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Balmorel open source energy system model

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ABSTRACT

As the world progresses towards a cleaner energy future with more variable renewable energy sources, energy system models are required to deal with new challenges. This article describes design, development and applications of the open source energy system model Balmorel, which is a result of a long and fruitful cooperation between public and private institutions within energy system research and analysis. The purpose of the article is to explain the modelling approach, to highlight strengths and challenges of the chosen approach, to create awareness about the possible applications of Balmorel as well as to inspire to new model developments and encourage new users to join the community. Some of the key strengths of the model are the flexible handling of the time and space dimensions and the combination of operation and investment optimisation. Its open source character enables diverse, worldwide applications for exploratory energy scenarios as well as policy analysis as the applications outlined demonstrate. The existing functionality and structural suitability for extensions make it a useful tool for assessing challenges of the ongoing energy transitions. Numerous model extensions have been developed as different challenges to the energy transition have arisen. One of these includes the option of running the model with unit commitment. To meet new challenges, further development is needed and consequently the article outlines suggestions for future development, such as including transport of local biomass as part of the optimisation and speeding up the model.

1. Introduction

The conversion of energy sources to electricity and the delivery of heat and transportation services are both technically complex and have large economic and environmental implications to society. For these reasons, energy system modelling has a long tradition spanning back to the 1950s when linear programming was utilised for capacity expansion planning [1]. Planning of more sustainable energy supply gained attention in energy modelling after the oil crisis in 1970s [2]. Today, energy system models are widely used by energy companies, policy makers and research institutions to increase insight into energy markets, future energy system development and implications of energy policies. The increasing efforts to replace fossil fuels with renewable energy resources in order to mitigate climate gas emissions and to address challenges like energy security, scarcity of resources and energy affordability, shift the temporal and spatial scope of analysis. Further, the electricity, heating and transportation sectors will likely become more integrated. These developments add new complexity to energy systems and thereby new challenges to energy system models. The benefits of energy system modelling tools become even more evident under this development. Balmorel is one such tool which has a long application history of extensive use in both public and private sectors.

Balmorel is a bottom-up partial equilibrium energy system optimisation model with a special focus on electricity and district heating sectors. The first version of Balmorel was released in 2001 by Hans Ravn et al. [3]. Since the first version, an extensive cooperation between research institutions and consultancies in several countries have gradually developed the model according to new

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needs and demands as the energy sector has evolved. The source code has been provided online since 2001 and was assigned the ISC license in 2017 [4]. Balmorel fulfils one of the preconditions for required transparency for energy models since its code is open source. Also, all input data and all data manipulations are in clear code, with documentation in Ref. [5]. The solution is obtained by application of solvers for which the principles and properties of the obtained solution have been part of the standard repertoire for decades [6].

The objective of this paper is three fold: 1) To describe the Balmorel model as of 2017.2) To discuss the experiences from close to 20 years of continuous model development. 3) To illustrate the main strengths and weaknesses of the model in its latest form (July 2017). First, a concise model description is given (Sections 2.1, 2.2, 2.3) including formulation details (Section 2.4), structure (Section 2.5) and its open source character (Section 2.6). Second, a brief overview of applications is given (Section 3). Finally, strengths (Section 4.1) and limitations (Section 4.2) of the model are discussed and potential future development (Section 4.3) as well as challenges of the open source character (Section 4.4) are outlined.

2. Model description

2.1. Overview

Balmorel is a partial equilibrium model for simultaneous optimisation of generation, transmission and consumption of electricity and heat under the assumption of perfectly competitive markets [3,5,7]. The model finds the optimal way to satisfy the energy demand maximising social welfare, viz., consumers' utility minus producers' cost of electricity and district heat generation, storage, transmission and distribution; subject to technical, physical and regulatory constraints.

Balmorel is written in the GAMS (General Algebraic Modelling System) modelling language [8] and built in a generic, extensible modular structure (cf. Section 2.5); therefore, new energy commodities (e.g. hydrogen or biofuels production) and features (e.g. transportation) might be included through addons in the basic modelling framework, which is described in this section.

The Balmorel core model is linear, but mixed-integer modelling may be applied, e.g. in order to represent economies of scale and unit commitment.

The model is data-driven and has a high degree of flexibility with respect to temporal and spatial options. Time might be defined chronologically in three layers, while the basic time unit (e.g., two hours, hour, half hour, etc.) is not predefined in the structure of the model. Concerning space, Balmorel is divided into three hierarchical geographical entities (cf. Section 2.2). The level of detail of the temporal and spatial dimensions will be user-defined.

Resources' market prices and final energy demands are exogenous parameters in Balmorel. Availability of some resources might be exogenously constrained, in case the system has no or limited access to interregional trade markets.

The base model includes conversion of energy resources to electricity and heat, storage and transmission and associated costs and losses related to energy distribution.

The supply side consists of various generation technologies, whose planned capacity, commissioning and decommissioning is defined exogenously. New capacity investment and endogenous decommissioning are found as a result of the optimisation. These technologies have specified fuel types, fuel efficiency, investment and operation & maintenance (O&M) costs, ratio between power and heat production (co-generation units), expected technical lifetime, as well as environmental characteristics for each technology; such as SO2, NOx or CH4 emissions. Variable renewable energy (VRE) technologies (e.g., wind, solar power, solar heat, run-of-river and reservoir hydropower) have production or inflow profiles exogenously given at each time segment and geographical entity, with the possibility of curtailment.

There are two types of storage implemented in Balmorel: short-term storages of electricity and heat and long-term storages of electricity, heat and hydrological reservoirs. All storages are limited by storage dynamics.

Electricity trade in Balmorel might take place between different Regions,[2] subject to the capacity of transmission lines -including existing, planned and endogenous investments- and their availability. Trade of electricity with third Regions, which are not explicitly modelled, can be defined by providing exogenous power flows per time segment or through prices and limits to power transmission, where the exact amount of electricity trade at each time segment with the third Region is determined endogenously.

Energy balance constraints ensure that energy supply equals demand at every time segment and geographical entity. The equilibrium condition provides energy commodity prices for all geographical entities and time segments. The optimal solution is found along with associated dual variables, or shadow prices.

Different running modes can be applied depending on the desired level of foresight for optimisation between time segments and if endogenous investments are taken into account (cf. Section 2.3).

Fig. 1 illustrates the core structure of the model. Depending on the application, various types of electricity and heat demands, additional technologies etc. can be defined. Where appropriate, the input may be differentiated with respect to technologies, time and space.

2.2. Spatial and temporal dimensions

2.2.1. Spatial resolution

Space is in Balmorel defined by using three layers of geographical entities. The entities are from broadest to narrowest: Country, Region and Area. The entities are organised in a hierarchy such that each Region or Area belongs to exactly one Country or Region, respectively. However, each Country can contain many Regions and each Region can contain many Areas.

The Country layer allows for general economic input to be defined, such as policy measures, renewable energy targets, resource restrictions and fuel prices. The Country level is also extensively utilised for summarising results.

Between Regions, power transmission limitations can be defined such that congestion can be modelled within a Country. Another distinguished feature of the Regional layer is that here the electric power demand is defined and electricity balance is maintained. Therefore, on the Region level, the marginal cost of supplying power demand can be observed, which can be interpreted as the geographically specific market price of power in the model output. The model may be set up for the Regions to depict market bidding entities, nodes or used for congestion analysis. No power grid is considered inside a Region i.e. a copper plate system is assumed.

Areas are used to represent individual geographical characteristics within a Region. Wind, hydro, solar and other climate conditions are defined on the Area level, as well the type and capacity of all power and heat generating and storage units. Because a Region can include multiple Areas, more than one set of climate conditions can be defined within a Region. For example, two Areas

[2] The words Country, Region, Area, Year, Season and Term are capitalised in this paper when referring to Balmorel model specific denotation.