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Economic potential for future demand response in Germany – Modeling approach and case study

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HIGHLIGHTS

- A novel demand response (DR) representation in an energy system model is introduced.
- The method can be transferred to any such model using simple linear optimization.
- The economic DR potential in Germany is assessed for a renewable energy scenario.
- Results show that DR can economically substitute up to 10 GW of power plants.
- DR furthermore affects renewable energy curtailment and power plant operation.

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ABSTRACT

The activation of demand response (DR) potentials offered by electricity consumer flexibility is one promising option for providing balancing power and energy in supply systems with high share of variable renewable energy (VRE) power generation. In this paper, a model-based assessment of the economic DR potential in Germany is presented. It relies on the extension of the REMix energy system model by flexible electric loads. In a case study considering a future German power supply system with a VRE share of 70%, possible cost reductions achieved by investment in DR are quantified. The sensitivity of the results to changes in the assumed DR costs and characteristics are analyzed in additional simulations. The results show that the major benefit of employing DR is its ability to substitute peak power generation capacity, whereas the impact on the integration of VRE power generation is lower. This implies that the focus of DR is on the provision of power, not energy. Even at rather pessimistic cost DR assumptions, more than 5 GW of power plant capacity can be substituted. Consumer flexibility furthermore triggers an increase in the operation of back-up power plants, whereas it decreases the utilization of pumped storage hydro stations. In the model results, the reductions in annual power supply costs achieved by DR add up to several hundreds of millions of Euros.

1. List of symbols

Table 1.

2. Introduction

2.1. Background

In the past years, solar photovoltaic (PV) and onshore wind power technologies have experienced significant cost reductions [1]. Both are increasingly contributing to the electricity supply in Europe and worldwide [2]. Due to the intermittent nature of wind speed and solar irradiation, they can however provide firm capacity only to a very limited extent or not at all. Fluctuations in their power generation consequently need to be balanced by other technologies in the energy system. Available options comprise dispatchable renewable or conventional (i.e. fossil-fuel or nuclear) power plants, as well as energy storage, load flexibility and long-range power transmission. With even higher variable renewable energy (VRE) capacities, balancing needs will continue to increase. Thereby, one promising option is seen in an increased load flexibility, or demand response (DR). It relies on short term customer action [3,4] and makes use of consumer demand elasticity, which is typically provided by thermal inertia, demand flexibility or physical storage.

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Table 1
Parameters and variables used in the modeling of demand response.

Symbol	Unit	Variable
$\boldsymbol{P}^{H}_{red}(t)$	GW_{el}	Demand response load reduction in shift class H
$\boldsymbol{P}^{H}_{inc}(t)$	GW_{el}	Demand response load increase in shift class H
$\boldsymbol{P}^{H}_{balRed}(t)$	GW_{el}	Balancing of earlier load reduction in shift class H
$\boldsymbol{P}^{H}_{balInc}(t)$	GW_{el}	Balancing of earlier load increase in shift class H
$\boldsymbol{W}^{X}_{levRed}(t)$	GW h_{el}	Amount of reduced and not yet balanced energy of technology X
$\boldsymbol{W}^{X}_{levInc}(t)$	GW h_{el}	Amount of increased and not yet balanced energy of technology X
$\boldsymbol{P}^{X}_{adCap}$	GW_{el}	Installed electric capacity of additionally DR consumers
$\boldsymbol{C}_{invest}$	k€/a	Investment costs
$\boldsymbol{C}_{op}$	k€/a	Operation and maintenance costs
		Parameter
t^{H}_{shift}	h	DR shifting time (maximum duration until balancing)
η^{H}_{DR}	$\frac{1}{100}$	DR efficiency
$t^{X}_{interfere}$	h	DR interference time (maximum duration of load change)
$t^{X}_{dayLimit}$	h	Waiting time between two DR interventions
$n^{X}_{yearLimit}$	$1/a$	Annual limit of DR interventions
P^{X}_{exCap}	GW_{el}	Installed capacity of all appliances in DR technology X
P^{X}_{maxCap}	GW_{el}	Maximum installable capacity of appliances in DR technology X
$s^{X}_{flex}(t)$	GW_{el}	Maximum load reduction relative to installed capacity
$s^{X}_{free}(t)$	GW_{el}	Maximum load increase relative to installed capacity
$\bar{s}^{X}_{flex}$	GW_{el}	Average load reduction potential relative to installed capacity
$\bar{s}^{X}_{free}$	GW_{el}	Average load increase potential relative to installed capacity
$c^{X}_{specInv}$	k€/MW	Specific investment cost
c^{X}_{OMFix}	%/year	Operation and maintenance fix costs
c^{X}_{OMVar}	k€/ MW h	Operation and maintenance variable costs
t^{X}_{amort}	years	Amortization time
i	%	Interest rate
$f^{X}_{annuity}$	–	Annuity factor

2.2. State of knowledge

The available literature on DR is mostly focused on qualitative analyses of benefits and challenges, technical description of modeling approaches of the DR behaviour of specific loads, evaluation of DR field studies or identification of technical potentials. Detailed studies of DR utilization are typically restricted to selected loads and/or small geographic areas.

Without addressing specific loads, Strbac [5] has identified a broad range of potential benefits achieved by DR, including higher profitability of power plants, avoidance of investments in additional generation or grid capacities, as well as increased VRE power integration. On shorter time scales of only a few seconds, DR can furthermore be applied for power quality and grid frequency stabilization using dynamic demand technologies. On the other hand, Strbac [5] also discusses the challenges of a higher utilization of demand flexibility for balancing purposes, ranging from economic to social and administrative aspects. Based on a review of existing studies and policy documents, as well as a quantitative analysis of the provision of reserve capacity in unforeseen events, Bradley et al. [6] conclude that an application of DR can generate economic benefits in the United Kingdom (UK). Taking into account load shifting of electric space and water heating, as well as controlled electric vehicle charging, Barton et al. [7] provide a model-based analysis of the potential DR application for the UK in hourly resolution. In three scenarios for the year 2050, they identify substantial reductions in VRE surplus power and residual load, as well as higher power plant capacity utilization. Their model, however, does consider neither capital and operational costs, nor restrictions in power transmission. Bergaentzlé et al. [8] assess the impact of DR measures on electricity supply costs in a selection of interconnected European countries with different power plant park composition. Their application of a simple optimization model considers a peak and an off-peak demand period, and shows that DR can improve system efficiency and reliability and reduce costs in systems based on conventional generation. In a model-based assessment of the Azores island of Flores, Pina et al. [9] show that residential load shifting can delay investment in new generation capacity and increase operation times of existing power plants. However, the simulation of DR operation is restricted to a number of representative demand and supply situations. The impact of DR on the electricity supply in Hawaii is assessed in [10]. The study relies on the application of a capacity expansion model in hourly resolution and reveals substantial cost reductions achieved by shifting of fictitious loads.

Without providing a quantitative assessment, Hamidi et al. [11], Soares et al. [12], Grünewald and Torriti [13], Torriti [14] have identified DR resources in a broad range of processes and devices throughout all sectors. According to [15–17], shiftable and sheddable loads in Germany add up to several GW. A first comprehensive quantification of DR potentials in Europe is provided by [18]. Whether and to what extent these potentials can be economically exploited is, however, not analyzed in any of these works.

A genetic algorithm for DR modeling is presented in [19]. It is applied to an assessment of theoretical DR potentials of residential and commercial loads in a representative model region in Germany. A DR modeling approach is also provided by [20]. The authors choose a representation of load shifting as storage device with variable reservoir size. However, restrictions in the frequency of DR, as well as losses and costs arising from load shifting are not taken into account. Based on a comparison of publicly available energy system models concerning the DR application in an island system, Neves et al. [21] conclude that the model representation of DR needs to be improved.

The impact of feedback and time-of-use tariffs on electricity demand and potential DR contribution has been investigated in field trials [22–24], as well as economic models [25–28]. The cited case studies of DR utilization in today's electricity supply systems are focused on small geographic areas and selected demand sectors or consumers, whereas the modeling approaches are applied exclusively to selected loads and exemplary demand profiles.

So far, no comprehensive and model-based assessment of the economic DR potential in Germany considering both the available flexibility resources and the overall supply system dispatch has been presented. This paper closes the gap between assessments of technical potentials of load flexibility, DR modeling approaches, as well as comprehensive energy system models and assessment of future power supply scenarios.

2.3. Scope and structure of this work

In this paper, the implementation of electric load shifting and shedding in the energy system model REMix is introduced. Subsequently, the novel modeling approach is applied to assess the economic competitiveness of DR in a future German electricity supply system primarily relying on fluctuating renewable resources. In doing so, different assumptions concerning DR costs and temporal availability of flexible loads are taken into account.

The paper opens with a brief description of the REMix model environment, before providing detailed insight into the DR modeling approach. In the following, the set-up and input data of the case study are introduced. Finally, model results are presented and discussed, and conclusions concerning the economic DR potential in Germany are drawn.