



Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making



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ARTICLE INFO

Article history:

Received 6 January 2015

Received in revised form

1 June 2015

Accepted 3 June 2015

Available online 17 July 2015

Keywords:

Large-scale energy system

Energy planning

Energy modelling

Decision-making support

ABSTRACT

Concerns related to climate change and security of energy supply are pushing various countries to make strategic energy planning decisions. This requires the development of energy models to aid decision-making. Large scale energy models are often very complex and use economic optimization to define energy strategies. Thus, they might be black-boxes to public decision-makers. This work aims at overcoming this issue by proposing a new modelling framework, designed to support decision-makers by improving their understanding of the energy system. The goal is to show the effect of the policy and investment decisions on final energy consumption, total cost and environmental impact.

The modelling approach and the model structure are described in detail. Final energy consumption is represented as the sum of three main components: heating, electricity and transportation. In this framework, a sequential modelling strategy allows the assessment of the competition between electricity and fuels in the heating and transportation sectors without increasing the model complexity. A monthly resolution is chosen in order to highlight seasonality issues of the energy system. Developed with the goal of being easily adaptable to any large-scale energy system, the modelling approach is currently implemented within an online energy calculator for the case of Switzerland.

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1. Introduction

Extending current trends to the year 2050, the IEA (International Energy Agency) projects a 70% increase in global energy demand and a 60% increase in greenhouse gas emissions compared with 2011. This would imply potentially devastating consequences related to climate change. Measures to constrain the expected increase in global temperatures to a 2 °C threshold show the need of limiting the increase in energy demand to 25% and to radically cut emissions by 50%. Thus, various countries are in the process of making strategic energy planning decisions in order to reach these ambitious goals [1].

Switzerland is one of the countries facing this energy transition. Although autonomous on a yearly balance, the country today already relies on electricity imports to face higher demand in winter months. Switzerland's governmental decision to phase out nuclear power plants by 2034 [2], which accounted for 40.7% of the electricity production in 2011 [3], will have as a consequence a

further increase in the seasonal energy deficit, raising as well issues related to energy security.

In this context, large-scale energy models can be developed to support public decision-makers in the definition of the energy strategy. A new modelling approach is proposed for this purpose. The modelling approach is currently implemented in the energy calculator of Swiss-Energyscope [4], an online platform developed by the Energy Center of EPFL [5] to spread energy literacy and help citizens and public decision-makers to understand and contribute to the debate about the Swiss energy strategy.

1.1. Literature review

Climate change and security of energy supply are among the key challenges modern society is facing. As a result, a considerable effort has been made in order to gather a better understanding of the energy sector. A large number of techno-economic models for national energy systems have been developed [6]. Techno-economic energy models simulate the configuration and operation of a given energy system, investigating trade-offs between energy efficiency, cost and emissions.

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Nomenclature

$D_{j,k}$	annual energy demand of type k in sector j
SpD_k	specific energy demand for energy demand type k
GDP	gross domestic product
Pop	population
S_f	inhabited surface per capita
$SpaceHeating_i$	heat demand for space heating for the three sectors in month i
$HotWater_i$	heat demand for hot water for the three sectors in month i
$ProcessHeat_i$	process heat demand for the industry sector in month i
$Engines_i$	electricity demand for engines for the industry sector in month i
$Lighting_i$	electricity demand for lighting for the three sectors in month i
$OtherElec_i$	electricity demand for other uses for the three sectors in month i
$BusCoachDemand$	annual passenger transport demand to be covered by bus & coach

$ptBus_i$	annual passenger transport demand for bus&coach with power train i
L	heating load
P	installed power
$Group_j$	percentage of total installed power for the technology group j
$Tech_{j,k}$	percentage of total installed power for the technology k of group j
$TechFuel_{j,k,l}$	percentage of total installed power for the combination of group j , technology k and energy vector l
$HeatI_{i,k,l}$	heat supplied by technology k with energy vector l during month i in industry sector
$HeatC_{i,m}$	heat supplied by combination of technology m during month i
$PowerC_m$	installed power of the combination of technology m
$Price_i$	price for fossil fuel in year i
C	economic cost in CHF
i	interest rate
n	lifetime in years
E	emissions

In the literature the words “tool”, “model”, “modelling framework” and “model generator” are used interchangeably to refer to these models. Nonetheless, [7] states that “an energy model is a simplified representation of a specific energy system, whereas a tool, modelling framework or model generator refers to the computer program enabling the creation of various models”. From the authors' point of view, a modelling framework is the methodology applied for the development of the model. This methodology can be adapted to countries or cities to respectively develop national or urban energy model. The word “tool” refers to the type of interaction between users and the model. Users select the tool depending on the question they want to answer.

Based on the performed literature review a classification of models and tools is proposed. Models can be divided into two categories: “evolution” and “snapshot”. Evolution energy models analyse the evolution of a national energy system over a time horizon. The time horizon extends from the initial year to the end year and is broken down into a series of multiple-year or single-year periods. Each period is in turn subdivided into time-slices. Time-slices represent time intervals with similar conditions (i.e. week-ends in winter, Monday mornings in summer, etc), with the purpose of better capturing seasonal, weekly or daily variations in energy supply and demand. Chronology is not taken into account in the use of time-slices. Three representative models of this category are MARKAL [8], OSeMOSYS [9] and 2050 Pathways model [10].

Snapshot models are used to evaluate the energy system configuration and operation over a timespan. “Energy system configuration” refers to the key characteristics of a national energy system, i.e. mix of technologies for electricity and heat supply, building stock, among others. The configuration of the energy system remains unchanged over the considered time span. The most common duration for the time span is one year, which is divided into chronological time-steps of 1 h or less. Two examples of this type of models are EnergyPlan [11] and HOMER [12].

Tools can follow two approaches: optimization and simulation. Often a model can be used for both purposes. Optimization tools provide the best solution for a defined objective. MARKAL [8] and OSeMOSYS [9] are optimization tools. Based on initial conditions and a set of assumptions (i.e. evolution of the prices of the fuels), these tools optimize the energy system evolution to meet

minimum cost. Simulation tools are designed to evaluate hypothetical scenarios. They evaluate different configurations and operations of the energy system from an energetic, economic and environmental point of view. The 2050 Pathways tool [10] shows the impact of certain decisions on the evolution of UK's national energy system. The decisions are linked to several energy domains such as power supply approaches or the measures to reduce demand. EnergyPlan [11] evaluates the consequences of different national energy investments and regulation strategies.

The main shortcomings of most of these tools are the complex user interaction and the computation time. The majority of the tools for modelling national energy systems requires a training period that can vary between one day and one month [6]. This creates a barrier between the decision making tools and the decision makers (politicians and citizens). Therefore the expert that has developed the model is typically the person in charge of building and presenting the possible energy scenarios to the decision makers [15]. The 2050 Pathways tool [10] breaks the mentioned barrier due to its reduced number of inputs, simplified outputs and low calculation time. Thus, under the ease-of-use point of view, the 2050 Pathways tool represents the state-of-the-art in this domain. Furthermore it does not require any download or installation as it is available under the form of a webtool [16].

Besides the ease-of-use shortcoming, simulation tools are considered to be a better option for users that are not specialists of the energy domain in comparison to optimization tools. The main limitation of optimization tools is that they offer a solution without guiding users in the understanding of the problematics of national energy systems. Furthermore, the optimization is often based on economic assumptions such as fuel prices evolution [13] or investment cost data [14], which tend to be highly uncertain. This uncertainty is very often not taken into account in the optimization.

Regarding the model type, the main gap of evolution models such as the 2050 Pathways model [10] is the fact that the concept of seasonal variation for supply and demand cannot be clearly studied as output data are aggregated to an annual level. Also, the implementation of technologies for heat and electricity storage cannot be investigated due to the lack of connection between the time slices. This is considered to be a key aspect since future energy scenarios will be characterized by high percentages of stochastic electricity

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