**Christine Krüger, Mathis Buddeke, Frank Merten,
Arjuna Nebel**

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Christine Krüger [a*], **Mathis Buddeke**[a], **Frank Merten**[a],
Arjuna Nebel[a]

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[a] Wuppertal Institute, Wuppertal, Germany

[*] Corresponding author: Christine Krüger, Wuppertal Institute, Döppersberg 19, 42103 Wuppertal, Germany

E-mail: christine.krueger@wupperinst.org

Phone: +49 202-2492-150

Fax: +49 202-2492-150

MODELLING THE INTERDEPENDENCIES OF STORAGE, DSM AND GRID-EXTENSION FOR EUROPE

Christine Krüger, Mathis Buddeke, Frank Merten, Arjuna Nebel
Future Energy and Mobility Structures
Wuppertal Institute for Climate, Environment and Energy
Wuppertal, Germany
christine.krueger@wupperinst.org

Abstract — **Energy systems with high shares of renewable electricity are feasible, but require balancing measures such as storage, grid exchange or demand-side management to maintain system stability. The demand for these balancing options cannot be assessed separately since they influence each other. Therefore, a model was developed to analyze these mutual dependencies by optimizing a concerted use of balancing technologies. This model is presented here. It covers the European electricity system in hourly resolution. Since this leads to a large optimization problem, several options for reducing system complexity are presented. The application of the model is illustrated with a case study outlining the effects of pumped hydro storage and controlled charging of electric vehicles in central Europe.**

Index Terms — **Demand-Side Management, Energy Storage, Europe, Power Balancing, Power System Modelling**

I. THE INTERDEPENDENCIES OF ENERGY BALANCING MEASURES

By now there are several studies showing that high shares of renewable electricity (RE) up to a share of 100% in Europe are feasible. But how much grid extension, demand-side management (DSM) and storage capacities are needed to maintain system stability? The need for these balancing options cannot be quantified separately since they influence each other: Grid extension will decrease the need for storage and DSM to some extent – but how much grid extension is reasonable? Energy storage and DSM are both suitable for a temporal shift of energy demand – but how does the implementation of DSM influence patterns of storage usage? These and other questions regarding the interaction of balancing measures are addressed with an integrated model of the European electricity system for the year 2050. This model represents each European country in one node and uses an optimization approach for the temporally and spatially resolved dispatch of the balancing options. The target of optimization is to maximize the use of RE by applying balancing measures in a concerted way.

The model has been developed in the context of the ongoing RESTORE2050 project[1].

II. DISPATCH MODELS FOR RENEWABLE ENERGY SYSTEMS

It has become increasingly common to use models to gain information about energy system infrastructure as more researchers now have access to the necessary computational power. Within the last decade particularly, many models have been developed and proven useful by producing feasible results for the components of complex energy system behaviour (e.g. [1], [2], [3], [4]). Each of these models addresses a different system size and aspect of technological diversity. While most of these models are based on optimization ([1], [3], [4]), others (such as [2]) use a pre-defined hierarchy for power plant dispatch or an agent-based approach [5]. What all these models have in common is a cost-driven dispatch of power plants and balancing measures. Having in mind that they are focusing on well-known generation technologies such as wind energy or fossil power plants and rest upon today's liberal energy markets, this is reasonable.

The RESTORE Model was developed to calculate dispatch of balancing measures in an energy system in the distant future. Since the liberalized energy market has only been in existence in Germany for 18 years, future market designs might significantly differ from today's and will most likely be strongly influenced by political restrictions.

In addition to that, an identification of operational costs for balancing measures is subject to high uncertainties, since some of them (e.g. large battery storage) still have a large potential for cost reduction. Since the costs of the different balancing measures differ, a least-cost optimization would lead to

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[1] RESTORE2050 – Regenerative Stromversorgung & Speicherbedarf in 2050", conducted by Next Energy, Universität Oldenburg and Wuppertal Institute, funded by the German Federal Ministry of Education and Research (BMBF) within the "Förderinitiative Energiespeicher".

preferential treatment for the cheapest balancing options, resulting in a merit order of balancing options, and would thereby not allow an analysis of the mutual interdependencies from a technological perspective.

Therefore the aim of this model is to maximize the usage of renewable energy and to minimize the necessary fossil backup capacity. This way the model is not influenced by economical restrictions.

An additional reason for developing this new model is the flexibility it offers to answer all the addressed research questions. For some of those, it is necessary to retain a high level of detail in some parts of the energy system, while other parts can be simplified. Therefore, a variety of measures to adapt the model to the needs of a specific task had to be applied. A closer look at these measures will be given in section V.

III. MODELING RENEWABLE INFEED AND BALANCING MEASURES

A. Calculating the Residual Load

The model has been developed to analyze the mutual interdependencies between different balancing options such as grid capacities, storage and DSM in energy systems with high shares of renewable electricity infeed. The balancing options are deployed in order to match energy demand and renewable energy supply spatially and temporally, thereby decreasing the need of fossil-fuelled electricity generation. Therefore the task of the optimization is to minimize the positive residual load, which is the mismatch between consumer load and renewable supply.

The backup power plant dispatch needed to cover the remaining load is not represented in this model[2]. Calculating /optimizing the installed capacities of renewables is also not done within the model, instead these are transferred from existing scenarios for high shares of RE supply in Europe such as [6] or [7]. Suitable scenarios have to represent a high share of RE (> 80%) and provide an adequately resolved data base, e.g. give detailed information of installed renewable capacities.

The optimization input for this model is the residual load curve of each region (i.e. each European country) in 2050 in hourly resolution. The residual load (RL) of each region i is calculated as the difference between the consumer load (L) and the infeed from RE (P_{RE}) for each hour t as shown in (1).

$$RL_i(t) = L_i(t) - P_{RE}(t) \tag{1}$$

The RE infeed curves consist of time series for fluctuating energy production from photovoltaic, wind (on- and offshore), hydropower, geothermal power, and wave power in hourly resolution for each country. Covering 10 years of weather data (2003-2012), simulations with changing infeed characteristics can be carried out. These time series are provided by the University of Oldenburg and are based on temporally and spatially highly resolved weather data and plant specifications. These electricity generation curves are scaled based on installed capacities according to the chosen scenario.

The consumer load in 2050 is calculated based on historical load data for each European country provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) [8]. Since there is a strong correlation between load and ambient temperature in most of the European countries, a correction of the influence of temperature on the load curve was performed for the year of origin (2011). Using the derived temperature dependency for each individual country, the load curves are matched to the chosen weather data. Then, these load curves were segmented into the loads of the residential, the commercial and the industrial sector. For each of these segments, a reasonable development towards 2050 was assumed and new electric loads such as electric vehicles and heat pumps were added. Also the heat pump load curves were generated for every country, based on the weather data. The sum of the resulting load curves corresponds to the overall demand given in the chosen scenario.

B. Implementing Balancing Measures

The model's task is to minimize the positive residual load by using the available balancing technologies:

- grid exchange
- controllable RE (biomass, concentrated solar power, hydro storage)
- storage units (pumped hydro storage, compressed air energy storage, hydrogen storage)
- DSM (in industry, households, heat pumps, cooling and freezing, electric vehicle charging)

Grid exchange, which allows a spatial balancing, is represented by defining maximum exchange capacities between neighbouring countries. Here, a grid extension according to [9] is assumed and the transmission lines are implemented in a simplified way as controllable high voltage direct (HVDC) lines.

Storage units are characterized by their maximum charging and discharging power, their utilizable capacity, conversion efficiency and partly also by a natural influx into the storage. The characteristics of the storage units are provided by Next Energy.

Controllable RE infeed and DSM are measures for the temporal shift of energy and therefore comparable to storage. Infeed from controllable RE is hence implemented as storage: The primary energy (biomass, solar irradiation, water influx) is modelled as influx into a storage with a defined capacity. This storage can be discharged, thereby converting the primary energy into electricity, but it cannot be charged, i.e. it cannot convert electricity back to primary energy. This approach permits the implementation of controllable RE according to other balancing options and thereby allows to optimize their dispatch towards the same target. DSM technologies are also implemented as storage units. In [10], Kleinhans presents an approach to represent DSM as a storage unit with temporally variable maximum charging and discharging power and capacity. Kleinhans accordingly calculated time series for DSM in industry, households, heat pumps, cooling and freezing and

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[2] This is due to the fact that in the chosen framework scenarios, solely gas fired power plants remain in 2050. If a more variegated power plant fleet shall be considered, the RESTORE-model can be coupled with existing plant dispatch models (see section II).

electric vehicle charging for each country and provided these data as input for this model.

Table I gives an overview of the implementation of the different temporal balancing measures and which of the characteristics are modelled as constant (“const”) or fluctuating (“f(t)”) boundaries.

TABLE I. IMPLEMENTATION OF TEMPORAL BALANCING MEASURES

	Charging (max) / Discharging (min) Power		***Capacity***		***Influx***
Technology	***max***	***min***	***max***	***min***	
Storage	const	const	const	0	f(t)
Controllable RE	0	const	const	0	f(t)
DSM	f(t)	f(t)	f(t)	f(t)	0

For storage, DSM and grid exchange, different states of development are defined, spanning between today’s state and a nearly full exploitation of the technical potentials. By modelling combinations of different states of different technologies, the mutual effects of the balancing options can be analyzed.

IV. OPTIMIZING THE CONCERTED USE OF BALANCING MEASURES

A. Target Function

The optimization task is to use all available balancing technologies in the best possible way to maximize the share of renewable electricity supply. The residual load is the difference between consumer load and infeed from RE. A positive residual load stands for a residual demand which needs to be covered by conventional power plants, while a negative residual load means an excess of renewable energy.

The model task therefore is to minimize the sum of the positive residual load across all regions and hours. This is reached by transferring excess energy either spatially (via grid exchange) or temporally (via storage or DSM) to other times or regions with a residual energy demand, which leads to lowered residual loads.

Since the magnitude of the remaining load peaks determines the installed power of a back-up fleet of conventional power plants, these load peaks are reduced as a priority. This can be reached by using a square term in the target function. Equation (2) shows the resulting target function.

$$\min \sum_{t} \left(\sum_{i} RL'_{i}(t) \right)^{2} \forall RL'_{i}(t) > 0 \tag{2}$$

The remaining residual load $RL'_i(t)$ in region i at time t is defined as the residual load RL plus the power used for charging storages (P_{stor}), buffering DSM (P_{DSM}) and export (P_{exp}) as shown in (3).

$$RL'_{i}(t) = RL_{i}(t) + P_{stor,i}(t) + P_{DSM,i}(t) + P_{\exp,i}(t) \tag{3}$$

B. Constraints

The three elements $P_{stor,i}(t)$, $P_{DSM,i}(t)$ *and* $P_{exp,i}(t)$ are the optimization variables, the values of which can be varied to achieve the optimal result. Their maximum and minimum power limits must not be exceeded. Also, the maximum and minimum storage capacities must be respected. This is realized by a set of linear lower and upper boundaries *lb* and *ub,* which define the margin in which the balancing options ($\vec{x}$) can be altered. Equation (4) shows the resulting linear inequality constraint.

$$lb \leq \vec{x} \leq ub \tag{4}$$

An additional equality constraint (5) has to be implemented.

$$E(t) = E(t-1) + \left[P_{charge}(t) + P_{influx}(t) + P_{sd}(t-1) \right] * \Delta t \tag{5}$$

This constraint links the storage charging and discharging power (P_{charge}), the influx (P_{influx}) and the self-discharge (P_{sd}) to the storage level E in each hour t.

V. HANDLING THE LARGE-SCALE OPTIMIZATION PROBLEM

Optimization of a highly resolved European energy system quickly leads to very high system complexity and thus to long computation time.

As a general approach to reduce complexity within the described model, the rolling horizons method is applied instead of a perfect foresight annual optimization. Using this, the annual simulation is split into much smaller optimization problems, each of them covering a time horizon t_{hor} in the range of one or two days, depending on the system configuration: These subproblems are solved starting at the beginning of the overall simulation time, always providing a time overlap $t_{overlap}$ from one time horizon to its chronological successor. Optimization results within $t_{overlap}$ of the previous subproblem are set as the starting point for the following one. This way a foresight horizon of at least $t_{foresight}=t_{hor}-t_{step}$ is provided. Taking into account that the accuracy of modern weather prediction models decreases with growing foresight horizon, this approach is likely to be somewhat closer to reality than a perfect foresight of all weather conditions in a whole year.

This rolling horizons method, however, is not suited for modelling seasonal storage, which is deployed to balance fluctuations over significantly longer time horizons. Therefore these storage technologies are modelled in a separate module with reduced temporal resolution. By aggregating several days into one time step, it is possible to optimize a complete year without splitting it into subproblems.

Even though the problem size can be reduced significantly by using the rolling horizons method and a modular adaption of long- and short-term balancing, simulations with full system complexity (32 countries, around seven storage units per country, t_{hor}=48 h resulting in roughly 5500 variables) are tough tasks and result in long computing time. As a wide range of research questions shall be addressed using the model, a main task during the development was to implement several additional options to reduce system complexity. These options allow the provision of detailed system information, where it is necessary for the specific question, and reduce complexity in other parts.

In general, three options are used to reduce system complexity:

- decrease optimization time t_{hor}
- decrease number of regions i
- decrease number of balancing measures

A. Reducing the Optimization Time t_{hor}

Obviously, the reduction of the optimization horizon leads to decreased complexity. To ensure a realistic dispatch of the balancing measures, a foresight of at least 24-48 hours is necessary, since this period covers today's market activity within intraday and day-ahead energy markets. Therefore, the option of an aggregated foresight horizon was implemented in the model. By keeping an hourly resolution at the beginning of an optimization horizon (e.g. 24h) it is possible to add more variables that represent an aggregated period of time within one variable, as shown in Fig. 1. For this aggregated time step, all hourly loads within each region are summed up and represented as one time step within the optimization. Adding several aggregated time periods to an hourly resolved optimization horizon, a long foresight time can be realized without increasing optimization problems. This option enables the model to account for future events. While strong fluctuation is evened out within the aggregated time steps, as the rolling horizons move through the overall simulation time, all events will at some point be in the highly resolved time horizon and thus treated accordingly.

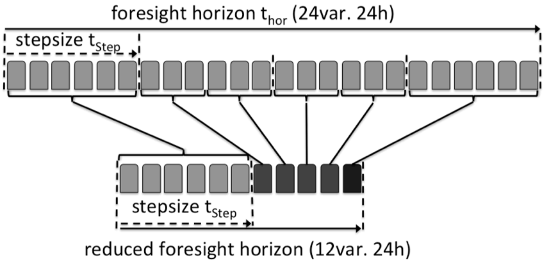

Figure 1. Exemplary vizualization of aggregated foresight time

B. B. Decreasing the Number of Regions (Nodes) within the Model

The database provides information (load curves, RE infeed) at country level. However, the full resolution of countries is not necessary for all simulations. Therefore, the model provides an option to group/merge countries into larger regions. When this is done, interconnection capacity limits between these countries are ignored and all load data and infeed data are merged to a single load or infeed curve. Also DSM potentials are merged and represented as a single balancing option. If storage units are located in each of the original countries, they will remain separate units, located in the resulting region. This option enables very flexible system configuration and can lead to a significant reduction of the problem size. The merging of regions has to be carefully adapted to the addressed research question.

C. Reducing the Number of Balancing Measures

When it comes to the implementation of storage units as balancing measures, large numbers of storage units of varying storage capacity and charging/discharging power exist within each country. All of these single units are included in a simulation by providing a list of storage properties. The equality constraints of the optimization, which are needed to link the power input/output $P_{charge}(t)$ and the capacity $E(t)$, lead to increased computing time. Reasonable calculation time can be exceeded when implementing several storage units per country. When analyzing the interdependencies between storage, grid exchange and DSM, it is not always necessary to keep full resolution of every unit, but instead the overall utilization of a group of units may be of interest (e.g. if the focus is on the interplay of DSM and grid, a full resolution of storages is not necessary). Therefore, another functionality was implemented to increase flexibility of the simulation model:

Storage units can be characterized by the type of temporal energy shift which they are usually used for. While spinning wheels for example operate in the range of seconds, pumped hydro storage normally balances fluctuations from minutes to several hours and even weeks or several months, mainly depending on the reservoir size. The operational characteristics can be described well using the ratio of storage capacity E and the installed charging power P_{charge}, resulting in a specific storage time T_{Stor} as shown in (6).

$$T_{Stor} = \frac{E}{P_{charge}} \tag{6}$$

For any simulation, ranges of different specific storage times can be defined. All units are then classified and merged with other units, matching the same range. This way it is possible to unify many storage units with similar characteristics within one instance of a storage unit.

Having these options of problem reduction at hand, the model is a very flexible tool to investigate interdependencies between balancing options in a large energy system and its subsystems.

VI. CASE STUDY: EFFECTS OF STORAGE AND DSM IN CENTRAL EUROPE

The following case study has been conducted to illustrate the functionality of the model and its results. In this case study, a group of central European countries (France, Germany, Belgium, the Netherlands and Luxembourg, representing about one third of the expected electricity demand in 2050 according to [6]) has been modelled in three different system configurations[3]:

i) grid exchange as the only balancing measure (grid capacities according to [9])

ii) pumped hydro storage in addition to grid exchange (with today's storage capacities, in total approximately 13 GW and 80 GWh)

iii) grid exchange, pumped hydro storage and controlled charging of electric vehicles as DSM (assuming a number of approx. 76 million vehicles with an average charging power of 3.5 kW)

The following Fig. 2 shows the sum of the regions' residual loads in these different configurations for a period of 100 hours (approx. four days) in January.

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[3] This case study is not a result from the RESTORE2050 project. In this project, the whole European electricity system is considered, whereas this case study is limited to a part of this system and only serves to illustrate the presentation of the model.

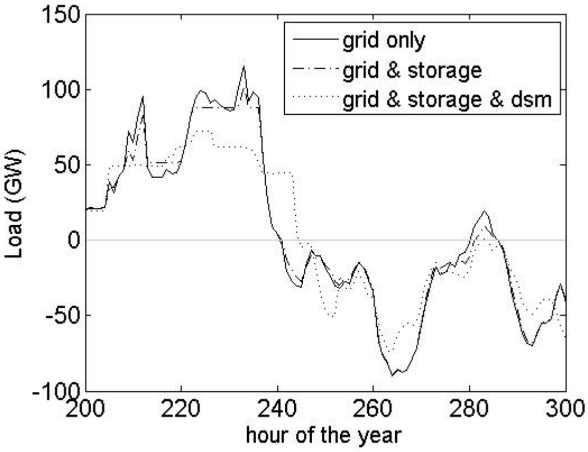

Figure 2. Time series of the residual load with different balancing measures

When comparing the effect of grid exchange alone to that of concerted grid exchange and storage usage, it can be observed that storages are discharged in peak load hours, thereby reducing the residual load, and charged in times of excess energy. The balancing effect is limited by the proportionally low storage power and capacity (13 GW, 80 GWh). In contrast to that, the additional controlled charging of electric vehicles has a very strong balancing influence. This is due to the high number of vehicles assumed to contribute. These effects can be observed clearly in the duration curve of the residual load (i.e. the curve of loads sorted in descending order) which is shown in Fig. 3.

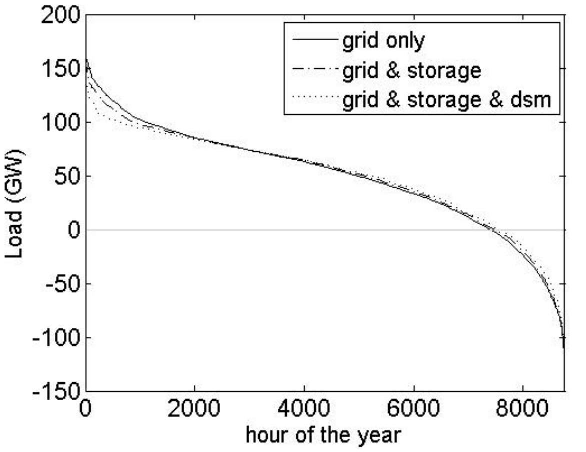

Figure 3. Residual load duration curves with different balancing measures

This depiction illustrates the effect over an entire year. Inter alia, it shows the effect that in order to lower peak loads (see hours 1 to 2000), energy is shifted from times when the residual load is lower (see hours 4000 to 8760). The results shown here serve to illustrate the functionality of the model. They represent only a small fraction of the possible examinations of model results.

VII. SUMMARY / CONCLUSIONS

The RESTORE-model was developed to analyze the interdependencies between energy storage, DSM and grid exchange in energy systems with high shares of RE. It consists of one node for each European country with specific curves for load and infeed. The utilization of the balancing technologies is optimized aiming at the minimization of residual loads. To reduce the complexity of the optimization, several measures have been implemented and are presented here: reducing optimization horizon, clustering regions and merging balancing options. The model is illustrated by showing a case study for five central European countries with different balancing measures. To investigate the interdependencies between the different balancing options, a detailed in-depth analysis of the performance under the different system configurations needs to be carried out. This also features analyses of single system components. This will be done in the context of the RESTORE2050 project, the results of which are expected to be published by the end of 2015.

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