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Integrating short term variations of the power system into integrated energy system models: A methodological review

Seán Collins[a,b,c,*], John Paul Deane[a,b,c], Kris Poncelet[d,e,f], Evangelos Panos[g], Robert C. Pietzcker[h], Erik Delarue[d,e], Brian Pádraig Ó Gallachóir[a,b,c]

[a] Environmental Research Institute, University College Cork, Cork, Ireland
[b] School of Engineering, University College Cork, Cork, Ireland
[c] MaREI Centre, Environmental Research Institute, University College Cork, Cork, Ireland
[d] Department of Mechanical Engineering, KU Leuven, Leuven, Belgium
[e] EnergyVille, Genk, Belgium
[f] VITO, Mol, Belgium
[g] Paul Scherrer Institut,Villigen, Switzerland
[h] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

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ABSTRACT

It is anticipated that the decarbonisation of the entire energy system will require the introduction of large shares of variable renewable electricity generation into the power system. Long term integrated energy systems models are useful in improving our understanding of decarbonisation but they struggle to take account of short term variations in the power system associated with increased variable renewable energy penetration. This can oversimplify the ability of power systems to accommodate variable renewables and result in mistaken signals regarding the levels of flexibility required in power systems. Capturing power system impacts of variability within integrated energy system models is challenging due to temporal and technical simplifying assumptions needed to make such models computationally manageable. This paper addresses a gap in the literature by reviewing prominent methodologies that have been applied to address this challenge and the advantages & limitations of each. The methods include soft linking between integrated energy systems models and power systems models and improving the temporal and technical representation of power systems within integrated energy systems models. Each methodology covered approaches the integration of short term variations and assesses the flexibility of the system differently. The strengths, limitations, and applicability of these different methodologies are analysed. This review allows users of integrated energy systems models to select a methodology (or combination of methodologies) to suit their needs. In addition, the analysis identifies remaining gaps and shortcomings.

1. Introduction

The transition to a low-carbon energy system is expected to require the electricity sector to integrate large amounts of variable renewable energy sources (VRES) [1–4]. The instantaneous electricity generation by VRES is highly intermittent, location specific and only predictable to a limited extent. A massive penetration of VRES, therefore, has a strong impact on the operation of the power system [5–9]. Capturing the economic and technical challenges related to a large-scale penetration of VRES, therefore, requires modelling the variability in system load and renewable generation, the limited flexibility of thermal units and the spatial smoothing of the variability. This requires models with a high level of temporal, technical and spatial detail.

Long-term planning models have been applied frequently to analyse scenarios for the evolution of the energy system over multiple decades. Due to computational restrictions, the level of temporal, technical and spatial detail in these models is typically low. In contrast, operational power system models focus on the operations of the power system using a high level of detail but do not consider its long-term evolution.

Multiple authors have recently analysed the impact of temporal detail [10–16], technical detail [10,11,17–20] and spatial detail [21–23] employed in long-term planning models. Depending on the representation of integration challenges, low levels of detail can either favour or disfavour VRES: For high penetrations of VRES, If electricity

* Corresponding author at: Environmental Research Institute, Lee Road, Cork, Ireland.
E-mail address: sean.collins@umail.ucc.ie (S. Collins).

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is treated as a homogeneous good or only a low number of averaged time-slices is used, the low level of detail leads to an overestimation of the value of baseload technologies and VRES, while the value of flexible generation technologies with higher generation costs is underestimated [10]. In contrast, if a model uses rather crude representations of integration challenges such as upper limits on VRES shares or fix backup requirements, the low level of detail can overly restrict the deployment of VRES compared to more detailed representations [24]. As a result, the cost of achieving ambitious greenhouse gas emission reduction targets can be either significantly under- or overestimated.

Moreover, the importance of capturing critical elements of power system operation for planning a reliable and adequate power system is analysed in [25–29], making clear that a reliable operation of the power system cannot be guaranteed for the scenarios generated by current long-term planning models. As such, Pfenninger et al. [30] consider 'resolving time and space' to be the main challenge for energy system optimization models. For such long term modelling analyses it is also critical from an operational perspective to capture the current state of play and development of technologies so as to ensure a realistic trajectory of future technology development is considered [31–35].

Bridging the gap between highly-detailed operational power system models and long-term planning models has become an active field of research, in view of the challenge of the transition to a less carbon-intensive energy system. Numerous methodologies to bridge this gap have recently been developed [10,24,30,36,37].

This paper presents a review of prominent methodologies developed to better capture the economic and technical challenges related to the integration of VRES in two families of long-term planning models, namely long-term energy system optimization models (ESOMs) usually focusing on country-level (or group of countries, e.g. EU-level) scenarios for the next decades, and Integrated Assessment Models (IAMs), which focus on global long-term scenarios for the full 21st century. The strengths, limitations, and applicability of these different methodologies described in the literature are analysed. This analysis allows users of long-term planning models to select a methodology (or combination of methodologies) to suit their needs. In addition, the analysis exposes the needs for further research.

The remainder of this paper is organized as follows. First, Section 2 identifies the problem space by presenting a comprehensive overview of the different types of models and the level of temporal, technical and spatial detail typically employed in these models. Second, Section 3 presents the different methodologies developed in the literature for improved capturing of the economic and technical challenges related to the integration of VRES in planning models. The strengths and limitations of each approach are discussed in detail. Finally, main conclusions are formulated in Section 4.

2. Overview of energy modelling tools

This section first presents a brief description of the models considered in this paper, i.e., operational power system models, energy system optimization models and integrated assessment models. Subsequently, the level of temporal, technical and spatial detail typically used in each of these models is discussed.

2.1. Operational power system models

Operational power system models analyse the operations of a given power system, i.e., investment decisions are not considered. While there are large differences in the focus and applications of operational power system models [38], the focus of this work is on unit commitment and economic dispatch (UCED) models. UCED models determine for every time step within a certain time horizon which units should be online and how much each unit should be generating in order to minimize the cost of supplying a given demand for electricity. Detailed technical constraints, such as the minimal operating level, restricted ramping rates, minimum up and down times, start-up costs and efficiency losses during part-load operation are accounted for on a unit by unit level. Properly accounting for the minimal operating level requires tracking the commitment status of individual units. As such, most current UCED models rely on mixed-integer linear programming (MILP). Due to a large amount of integer variables, solving UCED models can be computationally challenging. The time horizon of UCED models is typically restricted to one day up to one year. This time horizon is disaggregated into different time steps with a resolution in the range of 5 min up to one hour. Prominent examples of UCED models include PLEXOS [39], LUSYM [40], GTMax [41], ORCED [42] and EnergyPLAN [43].

While UCED models allow analysing the operation of the power system in detail, these models do not allow to consider the (cost-optimal) evolution of the installed generation capacity. Moreover, the scope of these models is restricted to the power system. Interactions with other energy sectors such as the heating and transport sector are generally modelled by exogenously specifying the demand for electricity.

2.2. Long-term energy system optimization models (ESOMs)

ESOMs are used mainly to generate scenarios for the long-term evolution of the energy system. As such, ESOMS compute the investments and operation of the energy system that result in a partial equilibrium of the energy system, i.e., ESOMs simultaneously compute the production and consumption of different commodities (fuels, materials, energy services) and their prices in such a way that at the computed price, production exactly equals consumption. This equilibrium is referred to as a partial equilibrium since the scope of ESOMs is restricted to the energy system (comprising the power sector, transport sector, heating sector, etc.), being merely a part of the overall economic system. To compute this partial equilibrium, ESOMs rely on the fact that this equilibrium is established when the total surplus is maximized (or when total cost is minimized in case of an inflexible demand). Optimization techniques, such as linear programming, are applied to retrieve the investments, production and consumption patterns as well as trade flows yielding a maximal surplus. In contrast to some of the IAMs discussed below, partial equilibrium models are bottom-up models, meaning that each specific sector is composed of multiple explicitly defined technologies which are interlinked by their input and output commodities. Regarding the geographical scope, ESOMs are generally applied to countries or regions, but can also be applied on a city level. The time horizon spanned is generally multiple decades. The main strength of ESOMs is that these models provide a comprehensive description of possible scenarios for the transition of the energy system by considering the inter-temporal, inter-regional and inter-sectoral relationships. A limitation of ESOMs that are applied to only one country is that they ignore the potential benefit of international cooperation for the integration of VRES via expanded transmission grids. Well-known examples of ESOMS are MARKAL/TIMES [44], MESSAGE [45] and REMIX [46].

2.3. Integrated assessment models

IAMs and ESOMs share many characteristics and can consist of the same modelling frameworks.[1] The main difference is their aim and

[1] The IAMs ETSAP-TIAM and TIAM-UCL use the TIMES modelling framework, while IIASA's MESSAGE IAM model is built on a MESSAGE modelling framework with additional non-energy sector modules. MESSAGE modelling framework is distributed by the IAEA for national and regional planning purposes. [47] ETSAP. http://www.iea-etsap.org/web/applicationGlobal.asp 2016, [48] UCL. https://www.ucl.ac.uk/energy-models/models/tiam-ucl/#etsap-tiam. 2016, [49] Messner S, Schrattenholzer L. MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy. 2000;25:267-82.