilities of these modules are as follows:

- The first module is a recursive-dynamic, multi-region, multi-sector CGE model for Switzerland and major European countries. The model assesses, at an aggregated level, the evolution of electricity supply and demand over time in the Swiss economy (overall investments, generation mix by technology, costs, prices), while at the same time allows the analysis of macroeconomic effects under alternative future scenarios of Swiss energy and climate policy.
- The second module is a generation expansion model (e.g. Ref. [44]) which determines capacity investments to meet future demand growth and replace units retirements, by minimizing investment costs, fixed and variable maintenance costs and operation costs (i.e., fuel, start-up and shut-down costs). The model represents technical constraints of conventional power plants, hydropower operating constraints, reserve allocation constraints and power exchanges between countries.
- The third module is the energy network model. It is an optimal power flow model (e.g. Ref. [45]), that includes electricity flow balance at each node by fully modelling the main transmission grid under operating limits (e.g., line flow and voltages). This detailed representation of the power system operation complements the generation expansion model as it is crucial to assess the operational flexibility needed when the power system has a considerable share of renewable generation.
- The decentralized generation model is the fourth module based on a stochastic dispatch optimization of aggregated decentralized energy resources (DER) in the distribution grid (e.g., Ref. [46]). It considers DER participation in electricity markets (e.g. day-ahead and balancing markets). The DER represented are storage units, flexible load profiles, wind and solar systems, and other local energy systems (e.g. prosumers). Sources of short-

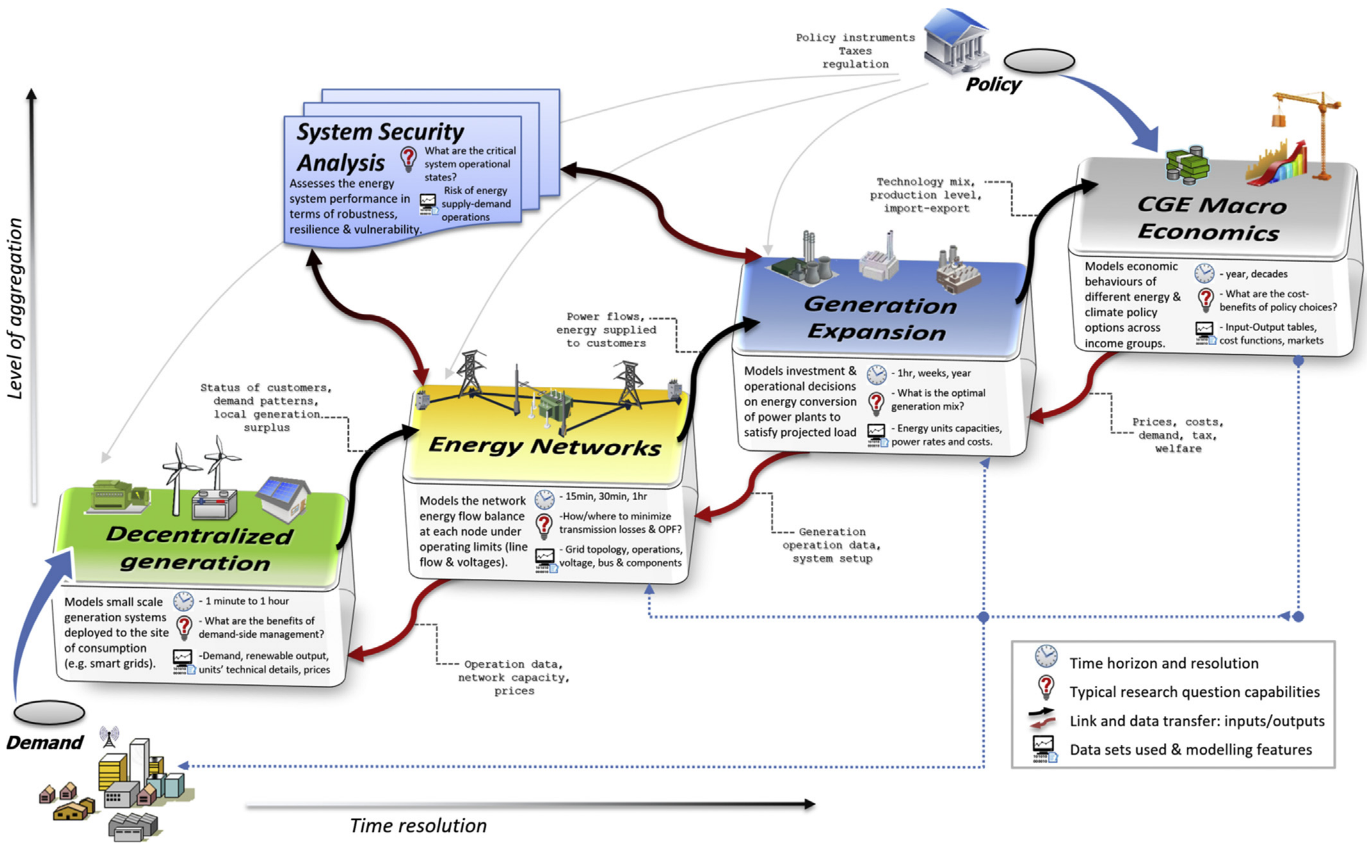

Fig. 2. Nexus models representing the central structure of the energy-economic system.

term uncertainty are electricity prices and renewable variable generation.

- The fifth module, the system security model, assesses the security of the supply by testing the capability of a power system with a large share of intermediate generators to withstand sudden changes like loss of power line or loss of generating units (e.g., Ref. [47]). This module provides insights for the adequacy of the capacity of the transmission system and the system critical states based on generation supply options.

For the connections between the different modules, interfaces are being developed that allow for the automatic exchange of information and data between the models. The automatic linkages will use a versatile programming like Python [48]. In the first phase of the Nexus project, the focus will be on electricity supply and demand, and future work will focus on including other sectors and energy carriers. One of the main points of the Nexus project is that the different research groups can use their own modelling tools. The Nexus framework is flexible and modular: In the future the models will be replicable and the framework can be extended with new modules (e.g., transportation, energy efficiency, or other energy markets).

3.1. First prototype

A first Nexus prototype has been constructed and is now being tested for analysing a nuclear phase-out scenario for Switzerland. It links the two of the main modules using scripts to exchange the information between the models. The prototype consists of the top-down CGE model and the bottom-up generation expansion model (GEP). In order to cope with the increased computational issues caused by the detailed unit commitment constraints within the GEP, the examined year is reduced to four representative weeks, one per season, resulting in 672 h. Consistency between the modules is secured by using the decomposition technique as described in Ref. [49]. With this technique the energy supply of the CGE model is taken from the bottom-up models. Prices for energy, maintenance, operation and investment costs are calculated in the top-down model and automatically sent back to the GEP. Investments in energy supply are calculated in the GEP-model while the prices for the investment goods are taken from the CGE model. The models are solved within a loop and the process continues until convergence between the models is reached. The top-down model is programmed in Gams [50]. All other models and the linkages are developed in Matlab [51]. Fig. 2 describes the qualitative features of the inputs-outputs exchange between modules and the type of information/decisions that are linking them.

4. Conclusions and future research

In this conceptual paper, we introduce the Nexus modelling framework that will provide an approach for linking models, representing a broader scope of the energy system, and will allow to investigate added-value insights from modelling the interactions between the main layers, sectors, and components of the energy-economic system. Nexus, will, in a first stage, concentrate on the electricity sector. Future research in this area will, for example, look the addition of other energy carriers. As the Nexus framework is modular, it can be extended in the future with other models (e.g., transportation sector, environmental) and other energy markets (e.g., gas). Once the linking among the models is complete, we aim to set up a platform allowing to interact with other researchers in the field. In a future stage, this platform would allow other modelling groups to either add new modules or test their own versions of existing Nexus modules.

The Nexus modelling framework will address interdisciplinary research and policy questions of the overall economy-energy system by linking a set of highly specialized models. Typical topics that can be researched in more detail are, for example, changes in the future Swiss energy policy (energy and CO2 tax or subsidy regime, complete liberalisation of the electricity market), or new developments in energy supply and grid infrastructure. With this framework, our future research includes the assessment of research questions that are only possible under a broader modelling framework of the energy system, examples of these are[7]:

- What are the needs with respect to flexibility options in a scenario with high RES deployment? Are decentralized flexibility providers (e.g., battery storage and demand-side management) an alternative to hydro storage?
- What are the parameters influencing the investment decisions for hydro storage vs. decentralized flexibility providers? What is the optimal mix of flexibility providers when assessing different policy designs (e.g., impact of subsidies)?

Addressing these questions and analysing the multiple dimensions of the energy transition for the EU requires close cooperation between specialists of different fields. This conceptual paper aims to contribute to the discussion on the value of interdisciplinary research and the need for more transparency in energy modelling. Our experience has shown that this generates benefits compared to non-interdisciplinary work on more comprehensive modelling. Researchers can concentrate on and improve their own models instead of trying to link models from other fields themselves. Work on the Nexus prototype shows, however, that groups of linked modules should have also detailed knowledge of the other modules when working on the linkages. Furthermore, reaching a common understanding of the synergies among models often takes more time than expected. The linkage between the top-down and bottom-up model also forced us to reconsider the assumptions underlying our own models. In this regard, a critical challenge for our modelling framework is to continue harmonizing model assumptions by addressing deeper questions surrounding the energy transition. These questions might be: How do policies (e.g. energy efficiency measures in industry and buildings, carbon prices for bulk generation, renewables support for prosumers) complement each other to achieve the EUs 2030 and 2050 emission targets?

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[7] We are implementing the Nexus models to analyse decarbonization pathways of the Swiss energy system with a strong focus on the role of flexibility providers.

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