Energy xxx (2016) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Building scenarios for energy consumption of private households in Germany using a multi-level cross-impact balance approach

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ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form
28 November 2016
Accepted 1 December 2016
Available online xxx

Keywords:
Cross-impact balance
Energy demand of private households
Socio-technical scenario construction
Energy bottom-up model

ABSTRACT

A major goal concerning the energy transition in Germany is the reduction of energy usage. In Germany in 2011, private households consumed 2194 PJ and have been identified as a sector with high energy reduction potential. The energy demand of this sector is dependent on many linked quantitative and qualitative factors (e.g., number of persons and demographic structure, expenditures, cost of energy-saving measures, willingness to invest, and level of coordination in international climate policy). In our study, we introduce a multilevel cross-impact approach which allows for the definition and quantification of data for scenario analysis while taking the interdependences between different factors on the global, national and sectoral levels into account. This approach makes it possible to overcome limitations that conventional energy models are usually confronted with. By applying a trend analysis in combination with information on the interdependence of relevant factors on the global and national levels, consistent sectoral views of the private household's future are created.

1. Introduction

To limit the effects of global warming to 2 °C, the EU has committed to reducing greenhouse gas emissions by 20% compared with 1990 by the year 2020. By 2050, the greenhouse gas emissions of the EU should be reduced by 80–95% in comparison to 1990 levels [1]. The German government has integrated these climate change targets in the German energy concept [2]. Due to the decision to accelerate the phasing out of nuclear energy, the contributions of climate change and energy efficiency in buildings are becoming increasingly important [3]. In Germany, approximately 28.5% of the final energy consumption stems from the household sector, making households crucial in energy reduction strategies. Indeed, the residential sector holds great potential for the reduction of energy use. Old buildings form the focus of this study, as more than 70% of current residential buildings were constructed before 1977, when the first insulation regulations were put in place. Renovations must occur to achieve carbon-neutral buildings as well as extensive time plans that include financing to double the modernization rate to 2% per year (see, e.g., [4]).

The energy demand of the private household sector depends on many factors such as the number of households, age distribution of the population, disposable income, costs of energy-saving measures, willingness to invest, and level of coordination in international climate policy (see, e.g., [5]). These factors have complex interrelationships with each other, which are sometimes expressed in scenarios explicitly, but very often are based on implicit assumptions (see, e.g., [6] or [7]). As one example of the use of implicit assumptions, trend projections of specific energy demand factors (as is often used in energy models) can be citied (see, e.g., [8,9]). Trend projections are based on the assumption that the explanatory variables will impact the dependent factor in the future in the same way as in the past. Especially for long-term analyses, assumptions about the continuation of trends have to be used very carefully because new technology will enter the market and black swans could occur (see, e.g., [10,11]). The danger of oversimplification might increase if only quantitative factors are taken into consideration while ignoring, e.g., driving forces such as

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http://dx.doi.org/10.1016/j.energy.2016.12.001
0360-5442/

behavior patterns and if international developments that may impact, e.g., national environmental policies are ignored [12].

These considerations are also strongly linked to questions on the selected system boundaries and the necessary and appropriate bandwidth of factors to be taken into account. For reasons of simplification, data that have been published by others are often used, ignoring possible feedbacks between one's own calculations and data extracted from somewhere else. Using data from different sources independently, ignoring feedbacks, leaving assumptions undocumented (implicit), as well as using assumptions without checking their links to each other may result in scenario inconsistencies (see, e.g., [13]).

The problems of scenario variety and consistency have been highlighted in several studies (see, e.g., [14]). In practice, however, there is still a lack of adequate approaches taking these aspects into consideration. In the following, we present such an approach, which has been further adapted to meet the requirements.

In the past, several techniques have been developed to meet the needs of interdependence analysis under the special conditions of multidisciplinary systems that include social systems (see, e.g., [15]). One of the most popular is a group of techniques denoted as Cross-Impact Analysis, originally introduced by Gordon and Hayward in 1968 [16]. The original intent of Cross-Impact Analysis was to assess the influence of interdependence on event probabilities in socio-technical systems. The analysis was based on expert judgments about the mutual influences of social, political, economic, environmental and technological events that may or may not occur in the future. Several method variants were also developed to serve specific purposes (e.g., [17]). This approach was partially used in combination with, e.g., fuzzy, multi-criteria and other methods (e.g., [18,19]). Weimer-Jehle introduced the Cross-Impact Balance Analysis as a variant of Cross-Impact Analysis designed to facilitate a traceable and systematic construction of qualitative or semi-qualitative scenarios based on expert judgments on the relevance and the interdependence of the scenario factors [20]. Since then, Cross-Impact Balance Analysis (CIB) has been applied in many analyses dealing with energy [21], sustainability [22], innovation [23], health care [24], waste ([25,26]), and climate change (e.g., [13,27]).

Although CIB seems to be well suited for assisting energy modelers by providing a method for systematically analyzing interacting driving forces and constructing diverse and consistent sets of framework assumptions we recognize a significant shortcoming: for a comprehensive study of driving forces of a energy system, many drivers on very different geographical and political levels have to be taken into account and this is conflicting with the usual size of CIB analysis, which typically comprises approx. 10–20 factors. The potential of applying CIB in the field of energy modeling could be therefore substantially improved by developing techniques to deal with higher numbers of factors.

In this paper, we use the Cross-Impact Balance (CIB) approach for creating consistent storylines taking quantitative and qualitative factors into account that are directly and indirectly relevant for the energy consumption of the residential sector in Germany. For avoiding aforementioned limitations of the CIB regarding the number of factors that could be taken into account and for improving the flexibility of the usage of the approach for other research questions, we present a multilevel Cross-Impact approach. First, we analyze trends and interdependencies of various quantitative and qualitative factors on the global, national and sectoral levels. Based on information on the links between these factors, level-specific futures will be identified. Afterwards, storylines will be created by matching the identified level-specific futures.

Using a technology-based bottom-up model for the residential sector, we calculate changes in specific energy savings and CO_2 reductions for this sector, taking the results of the CIB-analysis into account as a framework and taking into consideration that there is a certain degree of freedom in the concretization into numbers that results from the semi-quantitative characteristics of the states of the factors considered in the CIB-approach (see Ref. [28]).

In our analysis, we proceed as follows: In Section 2, the developed multi-level Cross-Impact Balance approach as well as the resultant consistent multi-level futures will be presented and discussed. The identified storylines are used in section 3 as a framework for the assessment of the energy demand and CO_2-emissions of the residential sector in Germany in the year 2030. Section 4 concludes our findings and reflects upon their significance.

2. Building storylines using multi-level CIB analysis approach

2.1. Preliminary remarks

For the creation of scenarios for the household sector, it is necessary to specify the social, political, economic and technological frameworks, taking the main drivers and their interactions into account (see e.g., [29]). An instrument to qualitatively assess drivers and interactions for the design of future views in a consistent way is Cross-Impact analysis [13]. After defining the system under study, the participating experts are asked for a list of factors, so-called descriptors, which may be directly or indirectly relevant for the selected research question. In the next step, the experts have to specify possible outcomes of the factors and judge the interactions among the outcomes by evaluating the direct influence of each outcome on another one. “0” will usually be used as the value if an outcome does not have any influence on the other one. A strong positive influence is indicated by using “+3”, and “−3” for a strongly negative influence. Lower influences are assessed by using “+2”, “+1”, “−2“, and “−1” [20]. The resulting Cross-Impact matrix provides information on all interactions among descriptor outcomes. Based on this matrix, possible futures can be identified by combining the resulting outcomes into a set. A future is considered to be consistent if, for each factor, the selected outcome is supported at least as strongly as any other outcome of the corresponding factor (measured in terms of the balance of all incoming impacts on the outcome). If another outcome dominates the selected one, this will be considered to be a contradiction between the assumed set of outcomes.

A common CIB analysis generally includes 10–20 descriptors so that the Cross-Impact matrix is not too large and complex. To overcome the limitation regarding the number of descriptors, we selected a multilevel approach linking different cross-impact matrices. Each matrix focuses on selected aspects, i.e., factors on the global, national and sectoral scales. By using different matrices, we are able to combine information of a great number of different descriptors without restrictions due to the size of the cross-impact matrix (Fig. 1).

The “global” Cross-Impact matrix aims to describe links between factors on the international level that could have an impact on energy supply and demand in Germany or on the development of the residential sector directly. A “national” Cross-Impact matrix is used to formulate relationships at the national level, and the “sectoral” Cross-Impact matrix considers relationships in a single sector. Identifying the key factors at the interface of the different levels that influence the scales below and including them into the matrices, the resulting level-specific futures can be merged into cross-cutting futures.[1] These cross-cutting futures serve as guidelines for the specification of parameters that can be used in a

[1] Level-specific futures are calculated by using ScenarioWizard 4.11 Software (see Ref. [30] for more information on the software).