Economic Potential for Future Demand Response in Germany – Modelling Approach and Case Study

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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 analysed 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.

Keywords:
Demand Response, Energy System Modelling, Load Balancing, Demand Side Management, Renewable Energy

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

1 List of Symbols

Table 1
Parameters and variables used in the modelling 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.
$\boldsymbol{W}^{X}_{levRed}(t)$	GWh_{el}	Amount of reduced and not yet balanced energy of technology X.
$\boldsymbol{W}^{X}_{levInc}(t)$	GWh_{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.
Symbol	**Unit**	**Parameter**
t^{H}_{shift}	hours	DR shifting time (maximum duration until balancing).
η^{H}_{DR}	$\frac{1}{100}$	DR efficiency.
$t^{X}_{interfere}$	hours	DR interference time (maximum duration of load change).
$t^{X}_{dayLimit}$	hours	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.
$\overline{s}^{X}_{flex}$	GW_{el}	Average load reduction potential relative to installed capacity.
$\overline{s}^{X}_{free}$	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€/MWh	Operation and maintenance variable costs.
t^{X}_{amort}	years	Amortization time.
i	%	Interest rate.
$f^{X}_{annuity}$	-	Annuity factor.

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.

2.2 State of Knowledge

The available literature on DR is mostly focused on qualitative analyses of benefits and challenges, technical description of modelling 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, [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, [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, [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, [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 re-

ductions 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. [8] assesses 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, [9] shows 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, [11; 12; 13; 14] have identified DR resources in a broad range of processes and devices throughout all sectors. According to [15; 16; 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 analysed in any of these works.

A genetic algorithm for DR modelling 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 modelling 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, [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; 23; 24], as well as economic models [25; 26; 27; 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 modelling 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 modelling 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 modelling 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 modelling 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.

3 Methodology: Enhancement of the REMix model

3.1 REMix Modelling Approach

REMix[1] is a deterministic linear optimization program realized in GAMS[2]. It has been developed with the aim of providing a powerful tool for the preparation and assessment of future energy supply scenarios based on a system representation in high spatial and temporal resolution [29; 30; 31]. Starting with renewable energy technologies, different power generation, storage and transmission technologies have been included in the model. The model set-up, as well as its input and output are shown is Figure 1.

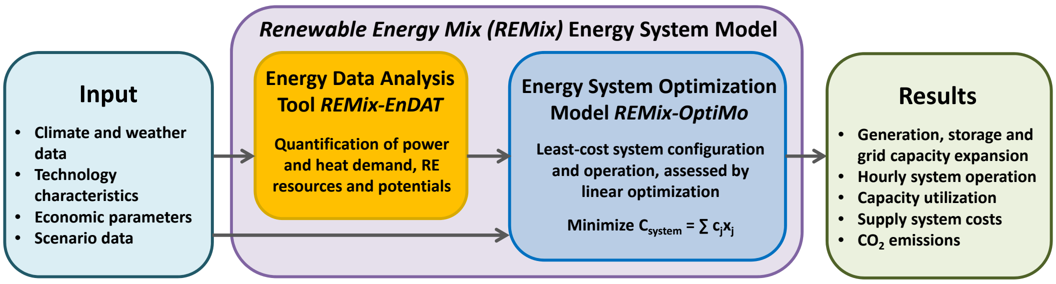


Figure 1. REMix model structure.

[1] Unless otherwise expressly provided, here and in the following the name *REMix* refers to the optimization model *REMix-OptiMo* within the overall modelling framework (see Fig. 1)

[2] General Algebraic Modeling System (GAMS) is a modelling system for mathematical programming and optimization (www.gams.com).

The model is programmed in a modular structure. Each technology is represented by an independent module, containing parameters, variables, equations and inequalities required for the representation of respective technical and economic characteristics. REMix is a multi-node model. Demand and supply within predefined geographical regions are aggregated to model nodes, which can be connected through AC or DC power lines. Within the nodes, all generation units of each technology are grouped and treated as one single power producer. This implies that the model does not account for individual power plants or blocks. Depending on the definition of model nodes, grid interconnections do not reflect single transmission lines but the overall net transfer capacity (NTC). Power flows within the regions, including low-voltage power lines, as well as distribution grids are not modelled. The model relies on a perfect foresight modelling approach and optimizes over the overall time horizon. REMix is designed to offer a high flexibility concerning geographical or technological focus. All modules can in principle be applied to regions of all sizes, ranging from world regions to single cities.

Most technology modules not only allow for technology dispatch, but optionally also for capacity expansion analyses. Additional power plants, transmission lines and storage facilities can be optimized by the model according to the available potentials and system requirements. Investments in new capacities consider the technology costs, as well as an amortization time and interest rate. They allow for the calculation of proportionate capital costs for the chosen optimization interval.

REMix is characterized by its objective function, boundary conditions and constraints. The latter are parametrized using a comprehensive set of input data. Model variables comprise technology-specific power generation, heat production, power transmission and storage in each time step and model region. If a capacity expansion is considered, the additional capacities in each region are furthermore taken into account. The objective function that is minimized is the sum of system costs in the overall investigation area. Its composition depends on the set of active technology modules.

The model application presented in this work uses the technology modules of VRE, reservoir hydro stations, conventional power plants, electricity-to-electricity storage, as well as DC power transmission. The mathematical equations of these modules are introduced in [32]. Here, the detailed model description is limited to the newly developed DR representation.

3.2 Modelling of Flexible Electric Loads

In this section, concept and modelling details of flexible power consumption in REMix are introduced. It contains all equations and inequalities implemented in the DR module.

3.2.1 Demand Response Modelling Concept and Input

DR measures considered in the REMix module include load shedding, as well as load shifting to an earlier or later time. Most important inputs to the model are hourly time series of available load flexibility. For each country, DR load and hour of the year, potential load increase $P_{free}(t)$ and load reduction $P_{flex}(t)$ are provided. They are defined relative to the maximum electric capacity P_{maxCap} that can be made available for DR. The hourly values reflect the load profile of the corresponding load, as well as the share of regular load and unused capacity available for load reduction or increase, respectively. In addition to the hourly load reduction and increase potential, techno-economic model input include shifting time t_{shift}, interference time $t_{interfere}$, efficiency η_{DR}, day limit t_{dayLim} and year limit $n_{yearLim}$ on the one hand, and specific costs for the exploitation $c_{specInv}$, annual provision c_{OMFix} and call of the DR potential c_{OMVar} on the other. Figure 2 illustrates the key parameters describing the DR application in REMix.

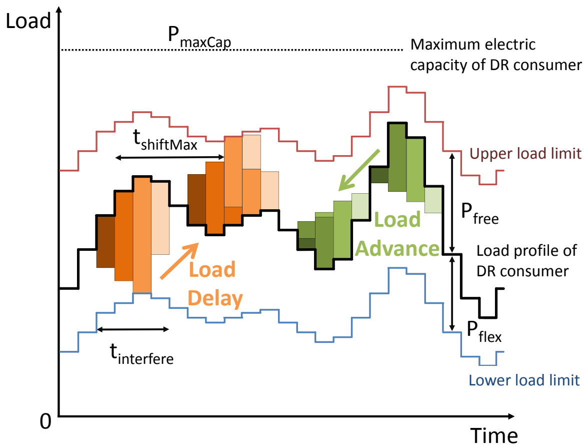


Figure 2. Parameters describing the DR application. $t_{interfere}$ limits the duration of DR interventions, $t_{shiftMax}$ the time between shifting and balancing of load. P_{flex} and P_{free} define consumer-specific loads available for DR.

Flexible consumers are modelled in REMix as functional electricity storage with limitations in storage time and availability. The latter includes temporal fluctuations in charging and discharging capacity on the one hand, and restrictions in frequency and duration of use on the other. The charging capacity of the functional storage is determined by the flexible load, its reservoir capacity by the maximum duration of DR interventions $t_{interfere}$, and its maximum storage period by the shifting time $t_{shiftMax}$. The shifting time defines until when load increases and decreases have to be balanced at latest, whereas the intervention time reflects a limit in duration of changes in the normal demand pattern. Taking into account an annual limit in number of DR interventions $n_{yearLim}$, the storable energy per year can be calculated.

Typically, load shifting provides a certain flexibility regarding the time that passes before loads need to be balanced again. This implies that all shifting times $t_{shift} \leq t_{shiftMax}$ can be realized. Consequently, the balancing of previous load shifts in time step t ranges between an upper limit set by the delta of all shifted and not yet balanced load and a lower limit defined by the delta of still unbalanced load shifts conducted until $t - t_{shiftMax}$. An implementation of flexible shifting times into REMix turned out to be inexpedient. The multiple usage of temporal sums that connect all time-steps of the annual calculation lead to extremely long model solutions times. For this reason, fixed shifting times are implemented instead. This implies that the moment of balancing of shifted load is already set when the load is increased or reduced at first. The impact of fixed shifting times on the model representation of load modifications can be reduced by the definition of various shifting times for each DR technology. Of course, the model then needs to assure that flexible loads are only shifted once. Figure 3 exemplary shows the distribution of the flexible load provided by one DR technology to various shift classes.

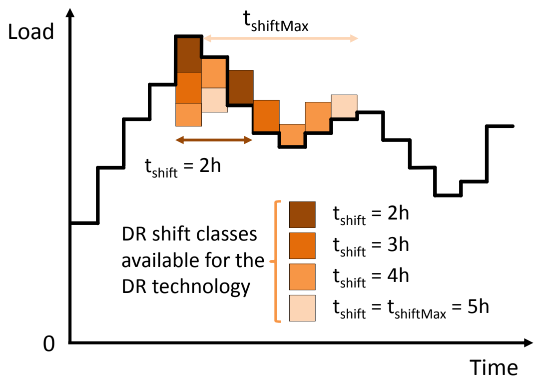


Figure 3. Exemplary illustration of the DR modelling concept in REMix

The linear programming approach of REMix requires further approximations in the modelling process. Without the application of discrete programming methods, it is not possible to directly link the DR operation of different time-steps. This affects the realization of limitations in the duration of DR load changes, as well as intervals between load interferences. Instead of measuring these time spans directly, restrictions in duration and frequency are implemented by assessing the amount of reduced or increased demand within predefined periods.

REMix input generally consists of sets and parameters. Parameters provide the technology and scenario input data for the GAMS optimization, whereas sets are the indices that specify the domains of parameters, variables and equations. The developed modelling concept requires the introduction of a set H_{DR} containing the DR shifting classes with all possible shift times of each DR technologies $X \in X_{DR}$. Each member of the set H is explicitly associated to one DR technology X.

In the following, all equations defining the usage of DR in REMix are introduced in detail. For better readability of the model equations, parameters and variable are displayed differently: variables are always written in bold font and parameters in normal font. Furthermore, all variables, parameters and equations are shown in a reduced denotation here. This concerns the boundary conditions of all variables only allowed to have positive values on the one hand, and the waiver of the sets indicating that all equations are applied to each model node and year on the other.

3.3 Demand Response Model Equations

For each DR shifting class H and time-step t, four variables are included in the optimization: load reduction $\boldsymbol{P}_{red}(t)$, load increase $\boldsymbol{P}_{inc}(t)$, balancing of previous load reductions $\boldsymbol{P}_{balRed}(t)$ and balancing of previous load increases $\boldsymbol{P}_{balInc}(t)$. Duration of load interference and amount of shifted load are assessed for each DR technology X and time-step t making use of fictitious DR storage levels for both delayed $\boldsymbol{W}_{levRed}(t)$ and advanced loads $\boldsymbol{W}_{levInc}(t)$, which contain all shifted and not yet balanced energy. In addition to the operation of available DR resources, also the expansion of available capacity $\boldsymbol{P}_{adCap}$ can be optimized.

3.3.1 Installed Electric Capacity of Demand Response Consumers

The electric capacity of processes and appliances that can in principle contribute to DR is limited by the available potential P_{maxCap} according to Eq. 1. It is composed of those loads already manageable via an information and communication (ICT) infrastructure P_{exCap} and those that can be accessed by investing in DR $\boldsymbol{P}_{adCap}$. If no DR capacity installation is considered, $\boldsymbol{P}_{adCap}$ is set to zero.

$$P^X_{exCap} + \boldsymbol{P}^X_{adCap} \overset{!}{\leq} P^X_{maxCap} \tag{1}$$

3.3.2 Load Shifting, Shedding and Balancing

All shifted loads need to be balanced after a given shift time t_{shift}. This concerns both load reduction ($\boldsymbol{P}_{red}$, $\boldsymbol{P}_{balRed}$) and load increase ($\boldsymbol{P}_{inc}$, $\boldsymbol{P}_{balInc}$) and has been implemented according to Eq. 2 and 3, respectively. If load is shedded instead of shifted, no balancing is required, thus: $\boldsymbol{P}_{balRed}(t) \overset{!}{=} 0$. Equation 2 and 3 contain a DR efficiency η_{DR}, describing a potential increase in energy demand caused by load shifting.

$$\boldsymbol{P}^{H}_{balRed}(t) \stackrel{!}{=} \frac{\boldsymbol{P}^{H}_{red}\left(t - t^{H}_{shift}\right)}{\eta^{H}_{DR}} \tag{2}$$

$$\boldsymbol{P}^{H}_{balInc}(t) \stackrel{!}{=} \boldsymbol{P}^{H}_{inc}\left(t - t^{H}_{shift}\right) \cdot \eta^{H}_{DR} \tag{3}$$

Maximum load decrease and increase in each hour are defined by the overall installed capacity and its current availability for DR. The normalized hourly time series of flexible $s_{flex}(t)$ and free load $s_{free}(t)$ reflect that the DR potential varies during the year, due to the characteristic demand pattern of the flexible consumers. They are calculated by dividing the hourly maximum load decrease $P_{flex}(t)$ and increase $P_{free}(t)$ by the maximum potential P_{maxCap}.
Bearing in mind that loads of one and the same DR technology X can be used by various shifting classes H, it must be assured that overall load increase and decrease are lower than the corresponding potentials. This concerns load shifting and shedding, as well as balancing of loads that have been reduced or increased in an earlier point in time, as described by Eq. 4 and 5. The assignment of shifting classes to DR technologies is denoted by the symbol $\mapsto$.

$$\sum_{H \mapsto X} \boldsymbol{P}^{H}_{red}(t) + \boldsymbol{P}^{H}_{balInc}(t) \stackrel{!}{\leq} \left(P^{X}_{exCap} + \boldsymbol{P}^{X}_{adCap}\right) \cdot s^{X}_{flex}(t) \tag{4}$$

$$\sum_{H \mapsto X} \boldsymbol{P}^{H}_{inc}(t) + \boldsymbol{P}^{H}_{balRed}(t) \stackrel{!}{\leq} \left(P^{X}_{exCap} + \boldsymbol{P}^{X}_{adCap}\right) \cdot s^{X}_{free}(t) \tag{5}$$

In the model, a storage level $\boldsymbol{W}_{lev}(t)$ is defined for both reduced and increased loads. It represents the amount of all shifted and not yet balanced load, comparable to a storage filling level. Its hourly balances are given by Eq. 6 and 7, respectively.

$$\sum_{H \mapsto X} \left(\boldsymbol{P}^{H}_{red}(t) - \boldsymbol{P}^{H}_{balRed}(t) \cdot \eta^{H}_{DR}\right) \stackrel{!}{=} \boldsymbol{W}^{X}_{levRed}(t) - \boldsymbol{W}^{X}_{levRed}(t-1) \tag{6}$$

$$\sum_{H \mapsto X} \left(\boldsymbol{P}^{H}_{inc}(t) \cdot \eta^{H}_{DR} - \boldsymbol{P}^{H}_{balInc}(t)\right) \stackrel{!}{=} \boldsymbol{W}^{X}_{levInc}(t) - \boldsymbol{W}^{X}_{levInc}(t-1) \tag{7}$$

The DR storage level is used for restricting shifted and not yet balanced energy and thus duration of DR interventions. Its upper limit is calculated from the maximum duration of DR interventions $t_{interfere}$ and the average available DR load $\overline{s}_{flex}$ of the corresponding technology, as described by Eq. 8 and 9.

$$\boldsymbol{W}^X_{levRed}(t) \overset{!}{\leq} \left(P^X_{exCap} + \boldsymbol{P}^X_{adCap}\right) \cdot \overline{s}^X_{flex}(t) \cdot t^X_{interfere} \tag{8}$$

$$\boldsymbol{W}^X_{levInc}(t) \overset{!}{\leq} \left(P^X_{exCap} + \boldsymbol{P}^X_{adCap}\right) \cdot \overline{s}^X_{free}(t) \cdot t^X_{interfere} \tag{9}$$

3.3.3 Limits in Frequency of Demand Response

DR utilization may be limited in frequency. In REMix, two different optional restrictions are implemented, both posing limits to the amount of shifted or shedded energy. One affects the annual number of DR applications $n_{yearLim}$ and thus overall DR energy, whereas the other can be applied to limit the DR utilization within a predefined time-span t_{dayLim}. The calculation of maximum amounts of shifted or shedded energy again relies on the average DR potential, as well as the maximum duration of DR interventions. Equation 10 and 11 define the restrictions in frequency of load reduction. The corresponding correlations for load increase are obtained by substituting $\boldsymbol{P}_{red}$ by $\boldsymbol{P}_{inc}$ and $\overline{s}^X_{flex}$ by $\overline{s}^X_{free}$, respectively.

$$\sum_t \sum_{H \mapsto X} \boldsymbol{P}^H_{red}(t) \overset{!}{\leq} \left(P^X_{exCap} + \boldsymbol{P}^X_{adCap}\right) \cdot \overline{s}^X_{flex}(t) \cdot t^X_{interfere} \cdot n^X_{yearLim} \tag{10}$$

$$\begin{aligned} \sum_{H \mapsto X} \boldsymbol{P}^H_{red}(t) \overset{!}{\leq} & \left(P^X_{exCap} + \boldsymbol{P}^X_{adCap}\right) \cdot \overline{s}^X_{flex}(t) \cdot t^X_{interfere} \\ & - \sum_{t'=1}^{t'=t^X_{dayLim}} \sum_{H \mapsto X} \boldsymbol{P}^H_{red}(t-t') \end{aligned} \tag{11}$$

3.3.4 Demand Response Costs

REMix considers DR investment $\boldsymbol{C}_{invest}$ and operation costs $\boldsymbol{C}_{op}$. Prerequisite for DR is the equipment of flexible consumers with an ICT infrastructure allowing for automatized or manual changes in demand pattern. Making loads available can thus require an investment, which is assessed according to Eq. 12. The annuity $f_{annuity}$ is calculated based on the amortization time t_{amort} and interest rate i as described in Eq. 13.

$$\boldsymbol{C}_{invest} = \sum_X \boldsymbol{P}^X_{adCap} \cdot c^X_{specInv} \cdot f^X_{annuity} \tag{12}$$

$$f^X_{annuity} = \frac{i \cdot (1+i)^{t^X_{amort}}}{(1+i)^{t^X_{amort}} - 1} \tag{13}$$

The operational cost reflect the expenditures caused by the provision and utilization of flexible loads and are calculated according to Eq. 14.

$$\begin{aligned} \boldsymbol{C}_{op} = &\sum_{X} \sum_{H \mapsto X} \sum_{t} \Big(\boldsymbol{P}_{red}^{H}(t) + \boldsymbol{P}_{inc}^{H}(t) \Big) \cdot c_{OMVar}^{X} \\ &+ \sum_{X} \boldsymbol{P}_{adCap}^{X} \cdot c_{specInv}^{X} \cdot c_{OMFix}^{X} \end{aligned} \tag{14}$$

4 Case Study

4.1 Scope, Scenarios and Model Configuration

The exemplary model application aims at an evaluation of the possible future role of DR in a German power supply system with high VRE share. It is assessed, whether and to what extend the exploitation of DR potentials can enable a reduction in VRE curtailment and demand for power plant capacity. In the case study, the energy system operation and back-up power plant capacity demand in Germany without and with DR are compared. A total of nine scenarios are evaluated: one without the availability of DR and eight with DR. The latter differ in the assumptions concerning costs and temporal availability of DR, and aim at a better understanding of the sensitivity of DR capacity expansion and operation to changes in these parameters. The scenario without DR is used for the determination of the least-cost allocation of generation and grid capacities within Germany on the one hand, and as reference case for the subsequent evaluation of the DR impact on the other. Figure 4 summarizes the characteristics of the considered scenarios.

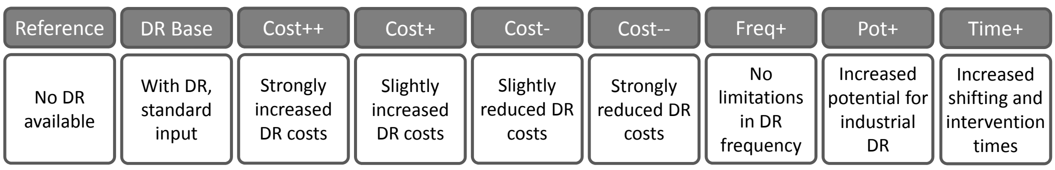


Figure 4. Overview of the assessed scenarios.

Due to its particular focus on a detailed analysis of DR, a simplified system representation is chosen in the case study; this concerns both power generation and balancing. Considered power generation technologies comprise solar PV, onshore and offshore wind turbines, run-of-river and reservoir hydro stations, as well as natural gas-fired gas turbines (GT) and combined cycle gas turbines (CCGT). The latter two are place-holders for peak-load and medium-load technologies, respectively, which are not subject to temporal fluctuations in resource availability. In order to achieve higher reductions in climate gas

emissions, they might be substituted by dispatchable renewable power generation (biomass, geothermal, CSP) or cogeneration plants. In this assessment, they are exclusively used for the identification of the demand for power plant back-up capacity and its interaction with DR.
The consideration of balancing options is restricted to DC power transmission, pumped storage hydro (PSH) stations, flexible gas power plants and DR. In the model, Germany is considered as an island system without any power grid interconnection to its neighbours. However, the country is subdivided to six regions, allowing for an assessment of power transmission within Germany, as well as the regional allocation of power generation capacities. The regional subdivision of Germany takes into account the control areas of the four transmission system operators as summarized in Table 2 .

Table 2
REMix model regions used in this work defined based on the region denotation in the *Regionenmodell* of the German transmission system operators [33].

Name	Regions included
Central	TNT3, TNT4 (Tennet)
East	50Hz0, 50Hz1, 50Hz3, 50Hz4 (50Hertz)
North	TNT0, TNT1, TNT2, 50Hz2 (Tennet, 50Hertz)
Southeast	AMP6, TNT5, TNT6 (Amprion, Tennet)
Southwest	TNBW1, TNBW2 (TransNet BW)
West	AMP1, AMP2, AMP3, AMP4, AMP5 (Amprion)

Depending on the scenario set-up, REMix evaluates the least-cost investment in power plants, grid lines and DR capacity, as well as the least-cost operation of all system components. The model output includes installed capacities of power plants and DR, as well as their hourly operation pattern.

4.2 Power Generation, Storage and Transmission Model Input

Generation, storage and transmission related model input comprises techno-economic technology parameter, installed hydro power capacities, as well as maximum installable capacities of wind and PV power plants.

4.2.1 Power Plant, Grid and Storage Capacities

Concerning the optimization of investments, the case study comprises two different aims: in the scenario without DR, the least-cost allocation of renewable power generation and grid capacity within Germany is determined, whereas in

Table 3
Installed capacities of hydro power plants.

	Run-of river MW	Reservoir MW	PSH-Conv. MW	PSH Stor. GWh
Central	160.2	2.1	597.4	4.8
East	167.9	0	2050.5	16.4
North	8.2	0	0	0
Southeast	2614.5	147.7	0	0
Southwest	1387.4	132.8	2492.9	19.9
West	511.9	67.4	1346.0	10.8

the scenarios with DR, the focus is laid on the investment in load flexibility.
In the scenario without DR, the model endogenous capacity expansion includes power generation in wind, PV and gas power plants, as well as transmission capacity between the regions. The overall VRE generation capacity as well as the ratio between solar and wind power capacity is predefined by the comprehensive scenario study presented in [34]. There, a 70% supply share of solar and wind power is envisioned for the year 2050, of which one quarter originates from solar PV and three quarters from wind power. These values refer to theoretical supply shares, which would be reached if no power production was curtailed or lost in storage and transmission.
The maximum installed wind and PV capacities in each region, as well the resource quality in terms of annual FLH is provided by the profound assessment of RE potentials presented in [29]. In contrast to the other RE technologies, the installed capacity of hydro power stations, including run-of-river, reservoir and pumped storage, is not subject to optimization in any of the simulations. Instead, the turbine and pump capacities installed in the year 2014 are assumed to be available also in the future (see Table 3).
In the scenarios with DR, power plant capacities are optimized only for GT and CCGT. The geographic allocation of VRE power generation, as well as the transmission capacity between the regions is not assessed, but assumed according to the output of the scenario without DR. By investing in DR, the model can increase the usage of VRE power production and avoid the installation and operation of power plants. Comparing the reference case without DR to the scenarios with DR, the impact of load shifting and shedding on capacity demand and system operation is obtained.

4.2.2 Power Demand and Technology Parameter

The annual power demand in Germany is assumed according to [34; 35] and amounts to 425 TWh, of which 46 TWh are located in the *Central* region, 126 TWh in *East*, 40 TWh in *North*, 54 TWh in *Southeast*, 49 TWh in *Southwest* and 109 TWh in *West*. Hourly demand values are obtained by multiply-

Table 4
Regional RE power generation full load hours.

	Hydro		Solar	Wind	
	Run-of river	Reservoir	PV	Offshore	Onshore
	h/a	h/a	h/a	h/a	h/a
Central	5152	3495	961	n.a.	2259
East	5155	n.a.	973	3345	2169
North	5151	n.a.	886	4310	2874
Southeast	5161	5097	1023	n.a.	1645
Southwest	5154	5158	1019	n.a.	1675
West	5152	5071	956	n.a.	2249

ing the annual demand with a normalized profile of the measured grid load in Germany in the year 2006. The year is selected according to the RE power generation profiles.
The power generation of solar PV, wind and run-of-river hydro power plants is dependent on the availability of intermittent resources. For each technology and region, normalized hourly generation profiles are incorporated into REMix. They have been calculated using meteorological data on the one hand, and technological characteristics on the other (see [29]). The generation profiles applied in this work rely on weather data for the year 2006 and represent an average annual RE availability compared to other recent meteorological years.
Reservoir hydro power features characteristics of both variable and dispatchable power plants. Its power generation can be adjusted within the restrictions given by reservoir size, filling level and minimum water flow rate. It is taken into account that some reservoir hydro stations dispose of pumps allowing for the provision of negative balancing power. The hourly water inflow is assumed according to [29]. For both pumped hydro and reservoir hydro stations a pumping efficiency of 89%, a turbine efficiency of 90% and an annual availability of 98% are applied. Annual FLH of all RE technologies are summarized for each region in Table 4.

The output of conventional power plants is only restricted by the installed and available capacity, and not dependent on any intermittent resource. Technology input data of gas power plant comprise net efficiencies, power plant availabilities, as well as investment and fixed operational costs (see Table 5). To all investments in new capacities, an interest rate of 6% is applied. In all scenarios, a gas price of 28.8 €/MWh and a CO_2 emission cost of 150 €/ton are considered.

In the scenario without DR, DC power lines can be installed by the model. Grid capacity expansion is limited to point-to-point DC connections between neigh-

Table 5
Power generation technology parameter: Firm capacity

	Efficiency %	Availability %	Invest. Cost €/kW	Amort. Time years	Operation Fix Costs % of Invest/a
Gas Turbine	47%	95%	400	25	4%
Combined Cycle	62%	96%	700	25	4%

bouring model regions. HVDC lines can be added with any nominal power. Transmission losses are assumed with 0.45%/100 km; additional 0.7% is lost at conversion from and to AC [36]. The costs of grid installation are assumed with 490 k€/km and 162000 k€for each converter station, with an amortization time of 40 years and fixed operational costs of 0.6% of the investment per year.

4.3 Demand Response Model Input

4.3.1 Available Demand Response Potentials

The applied DR potentials in Germany rely on the comprehensive assessment of flexible loads presented in [18]. There, hourly values of maximum load increase and decrease are identified for 30 different electricity consumers (see Table 7 in 45 countries. The overall potentials in Germany are subdivided to the six regions according to the geographic allocation method introduced in [18]. Given that this case study focuses on an assessment of future DR utilization, the original data, which reflects the available loads in the year 2010, needs to be extrapolated. The technology specific extrapolation of DR potentials is described in detail in [37].

In the assessment of theoretical DR potentials introduced in [18], no limitations in shifting of residential and commercial loads have been taken into account. Due to the high impact on comfort and working routines caused by changes in the consumption pattern, the theoretical potential is reduced to an approximated social potential for the REMix case study. Therefore, the parameters s_{red} and s_{inc}, which reflect that only a share of the regular load or unused capacity might be available for load reduction or increase, are partly adjusted to values below 100% according to Table 6. The estimates consider the load shifting impact a particular device has on user convenience and represent a rather optimistic estimate, if compared to the outcome of field studies assessing participation of residential consumers in DR [24; 38]. Procedural limits of industrial and commercial DR have already been considered in the assessment of theoretical potentials (see [18]).

Table 6
Assumed customer participation in demand response measures.

Process/Consumer	s_{red}	s_{inc}
Freezer/Refrigerator	80%	100%
Washing Machines	20%	15%
Tumble Dryer/Dish Washers	40%	15%
Res. air conditioning	40%	100%
Res. circulation pump	90%	100%
Res. storage heater/water heater	100%	90%
Retail cooling	60%	100%
Cold storage	70%	90%
Gastronomy cooling	30%	90%
Com. ventilation	30%	100%
Com. air conditioning	25%	100%
Com. storage heater/water heater	100%	90%
Pumps in water supply	90%	90%
Ind. ventilation	50%	100%

4.3.2 Aggregation of Demand Response Loads

The consideration of DR has a comparatively high impact on the REMix solution time. For this reason, the processes and appliances considered in [18] are aggregated to DR technologies. All consumers of one technology are assumed to have the same techno-economic DR characteristics. In this work, the 30 consumers assessed in [18] are summarized to seven technologies according to table 7. Depending on the maximum shifting time, between one and eight shifting classes is defined for each of the technologies, adding up to a total of 30 classes. Each shifting class is characterized by a shifting time, and a DR efficiency. The latter reflects a load pick-up caused by a modified load profile, as it is typically observed for heating, ventilation and air conditioning (HVAC) devices, but also for refrigeration and some industrial processes. For some DR technologies, it is assumed that longer shifting times go along with a higher load pick-up (see Table 7).

Taking into account theoretical potentials, customer participation and aggregation, DR potentials are calculated for each technology and model region. Table 8 summarizes the resulting capacities, as well as average load reduction and increase.

Table 7
Grouping of DR loads and techno-economic parameter of DR shift classes.

Technology	Consumers/processes included	t_{shift} hours	η_{DR} %
HeatingAC-Res	Residential AC, heat circulation pumps, freezers and refrigerators	1, 2	97%
HVAC-ComInd	Commercial and industrial AC and ventilation, retail cooling	1, 2	97%
CoolingWater-ComInd	Cooling industry and catering, cold stores, water supply and treatment	1, 2, 3 4, 5, 6	98%, 97.5%, 97%, 96.5%, 96%, 95.5%
ProcessShift-Ind	Pulp, paper, cement, CaC_2 and air separation industry	2, 4, 8, 12, 16, 24, 36, 48	99%
WashingEq-Res	Dish washers, washing machines, tumble dryers	1, 2, 4, 6	100%
StorHeat-ResCom	Residential and commercial electric storage water heaters	1, 2, 4, 6, 8, 10, 12	98%, 97.5%, 97%,96.5%, 96%, 95.5%, 95%
ProcessShed-Ind	Aluminum, copper, zinc, steel and chlorine industry	8760	100%

Table 8
Installable DR capacity, average load reduction and increase in MW_{el} by region.

DR Technology	Central	East	North	Southeast	Southwest	West
	Installable capacity in MW_{el}					
HeatingAC-Res	1180	2366	1110	1652	1470	3650
HVAC-ComInd	1909	4729	1818	2238	1823	4604
CoolingWater-ComInd	329	815	313	386	314	793
ProcessShift-Ind	322	729	442	478	534	1818
WashingEq-Res	3548	7113	3338	4968	4419	10974
StorHeat-ResCom	1964	3936	1847	2749	2445	6073
ProcessShed-Ind	285	646	392	424	473	1611
	Average load reduction in MW_{el}					
HeatingAC-Res	106	212	100	148	132	327
HVAC-ComInd	151	375	144	178	145	365
CoolingWater-ComInd	101	251	96	119	97	244
ProcessShift-Ind	141	320	194	210	234	798
WashingEq-Res	39	78	37	54	48	120
StorHeat-ResCom	82	165	77	115	102	254
ProcessShed-Ind	188	424	257	279	311	1058
	Average load increase in MW_{el}					
HeatingAC-Res	1045	2095	983	1463	1302	3233
HVAC-ComInd	1519	3761	1446	1780	1450	3662
CoolingWater-ComInd	110	272	104	129	105	264
ProcessShift-Ind	60	91	55	116	95	223
WashingEq-Res	515	1032	484	721	641	1592
StorHeat-ResCom	1693	3394	1593	2370	2109	5237
ProcessShed-Ind	0	0	0	0	0	0

4.3.3 Demand Response Technology Parameters

The considered DR technologies differ in shifting and intervention time, as well as frequency and cost of DR utilization. Depending on the devices included, also the applicable DR measures – load shedding, load advance and load delay – are limited. Energy-intensive manufacturing processes are assumed to be available only for load shedding, whereas residential, commercial and cross-sectional industry consumers can be shifted either or both to an earlier or later moment. Interference times are shorter for heating and cooling devices without storage, and longer for technologies providing physical or thermal storage. Off-times between interventions are primarily relevant for heating and cooling without storage, whereas annual limits are only applied to industrial loads. Specific investment costs are lower in industry and commercial sector, where single DR loads are typically higher, whereas operational costs are assumed to be lower for residential appliances. In the estimation of investment costs, values of 25€ per residential appliance and 50€ per commercial and industrial cross-sectional technologies are considered. To all technologies, an interest rate of 6% and an amortization time of 20 years are applied. Operational DR costs reflect expenditures arising from maintenance and utilization of the ICT infrastructure, as well as compensation for losses in production output and comfort. All techno-economic parameter are summarized in Table 9, which as well provides average annual load reduction availabilities $\overline{s}_{flex}$.

Table 9
Techno-economic parameter of DR technologies in scenario DR Base, extracted or derived from [16; 17; 34; 39; 40].

Technology	DR Measure	$t_{interf.}$	t_{dayLim}	n_{year}	$c_{specInv}$	c_{OMFix}	c_{OMVar}	$\overline{s}_{flex}$
		hours	hours	1/a	k€/MW	%/year	€/MWh	%
HeatingAC-Res	Delay	1	4	none	250	3%	10	9%
HVAC-ComInd	Delay	1	4	none	10	3%	5	8%
CoolingWater-ComInd	Adv./Del.	2	8	none	5	3%	20	31%
ProcessShift-Ind	Adv./Del.	3	24	365	0	0	150	44%
WashingEq-Res	Delay	8760	none	none	30	3%	50	1%
StorHeat-ResCom	Advance	12	none	none	20	3%	10	4%
ProcessShed-Ind	Shedding	4	24	40	0	0	1000	66%

4.4 Demand Response Input Variations

Given that future DR investment and operation costs are subject to major uncertainty, a broad range of cost values is taken into account. Furthermore, by increasing the overall potential and eliminating restrictions in DR load flexibility, specific requirements for load shifting and shedding are studied in detail. Table 10 provides an overview of the considered variations. For each of them, the impact on exploitation and utilization of DR potentials, as well as on capacity demand and VRE curtailment is assessed.

Table 10
Overview of input modifications considered in the sensitivity runs of DR capacity optimization.

Scenario	DR parameter
Cost++	$c_{specInv}$, c_{OMFix} and c_{OMVar} multiplied by four
Cost+	$c_{specInv}$, c_{OMFix} and c_{OMVar} doubled
Cost−	$c_{specInv}$, c_{OMFix} and c_{OMVar} reduced by half
Cost−−	$c_{specInv}$ and c_{OMFix} set to zero, c_{OMVar} reduced to a quarter
Freq+	No limitations in DR frequency of use
Pot+	Doubled potential in *ProcessShed-Ind*, *ProcessShift-Ind*, *CoolingWater-ComInd*
Time+	$t_{interf.}$ doubled[a]; t_{shift} doubled[b]

[a] With exception of *ProcessShift-Ind*, where a multiplication with 1.5 is applied.
[b] With exception of *HVAC-ComInd* and *HeatingAC-Res*, where no changes are applied.

5 Case Study Results

5.1 Reference Scenario without Demand Response

The reference scenario without DR fulfils two tasks in the case study. On the one hand, it provides the regional distribution of VRE power generation capacities as well as grid connections between the regions to the scenarios with DR, and on the other hand it is applied as benchmark for the evaluation of the DR impact on capacity demand and system operation.

Figure 5 shows the endogenously calculated VRE and grid capacities. The overall capacities add up to approximately 55 GW for onshore wind, 26 GW for offshore wind, 60 GW for solar PV, 33 GW for CCGT and 22 GW for GT. Differences in resource quality cause a strong regional concentration of wind and solar power: whilst the former are preferably installed in the regions *North* and *East*, the latter are mostly locates in the regions *East*, *Southeast* and *Southwest*. The complementary conventional power plant capacity reaches

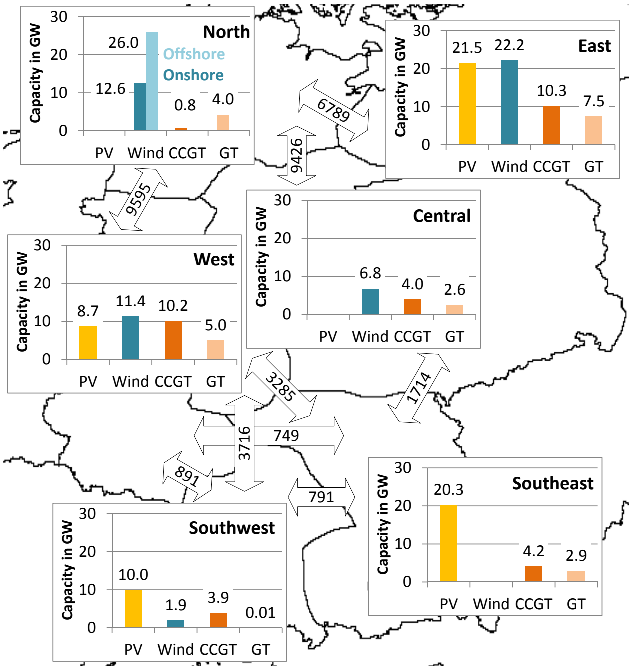


Figure 5. Model output: installed VRE, back-up power plant and grid capacity in the scenario without DR. Power plant capacities in GW, grid capacity in MW.

highest values in *East* and *West*, whereas it is lowest in *Southwest* and *North*. Concerning the ratio of mid-load CCGT capacity and peak-load GT capacity, substantial regional differences appear: values range from 0.19 in Germany *North* to more than 750 in *Southwest*. In all other regions it reaches between 1.4 and 2.1. The ratio between VRE capacity and back-up capacity is lowest in the *Central* region (1.1) and highest in the *North* region (8.1). The model endogenous grid installation adds up to a total NTC of 37 GW. Power lines are predominantly built in North-South direction, whereas only very low capacities are installed in East-West direction (see Figure 5). Highest capacities are available between Germany *North* and the regions *West* (9.6 GW) and *Central* (9.4 GW), respectively. From the *Central* region, ongoing lines to the regions *Southwest* and *Southeast* with a transfer capacity of more than 3 GW each are added. It is important to keep in mind that these transmission capacities have been obtained using a NTC transport model (see [29]), and that they might be higher if calculated in a more detailed AC load flow model.

Figure 6 provides the annual full load hours (FLH) of back-up power plants and PSH stations, as well as the annual power transmission over region borders. Power flows are found to be mostly directed southerly: over the year the *North* region exports almost 90 TWh of electricity, of which roughly one third is transmitted to each of its southern neighbours. Annual FLH of PSH exhibit only minor differences between the regions: they reach values between 820 and 980 h/a and are highest in the *East* region. Much higher regional differences are found for back-up power plants. For CCGT, annual FLH be-

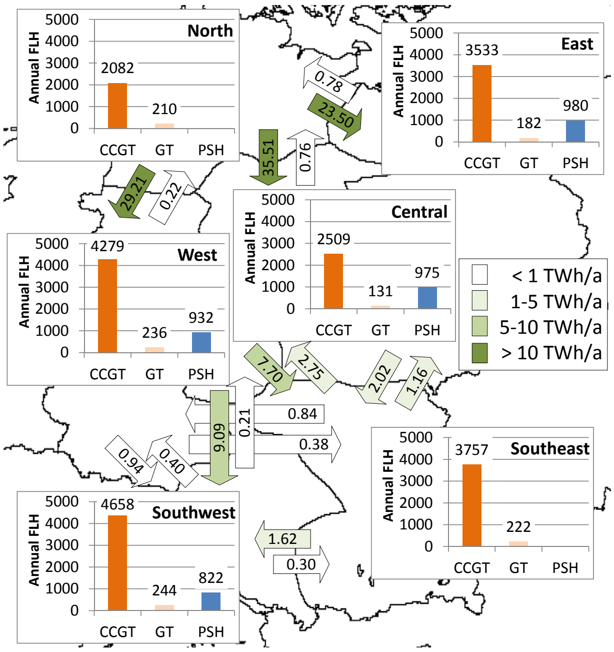
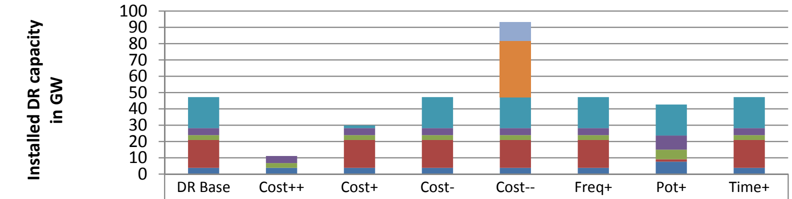


Figure 6. Model output: Power transmission as well as annual full load hours of conventional power plants and PSH in the scenario without DR.

tween 2082 h/a in Germany *North* and 4658 h/a in Germany *Southwest* are identified. The CCGT capacity utilization is thereby clearly related to the wind share in electricity supply and is lowest in the regions with most wind generation capacities. The less efficient GT power plants reach much lower annual FLH, ranging from 131 h/a in Germany *Central* to 244 h/a in *Southwest*. In contrast to CCGT, no clear correlation between annual GT utilization on the one hand, and available power generation and grid infrastructure on the other can be determined. VRE curtailment takes place almost exclusively in the *North* region: there, it reaches 24.4 TWh, compared to 2.1 TWh in *East*, 0.9 TWh in *Southeast* and less than 0.02 TWh in all other regions.

5.2 Scenarios with Demand Response

In the scenarios with DR, the model can invest in DR in order to reduce back-up capacity or fuel demand and thus system costs. Figure 7 shows the exploitation of DR potentials across the considered scenarios. The highest capacity of more than 93 GW is reached in scenario *Cost−−*. It is equivalent to the overall potential, which is fully exploited in the absence of investment costs. It is important to keep in mind that this value does not represent the maximum load reduction, but the overall electric capacity of DR loads. More than two thirds of this capacity is constituted by residential appliances with very low utilization, such as washing and cooling equipment (see [18]). In all other scenarios, the model endogenous exploitation of DR potentials is mostly limited to industrial and commercial sector loads. Only exceptions are electric water heaters with thermal storage (*StorHeat-ResCom*), which are completely accessed across all scenarios except for those with increased costs. In contrast to that, the loads summarized to the DR technologies *ProcessShift-Ind*, *ProcessShed-Ind* and *CoolingWater-ComInd* are accessed across all scenarios. DR potentials in commercial and industrial cooling and ventilation (*HVAC-ComInd*) are fully exploited in all scenarios except for those with very high costs (*Cost−−*) and doubled industrial potential (*Pot+*). In the latter case, they are substituted by the higher potentials in other, less expensive industrial DR technologies. Comparing all scenarios it appears that the applied investment costs have a very high impact on the installation of DR capacity, whereas changes in the temporal availability of potentials do not significantly influence the outcome.

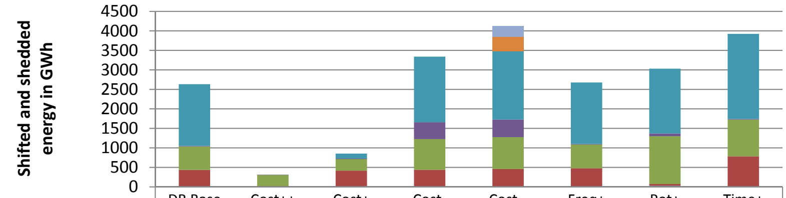


	DR Base	Cost++	Cost+	Cost-	Cost--	Freq+	Pot+	Time+
HeatingAC_Res	0	0	0	0	11.43	0	0	0
WashingEq_Res	0	0	0	0	34.36	0	0	0
StorHeat_ResCom	19.01	0	1.67	19.01	19.01	19.01	19.01	19.01
ProcessShift_Ind	4.32	4.32	4.32	4.32	4.32	4.32	8.65	4.32
CoolingWater_ComInd	2.95	2.95	2.95	2.95	2.95	2.95	5.90	2.95
HVAC_ComInd	17.12	0	17.12	17.12	17.12	17.12	1.44	17.12
ProcessShed_Ind	3.83	3.83	3.83	3.83	3.83	3.83	7.66	3.83

Figure 7. Model output: Accesssed capacity of DR loads.

Figure 8 shows the annual application of DR in terms of shifted and shedded energy. It ranges between 310 GWh in scenario *Cost++* and more than 3900 GWh in *Cost−−* and *Time+*. By far the highest contribution to electric load shifting comes from the loads summarized in *StorHeat-ResCom* and *CoolingWater-ComInd*. On the contrary, the application of industrial loads is much lower. Even though they account for the lion's share in DR capacity in scenario *Cost−−*, the amount of load shifting of residential washing and cooling appliances is comparatively low.

The variation of DR costs results to have the highest impact on the overall DR application. This concerns all considered DR technologies. It appears that the utilization of load shifting in energy intensive industries (*ProcessShift-Ind*) is very sensitive to the application of lower costs. If costs are reduced by half, the annual load shift increased almost by factor 30. In contrast, the application of higher or even lower costs does not have a major influence on industrial DR. The negligence of limitations in DR frequency (*Freq+*) does not significantly increase the DR application. However, it causes some minor shifts in overall load shifting between the DR technologies. A similar effect is found in scenario *Pot+*, where shifting of *CoolingWater-ComInd* almost completely substitutes *HVAC-ComInd*. If compared to scenario *DR Base*, an increase in load shifting by around 10% is found, despite a lower DR capacity. The application of longer shifting and interference times (*Time+*) increases the overall amount of shifted and shedded energy by half. It promotes the substitution of load shifting and shedding in energy intensive industries by cheaper alternatives. Comparing the regions within Germany, DR activities are found to concentrate to the regions *West* and *East*. In scenario *DR Base*, 29% and 23% of the overall load shifting and shedding takes place there, compared to 16% in *Southeast*, 11% in *Southwest* and 10% each in *North* and *Central*. A similar distribution is found in all other scenarios.



	DR Base	Cost++	Cost+	Cost-	Cost--	Freq+	Pot+	Time+
HeatingAC_Res	0	0	0	0	273	0	0	0
WashingEq_Res	0	0	0	0	367	0	0	0
StorHeat_ResCom	1583	0	127	1682	1756	1579	1661	2183
ProcessShift_Ind	15	8	15	432	451	14	70	14
CoolingWater_ComInd	601	302	295	787	818	607	1228	943
HVAC_ComInd	430	0	412	434	449	474	43	780
ProcessShed_Ind	4	3	4	4	8	4	28	3

Figure 8. Model output: annual amount of shifted and shedded energy.

The hourly operation of DR resources is shown exemplary for scenario *DR Base* in Figure 9. It reveals that DR is preferably used for reducing the demand in morning and evening hours, at the expense of a higher demand during midday and night-time. The latter are characterized by high PV power production on the one hand, and low demand on the other. Seasonal variations in DR activities indicate a higher utilization of the available DR loads in winter. Periods without any utilization of DR are equivalent to those with a very high wind power output. Very high load reductions and increases of more than 7 GW occur only in very few hours of the year, whereas the regular DR application stays below approximately 4 GW of load decrease and increase. Hours with highest load reductions are concentrated to evenings in the winter months, which are typically the times of peak demand in Germany.

In the following, the impact of DR on other system components is assessed. Figure 10 shows the differences in the demand for conventional back-up power plants caused by DR. The model results reveal a decrease in capacity demand ranging from 5.3 GW in scenario *Cost++* to 10.6 GW in *Pot+*, equivalent to 10% to 19% of the value determined in the reference scenario without DR. It is striking that differences between scenarios are much higher for the installed DR capacity (see Figure 7) than they are for the impact on capacity demand. This results from the high temporal availability of industrial DR potentials, which are accessed across all scenarios. The ratio of peak load reduction and DR capacity ranges between 9% in scenario *Cost−−* and 47% in *Cost++*.

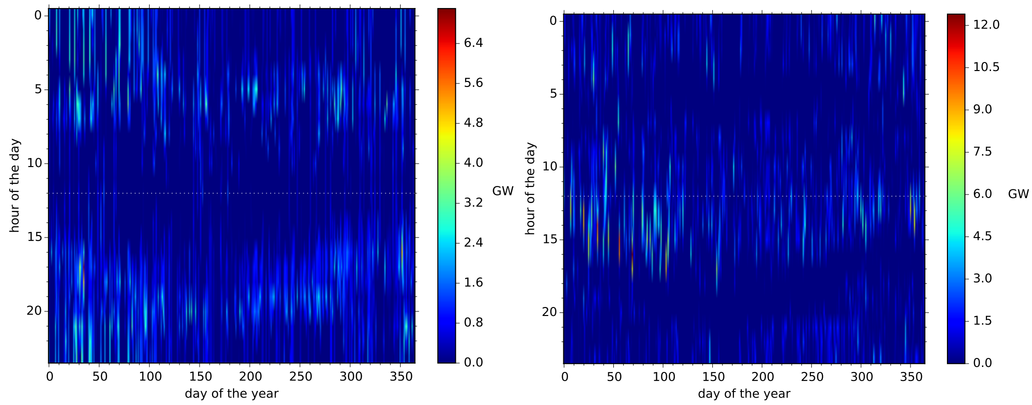


Figure 9. Model output: hourly DR load reduction (left) and increase (right) in scenario DR Base.

DR mostly substitutes peak generation capacity, here represented by GT; they account for 90% to 98% of the overall power plant capacity reduction. Comparing the scenarios, it appears that the consideration of lower costs and longer shifting times favours the substitution of medium-load capacity, here represented by CCGT. On the contrary, for GT highest values are found in the scenario with additional industrial DR potentials. These results suggest that DR potentials in the energy intensive industries, characterized by low investment and high variable costs, are only used for substituting peak generation capacity, whereas those with the contrary costs structure, as they are assumed for heating, cooling and ventilation across all sectors allow for a replacement of medium load generation as well.

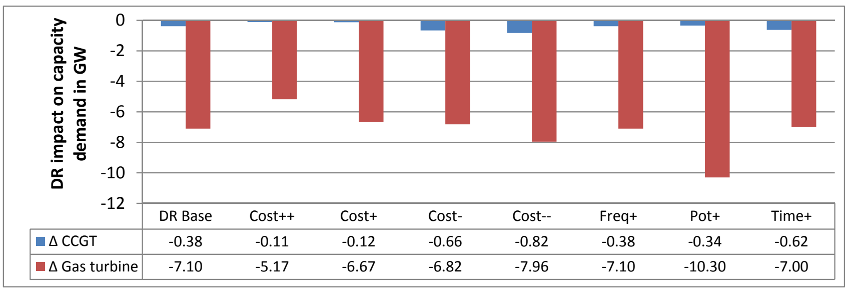


Figure 10. Model output: impact of DR on the model endogenous installation of conventional back-up power plants.

The impact of DR on VRE curtailment is displayed in Figure 11. It shows that DR enables the additional integration of VRE power generation. Depending on the scenario assumptions it reaches values between 0.24 TWh (*Cost++*) and 1.68 TWh (*Time+*), equivalent to 0.9% and 6.1% of the curtailment found in the reference case without DR, respectively. Comparing the avoided curtailments with the overall amount of shifted and shedded energy, values between 9% (*Cost++*) and 64% (*Time++*) are identified.

DR also affects the operation of generation and storage facilities. This is shown by Figure 12, where annual FLH of CCGT, GT and PSH are displayed. Most

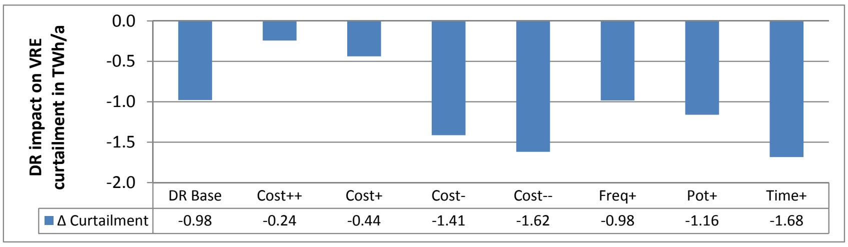


Figure 11. Model output: impact of DR on VRE curtailments.

significant impact is determined for the operation of GT, which can increase their average annual FLH by between 54 h/a and 118 h/a. Given that GT are used exclusively for peak supply, this is equivalent to a growth by around 27% to 60%, compared to the scenario without DR. It is achieved by the substitution of roughly half of the GT capacity by DR.
In contrast, annual FLH of PSH decrease by the availability of DR in all scenarios except for those with comparatively high DR costs. This result suggests that DR technologies with low variable costs can provide cheaper storage function than PSH, whereas those with high variable costs favour the operation of PSH. For CCGT, the contrary effect is found: the annual operation hours increase across all scenarios except for those with high DR costs, where almost no change occurs. This must be seen in relation with the much lower substitution of CCGT capacity identified there. The change in annual FLH caused by DR ranges between -13% and +4% for PSH and between -0.02% and +1.2% for CCGT.

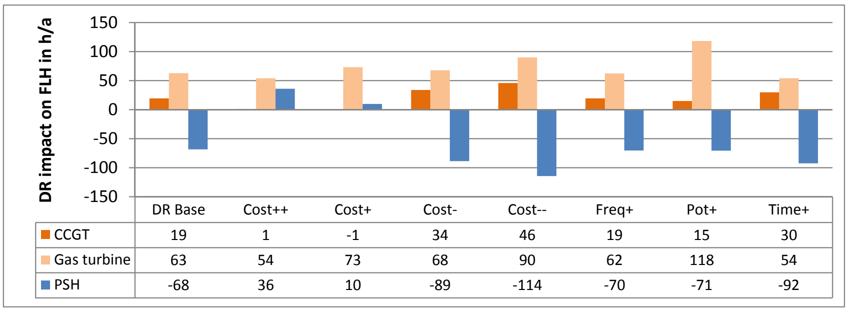


Figure 12. Model output: impact of DR on annual full load hours of power generation and storage.

The identified model-endogenous investment in DR results from its economic advantage over the considered alternatives for provision of balancing power and energy. This is reflected by the calculated overall system costs, which are found to be lower in the scenarios with DR. Figure 13 shows the cost reduction in each scenario, compared to the reference scenario without DR. They arise from the decrease in installation and operation of gas power plants achieved by a higher VRE integration. The reductions between 230 billion Euro and 580 billion Euro correspond to 1.4% to 3.6% of the overall electricity production costs found in the scenario without DR. They comprise the proportionate investment costs of gas power plants and DR, as well as variable operational costs of all considered system components. In the reference scenario without DR, they amount to roughly 35330 billion Euro including investment in grid and VRE, of which 16221 billion Euro result from gas power plant capital costs and system operation costs. These overall annual costs correspond to electricity unit costs of 83.1 €/MWh and 38.1 €/MWh, respectively. The latter are reduced by DR to values between 36.8 €/MWh and 37.6 €/MWh.

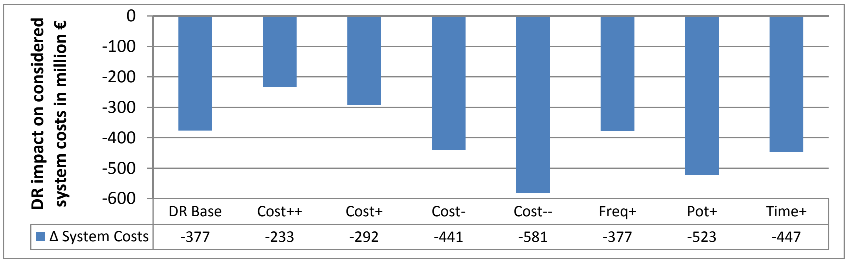


Figure 13. Model output: impact of DR on considered annual electricity supply costs.

Comparing the scenario-specific cost reductions in Figure 13 with the corresponding DR utilization (Figure 8 and its impact on power plant demand (Figure 10) and VRE curtailments (Figure 11) it can be derived that the cost reduction is mostly achieved by avoiding back-up capacity, and to a lower extent by saving fuels and CO_2 emission certificates.

6 Summary and Discussion

In this paper, a representation of electric load shifting and shedding in a linear optimization energy system model has been introduced. Due to the fact that model complexity and thus solution times increases with the number of variables and constraints, it features a reduced level of detail compared to other models particularly focused on DR behaviour of single technologies. In the REMix implementation of DR, load decrease and increase are not considered globally, but can be attributed directly to predefined technologies. This modelling concept allows for an evaluation of DR behaviour of individual consumers. The newly developed shift class representation of DR loads, which assigns one or various fixed shift times to each DR technology, was found to considerable improve the model performance. With this formulation, the model can endogenously determine the interval between load modification and its balancing, which is equivalent to the application of flexible shift times if various shift classes are defined.
Given that the DR activity status in each hour of the year is not reflected in the linear programming approach of REMix, limitations in DR load interventions are implemented making use of a fictitious storage level. As the calculation of the maximum energy that can be shifted before a balancing

must start relies on average values of the available potential, this approach cannot completely assure that maximum load intervention durations are not surpassed. On the other hand, it might also reduce the possibilities of load shifting, when the calculated maximum storage level is reached already in a shorter period. Both effects are particularly important for DR technologies with highly fluctuating power demand. The DR storage level is furthermore used for the consideration of limitations in DR frequency. This implies that these limitations are not applied to the number of hours DR is used or halted, but to the amount of energy shifted or shedded within a certain period. For highly fluctuating demand profiles of DR technologies, this approximation results in an underestimation of the available potential in peak demand hours, and an overestimation in off-peak hours.

Despite its limitations, the extended model has proven to realistically reproduce load shifting and shedding behaviour of flexible electric loads. The case study demonstrates the model's capability to answer questions regarding the opportunities and restrictions of DR and provides an indication of its economic potential in Germany. In the considered scenarios, electricity consumers with an overall capacity between 11 GW and 93 GW are accessed for DR, equivalent to 16% and 137% of the scenario peak load, respectively. However, due to the temporal variability of the usage patterns of the corresponding consumers, these values are not equivalent to the load available for reduction or increase in each hour. The model endogenous exploitation of DR potentials is attributed almost exclusively to industrial and commercial sector loads, whereas those in the residential sector are hardly accessed. Only exceptions are storage water heaters, which combine a comparatively intense utilization with high electric capacities. The very limited DR utilization of residential washing and cooling appliances arises from their low operation hours, high specific investment costs, as well as the assumed DR participation factors.
Variations in DR costs are found to have a high impact on the exploitation of DR potentials. A doubling in investment costs eliminates almost all non-industrial DR, whereas a halving enables a much broader usage of heating, ventilation and cooling applications for DR. Longer shifting and intervention times have comparatively low impact on the exploitation of DR potentials, and high impact on the overall shifted and shedded energy. The contrary effect is found for additional potentials and less restrictions in temporal availability; both variations especially favour the peak load reduction achieved by industrial DR, which partially substitutes other DR technologies.

According to the REMix results, the overall shifted and shedded energy does not exceed 4.2 TWh or 1% of the annual demand. This implies that the focus of DR is on the provision of power, not energy. Against this background, the development of further potentials particularly in industry, where investment costs are comparatively low and application costs high, appears attractive. This is underlined by the result that the peak load reduction enabled by DR is much less sensitive to changes in the DR cost structure than the amount of shifted or shedded energy. Even at higher costs, the usage of industrial DR is economically beneficial compared to the installation of additional generation capacity.

The DR impact on generation capacity requirements and VRE curtailment suggests that it is mostly applied for the purpose of residual load reduction, and not for achieving a higher VRE integration. DR reduces the residual peak load and thus the demand for firm generation capacity by between 5.3 GW and 10.6 GW. On the other hand, the functional energy storage size provided by DR is not only limited by the available potential, but also by the maximum duration of load interventions, as well as the need to balance most of the load change within a given shift time. With estimated intervention and shift times between one and 48 hours, the field of application of the considered DR consumers is restricted to the balancing of short-term fluctuations. For this reason, in the scenarios VRE curtailments can be cut only to a very limited extent of less than 1.7 TWh. This value might be higher in a system with increased PV generation, as the daily fluctuations in solar irradiation have a time scale comparable to the typical DR load shifting times. This is thoroughly analysed in a more comprehensive REMix study presented in [37]. Concerning the operation of power plants, the REMix results show that DR tends to have an increasing impact on the operation of flexible power plants, whereas the operation of PSH stations is reduced. This is related to the flattening of the residual load curve in the first case, and the provision of more efficient storage function in the latter.

The fact that other balancing technologies, such as thermal storage, batteries or an extended European transmission grid are completely disregarded might cause an overestimation of the economic DR potentials identified in this work. However, other REMix studies show that depending on the overall system set-up different technologies are not competing, but complementary in the provision of balancing power and energy [37]. On the other hand, an underestimation of the DR potential might result from the aggregated consideration of conventional power plants and the negligence of ramping limitations, as well as minimum operation and down times.

The results of the case study are to a high degree dependent on the applied cost assumptions. Whether and to what extent DR will be economically competitive to flexible power plants and other balancing options in future supply systems with high VRE shares is very much influenced by the development of their corresponding costs.

The economic attractiveness of DR is furthermore correlated to the power supply structure and particularly to the VRE supply share. In a system with high capacities of dispatchable generation or storage, the need for other balancing technologies is typically lower. On the other hand, in a 100% VRE supply system with even higher balancing demand, DR might be used to a higher extent than in the scenarios considered here. The extent to which DR is used is furthermore related to the overall electricity demand and its hourly

profile. From this follows that the results of the case study might be different assuming another demand and supply structure.
REMix is currently designed to analyse energy systems of world regions, countries or states. From this arises that any DR benefit occurring at smaller scales, such as the provision of ancillary services or a reduced need for distribution grid reinforcements cannot be reflected by model. In addition to that, the utilization of load flexibility in the balancing power market as well as on time scales shorter than one hour, e.g. for dynamic load management, is not accounted for. These model-specific limitations might result in an underestimation of the economic DR potential.
Further limitations are related to the simplified consideration of electricity consumer behaviour, as well as industrial market conditions. Whether and to what extent residential DR is economically competitive does not only depend on economic, but also on social parameters, particularly the participation in DR measures. In industry, the cost of load shifting and shedding is closely connected to external factors such as the wholesale electricity price, as well as the current market situation of the corresponding manufacturing product.

7 Conclusion and Outlook

The novel modelling approach for DR introduced in this paper has proven to realistically reflect load shifting and shedding mechanisms. Integrated in the global energy system model REMix, it can be applied to other countries than Germany as well. By using a linear optimization approach with cost minimization, economic benefits of DR can be evaluated, as well as its interaction with other load balancing technologies. The hourly resolution of the model allows for a detailed analysis of DR behaviour and its correlation to the operation of other system components.
The simulations dedicated to the assessment of future potentials in Germany reveal that the economic application of DR is mostly limited to short-time peak shaving of residual loads. From this arises that it is particularly competing with peak load power plants and short- to medium-term storage technologies. The model results show that load flexibility provides substantial amounts of positive balancing power, which can substitute other firm generation capacity. Even under the most pessimistic cost assumptions applied here, investment in DR is economically competitive to GT installation. The typical load shifting times of DR are especially suited for a combination with PV power generation, given that it features fluctuations in the same time range.
In the REMix assessment, DR utilization is found to reflect fluctuations of the residual peak load. DR measures are preferably taken on winter days with low wind power availability, and applied for reducing morning and evening peak demands, at the expense of a higher demand during midday and in the

night. The temporal variations in DR application highlight the particular importance of load profiles in the assessment of DR potentials. Based on the results of this work, it can be concluded that consumers with load flexibility are particularly suitable for DR if they are able to reduce their load on winter evenings. With the DR application mostly restricted to industrial and commercial sector loads, the REMix results suggest that an economic installation of smart meter technologies in the residential sector requires additional revenues than those arising from trans-regional load balancing.
The scenario study presented in this work provides a first approximate economic assessment of the potential balancing of VRE power generation by load shifting in Germany. It must be complemented by further and more detailed studies. This includes the development and evaluation of business cases for load flexibility on the one hand, and a more profound assessment of the DR contribution to power system stability on the other.

8 Acknowledgement

Parts of the research for this work have been performed in the framework of the project 'Opportunities and constraints for load balancing by energy storage, shiftable loads and electricity-driven Combined Heat and Power in energy systems with high renewable energy shares', funded by the German Federal Ministry of Economics and Technology. The author thanks a number of colleagues for their contribution to this paper: Yvonne Scholz and Thomas Pregger for their helpful comments concerning the design of the case study, Dominik Heide for his technical assistance in the model implementation, Hendrik Schmidt for his help in the model validation and the whole REMix team for the continuous discussion about the model development and results.

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