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Assessment of grid optimisation measures for the German transmission grid using open source grid data

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Abstract. The expansion of capacities in the German transmission grid is a necessity for further integration of renewable energy sources into the electricity sector. In this paper, the grid optimisation measures 'Overhead Line Monitoring', 'Power-to-Heat' and 'Demand Response in the Industry' are evaluated and compared against conventional grid expansion for the year 2030. Initially, the methodical approach of the simulation model is presented and detailed descriptions of the grid model and the used grid data, which partly originates from open-source platforms, are provided. Further, this paper explains how 'Curtailment' and 'Redispatch' can be reduced by implementing grid optimisation measures and how the depreciation of economic costs can be determined considering construction costs. The developed simulations show that the conventional grid expansion is more efficient and implies more grid relieving effects than the evaluated grid optimisation measures.

1. Introduction

Due to an increasing share of renewable energy sources (RES) in the German electricity sector, a secure and reliable energy transmission becomes necessary. The conflict between cost and supply reliability, grid operation and planning faces major challenges. Grid expansion is reliable but unpopular with the public [1] and cost-intensive [2], while several 'Grid Optimisation Measures' (GOMs) are also able to reduce or redistribute transmission load in order to avoid curtailment, redispatch and the construction of new lines. The research project *MONA 2030*[1] analyses and compares the GOMs 'Demand Response' (DR), 'Power-to-Heat' (PtH), 'Overhead Line Monitoring' (OLM) and 'Grid Expansion' (GE) [3]. The FfE energy system model ISAaR[2] is applied for assessing the potential, availability, reliability and cost efficiency of these grid optimisation measures. An evaluation of the measures is carried out for the year 2030 regarding the German transmission grid in consideration of the neighbouring countries. Several approaches are applied to handle OpenStreetMap (OSM) grid data. SciGRID [4], osmTGmod [5] and Gridkit [6] are used as grid data sources beside

[1] MONA 2030 (funding code 03ET4015) is co-funded by German Federal Ministry of Economic Affairs and Energy through the funding initiative "Zukunftsfähige Stromnetze".
[2] ISAaR: Integrated simulation model for planning the operation and expansion of plants with regionalisation.

data without an open source license like the BNetzA “Integral” dataset[3] [7] or the grid data sets of the TSOs TransnetBW [8], Amprion [9], 50Hertz [10], Tennet [11] and APG [12][4].
Focus of this paper is the documentation of the modelling methodology, the used grid data, the GOM scenarios and the discussion of simulation results.

2. Method

A valid assessment of GOMs has to be based on quantifiable parameters. Therefore, an approach is developed to meet the requirements of an adequate power flow simulation and a realistic modelling of the GOMs’ dispatch. Two major criteria for the planning of grid development are the parameters redispatch and curtailment. Both values call for a comparison of market simulation results and grid based calculations. In order to analyse the impact of grid-orientated GOMs like ‘Overhead Line Monitoring’ and ‘Grid Expansion’, a market simulation with low detailed spatial resolution is performed. Thereupon, a so called PTDF (Power Transfer Distribution Factors) run with fixed load and generation data from the market simulation for each node is conducted (see [13] and [14] for reference). While this method is quite suitable for grid-orientated measures, the assessment of measures like ‘Power-to-Heat’ and ‘Demand Response’ is more challenging. Their dispatch is influenced by grid restrictions and factors like district heating demand, electricity cost or operational restrictions (e.g. for DR). Therefore, the FfE energy system model ISAaR is extended to perform an integrated dispatch of power plants, renewable energy, Power-to-Heat elements, heat plants and industrial consumers with DR, considering a PTDF-linearised grid consisting of DC and AC lines. This approach allows for performing a uniform comparison among all GOMs regarding the parameters curtailment, redispatch, and economic costs. The coupling of electricity and heat generation within the model benefits the evaluation of combined system costs and facilitates comparisons of GOMs considering effects on the complete, coupled energy system.
The following description of the methodology is divided into three subsections:

1. Description of the ISAaR model with focus on the modelled elements of the energy system.
2. Implementation of a linearised power flow approach, known as PTDF.
3. Discussion of the setup of the optimisation sequence.

2.1. ISAaR Model

The FfE energy system model ISAaR has been developed within the project “MOS – Merit-Order of Energy Storage” [14]. The linear model optimises the deployment and the expansion of power plants. In order to evaluate the previously mentioned GOMs, the models’ structure is modified as shown in **Figure 1.**

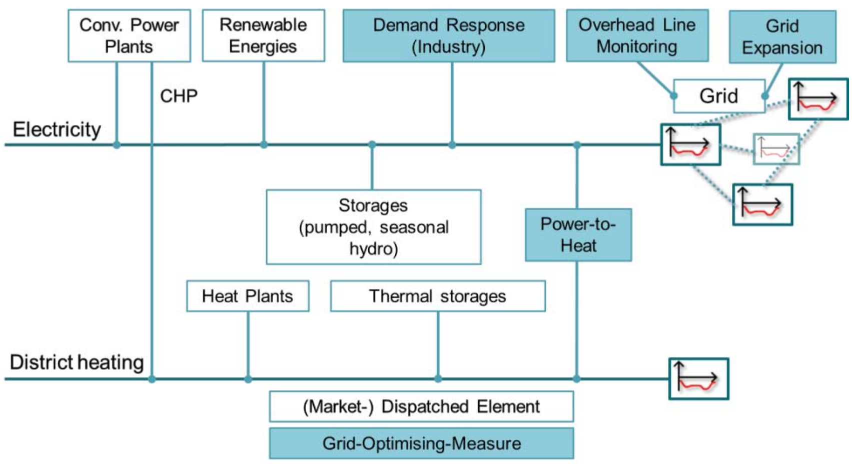

Figure 1. Schematic Overview of the ISAaR models’ structure.

[3] This dataset was made available by BNetzA for exclusive project use.
[4] Each dataset is publicly available via download; no license information is given.

The spatial resolution for the electricity sector in the German-Austrian market region is grid nodes (#496) and for the heating sector grid regions (#26). The grid regions are described in [16] for Germany and in [17] for Austria. At each node or in each region a load equation is set for the electrical and the thermal sector. Additionally, the thermal sector is divided into two parts: public demand and industrial demand. This adjustment is caused by major differences in the seasonal characteristics of the load curves.
In general, the model follows the basics of linear programming for energy systems as described in [18] and [19]. Differing from the traditional formulation for power plants and storages, the mathematical formulation for non-typical elements like Demand Response, Power-to-Heat or combined heat and power plants (CHP) are described in detail in [15].

2.2. Technical Implementation

Many energy system modellers use predefined software like GAMS [20], whereas our approach is based on a combination of Matlab®, PostgreSQL, and CPLEX®. Especially the usage of PostgreSQL ensures a high degree of flexibility in generating and combining scenarios. The internally developed "process model" ([15] and [21]) is an important element when working with large amounts of data covering grids, renewable energies, loads and power plants. The technical implementation of the ISAaR model is shown in **Figure 2**.

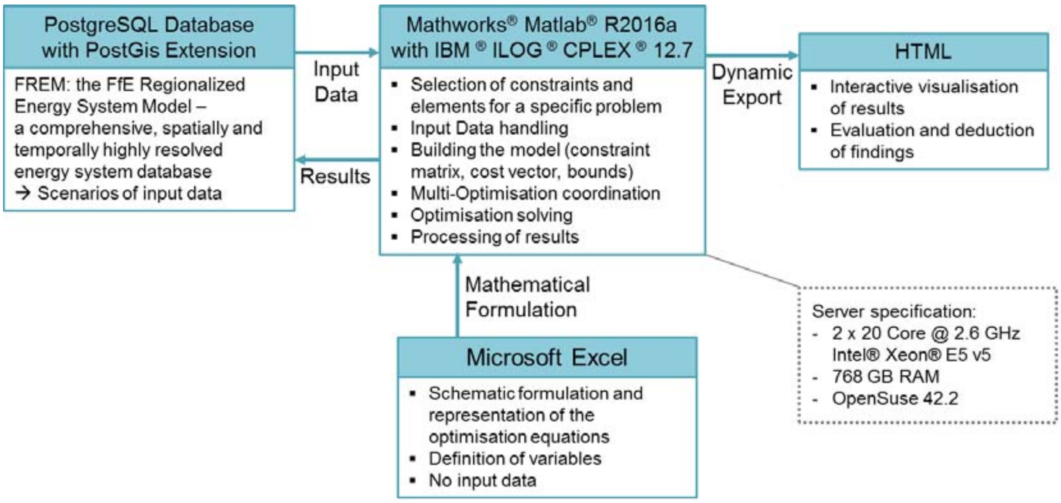

Figure 2. Technical implementation of the ISAaR model.

Standard simulation runs use a rolling horizon (168 h) approach for a whole year and take around 20 to 30 h of computation time. Up to six simulations can be solved simultaneously in parallel configuration. The standard model consists of 496 nodes, applied in a PTDF-grid simulation and the elements mentioned in Figure 1.
Simulation results are visualised interactively by an html-webpage for the evaluation of outcomes and the derivation of insights. A *Leaflet* JavaScript map [22] displays the load of transmission lines and the amount of curtailment and redispatch. Power plant deployment, the utilisation of renewable energy and further analysis is depicted in charts by *amCharts* [23].

2.3. Grid Modelling: DC power flow

Typical grid representations as given in [24] provide good accuracy but come up with computational expenditure. In order to reduce complexity while providing reasonable accuracy, the ISAaR model uses a DC power flow, a linearization of non-linear power flow equations. A clear derivation of this method is given in [25] and [14]. Load flow equations are simplified, assuming no voltage drops, small voltage angles along a transmission line and the disregard of reactive power and line losses. The calculation of the utilisation of overhead lines $\boldsymbol{P_{link}}$ is simplified by a multiplication of the PTDF matrix (Power Transfer Distribution Factors matrix) and the vector $\boldsymbol{P_{node}}$, representing power injections at the grid nodes:

$$\boldsymbol{P_{link}} = PTDF \cdot \boldsymbol{P_{node}} = (B \cdot A) \cdot (A^T \cdot B \cdot A)^{-1} \cdot \boldsymbol{P_{node}} \,. \tag{1}$$

A [V]:	Incidence matrix, describing the grid topology
B [1/Ω]:	Diagonal matrix of line susceptances $B = diag(1/x)$
$\boldsymbol{P_{node}}$ [W]:	Vector of power injections at the grid nodes
$\boldsymbol{P_{link}}$ [W]:	Vector of power flows of the overhead lines

Due to its singularity, the expression $(A^T \cdot B \cdot A)$ cannot be inverted. Therefore, one random node of the network has to become a reference point and must be removed from **equation 1**. A power injection in $\boldsymbol{P_{node}}$ can then be interpreted as a transaction $\boldsymbol{T}$ of energy from one node of the network to the declared reference point. The values in a column of the PTDF matrix represent the share of the power from a corresponding power transaction in $\boldsymbol{T}$ flowing through the lines of the network. Equation 1 establishes a causal link between the resulting power flow and the power transaction between nodes. Since the European transmission network consists of transmission lines with different voltage levels a transformation of line parameters for normalisation is applied:

$$X^* = a^2 \cdot X \text{ with } a = 1/u \,. \tag{2}$$

X [Ω]:	Line reactance
X^* [Ω/V²]:	Normalised line reactance
u [V]:	Voltage level of the line

This transformation integrates all AC lines into one PTDF matrix. High voltage direct current (HVDC) lines have the ability to control the flow of current and are therefore, contrary to AC lines, independent from power injections at the grid nodes. A HVDC line is included into the PTDF matrix by creating a new transaction $T_{x\to y}$ from line start node x to the line end node y. Its power flow is assigned to $P_{link,DC}$:

$$\begin{bmatrix} \boldsymbol{P_{link,AC}} \\ P_{link,DC} \end{bmatrix} = \begin{bmatrix} PTDF & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{T_{AC}} \\ T_{x\to y} \end{bmatrix} . \tag{3}$$

$\boldsymbol{T_{AC}}$ [W]:	Transaction of power towards the reference point
$T_{x\to y}$ [W]:	Transaction of power over a HVDC line from start node to end node

2.3.1. Accuracy of DC power flow
The linearisation of the power flow is accompanied with a decreased level of accuracy. In the papers of [26] and [13], the authors show a reasonable precision of the DC power flow if line loads are smaller than 70 % and deviations of voltage levels in the grid are reasonably small.

2.3.2. Correction of line data
With the collected grid data, mentioned in chapter 4.1, the grid model is generated and the outcome is revised. Due to the variety of data sources, some lines possess faulty and dissimilar line parameters (especially line reactances), resulting in distorted power flows in the ISAaR model. To overcome this issue, these inconsistencies are rectified in a systematic correction process which is described in [27]. Only obviously wrong parameters are corrected utilising further available line data and applying standard values where necessary.

2.4. Optimisation Sequence
Figure 3 reveals the structure of the models' optimisation sequence which allows for an analysis of the complete European energy system as computational effort is reduced. The two European simulations generate cross-border-flows for further simulations of the German-Austrian energy market which depend on available net transfer capacities between market regions and the power plant

capacities in Europe. Therefore, a European market simulation (EU-Ma[5]) is performed first. The cross-border congestion management of this simulation run is based on the NTC (Net Transfer Capacity) approach. Cross-border line projects are considered with the same ratio of NTC to thermal capacity as existing cross-border links. The spatial resolution of load data and renewable generation corresponds to the NUTS 3 level [28]. Power plants are modelled per unit based on the 'Platts power plant database' [29][6] in combination with the TYNDP[7] scenario "Vision 2" [30]. The values for load and installed capacity of renewable energy per country are also derived from [30]. The regionalisation is based on a geospatial analysis in combination with weather data (7 km grid) from the "COSMO-EU" dataset [31] and statistical data like Eurostat [32]. Further information and citation of used data can be found in [27].

For the following step (EU-Ne[8]), the aggregated European transmission grid (see section 4.1.) is added to the model. Due to the high number of nodes (#1500) and lines (#2800), resulting in exceeding computation capacities, a simple PTDF run is performed with a fixed plant dispatch. The optimised elements are HVDC lines, synthetic generation plants and synthetic consumers to keep every load equation feasible. The dispatch of those synthetic elements may be interpreted as (cross-border) demand of curtailment and redispatch.

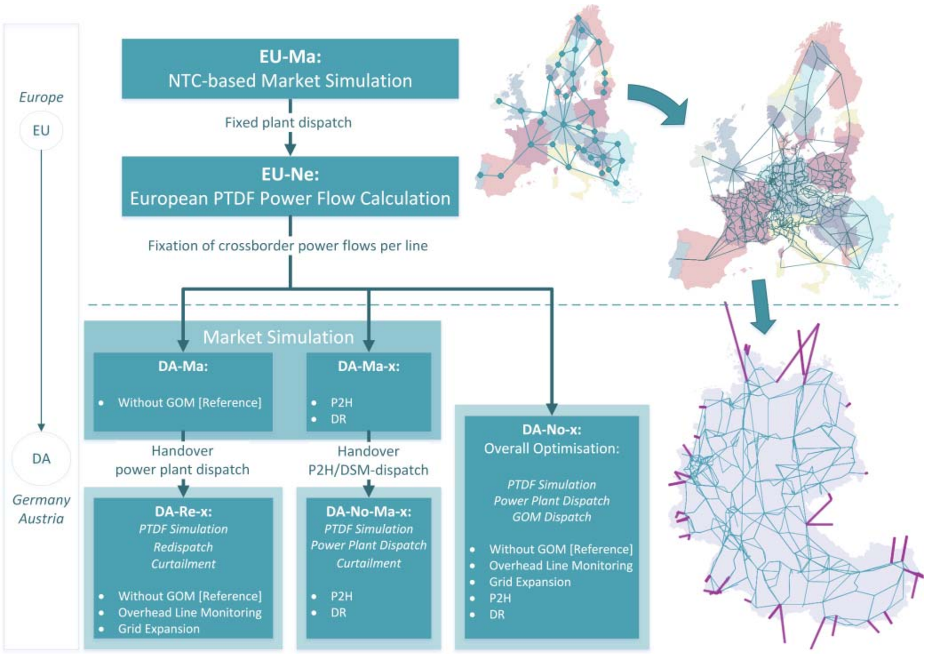

Figure 3. Schematic representation of the optimisation sequence.

With fixed, previously calculated European cross border flows, a market simulation for the German-Austrian market region is performed (DA-Ma). To compare market and grid related dispatch of the GOMs Power-to-Heat and Demand Response, a market simulation considering these GOMs (DA-Ma-x[9]) and a PTDF run with fixed market dispatch of GOMs (DA-No[10]-Ma-x) is performed. For grid related GOMs ('Overhead Line Monitoring' and 'Grid Expansion'), a PTDF run with additional costs on deviation from market dispatch is set up in order to quantify curtailment and redispatch volumes (DA-Re-x). It is not possible to determine the redispatch volume if a load-manipulating GOM like

[5] Ma: Market
[6] The 'Platts power plant database' is a commercially available dataset.
[7] Ten-Year Network Development Plan
[8] Ne: "Netz" (Grid)
[9] „x" is a placeholder for different GOMs.
[10] No: "Netzoptimierung" (grid optimisation)

'Demand-Response' or 'Power-to-Heat' is used. Therefore a third PTDF run is carried out. This run contains an optimised power plant dispatch and GOM dispatch. The resulting overall economic costs for power and heat generation from two simulations with and without the GOM are taken to assess the GOMs impact.

3. Grid Optimising Measures (GOMs)

The impact of a GOM is strongly dependent on its level of implementation. For example, the grid expansion of multiple lines may lead to higher specific savings than expanding one single line. In order to consider this effect, several scenarios are formed to represent different implementation levels of the GOMs 'Overhead Line Monitoring' and 'Grid Expansion'. The selection of lines to be upgraded or monitored first, is based on their line loading in the reference case.

3.1. Overhead Line Monitoring (OLM)

'Overhead Line Monitoring' allows to recognize and exploit additional existing weather-related transmission capacities. The temperature of a line is monitored in order to control its slack and thus keep to valid norms (DIN EN 50341) while avoiding early ageing [33]. With equations for the thermal balance in an overhead line discussed in [3], the line temperature can be approximated dependent on weather conditions and the heat input ($I^2 \cdot R(T_C)$) through current flow:

$$q_c + q_r = q_s + I^2 \cdot R(T_C)\,. \tag{4}$$

q_C [W/m]: Heat removal through convection
q_r [W/m]: Heat removal through radiation
q_s [W/m]: Heat input through solar radiation
I [A]: Current through power line
$R(T_C)$ [Ω/m]: AC resistance of power line at line temperature T_C

The maximum current in the overhead line can be calculated for the maximum line temperature T_C and the prevailing weather-conditions wind velocity, wind direction, solar radiation, and ambient air temperature. Divided by the maximum norm-line transfer capacity of the overhead line, its additional transmission capacity can then be depicted.

Knowing the route of all German transmission lines and the weather data for the year 2012, the available potential of additional transmission capacities is computed for every single line and for every hour of the year. Furthermore, technical restrictions of OLM are considered: on the one hand, current flow is restricted through limitations in elements like circuit-breakers. On the other hand, current flow has to be limited due to a higher voltage drop and the increased need of reactive power in the lines, leading to a risk of system instabilities. Thus, additional transmission capacities are restricted to 50 % of the norm line transfer capacity, except the current flow is restricted further by technical limits of other elements.

3.2. Power-to-Heat (PtH)

As shown in **Figure 1**, Power-to-Heat (PtH) is a sector coupling element. The dispatch of this element depends on the thermal load situation in its assigned district or industrial heating network. On the one hand, PtH is used as an additional load which may avoid curtailment of renewable energy if placed at a convenient location within the transmission grid. On the other hand, PtH, in combination with CHP plants and thermal storages, leads to an increased system's flexibility.

Provided that future PtH expansions are not driven by grid related reasons, the penetration rate is set to 25 % of the thermal power input of existing district heating networks (state 2015). Assuming that the largest German district heating networks are equipped with PtH-devices by 2030, 9.2 GW of PtH capacity is expected to be installed.

3.3. Demand Response (DR)

Power demand of the industry sector can be flexibilized and thus be utilised for temporarily unloading bottlenecks in the transmission network. In [34], the technical potential of demand response is assessed and its economic considerations are elaborated. In the ISAaR model, 2.2 GW in large electricity-consuming companies and 1.6 GW in cross-sectional processes are available for flexible usage. In general, the two fields of DR-application, modelled in ISAaR, are the shift and the loss of production. Conditions on the frequency of demand response dispatch are set in [15]. The regionalisation of DR is oriented to the allocation of employee-numbers and heavy industry locations.

3.4. Grid Expansion

Besides 'Overhead Line Monitoring', 'Grid Expansion' (GE) is another approach to add transmission capacities to the grid. 'Grid Expansion' can be realised in several ways. There are the options of constructing new transmission lines in used or new paths, adding circuits to an existing line or increasing its voltage level. Depending on the individual project, grid planners have to choose the best expansion method for an appropriate grid operation. GE usually comes with high investment costs, but also with high benefits for the transmission grid due to decreased curtailment of renewable energy and reduced redispatch volume.
In the reference scenario, an analysis of all transmission lines is conducted. The most stressed lines are then considered for 'Grid Expansion'- measures in several scenarios. For 220 kV AC lines, the voltage level is increased to 380 kV. For 380 kV, new AC lines with a norm voltage of 380 kV are built with two circuits on the existing path.

4. Input Data

Due to the enormous quantity of input data, the focus of this chapter addresses grid data. Further information on input data can be obtained in [35] (scenario "standard").

4.1. Grid Data

Figure 4 gives an overview of the used grid data. In the ISAaR model, the open-source toolkit Gridkit [6] is used to describe the transmission grid of Europe outside Germany and Austria. With an aggregation process, the grid is simplified in countries distant from and not neighbouring Germany and Austria (see [27]). Due to a lack of reasonable line parameters, standard values from literature are used. With results from the SciGRID project [4], grid data in Germany is validated. Applying the data from the model osmTGmod [5], precise geographic information of transmission lines can be obtained and utilised for the computation of additional transmission capacities with OLM. In parts of the grid, where the transmission capacity of the distribution grid becomes relevant (especially the Ruhr area and the region at the German-Austrian border), secondary lines (110 kV) are considered. Line data is directly taken from Open Street Map [36]. Detailed information on the collection of grid data is given in [27].

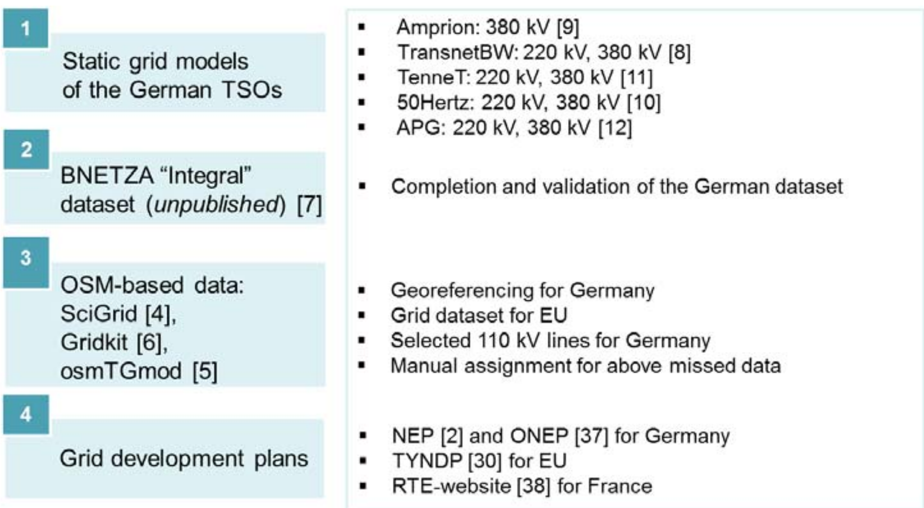

Figure 4. Origin and usage of different grid data sources.

4.2. Surrounding Scenario

To perform simulations of the unit commitment in 2030, assumptions on the energy system have to be made. Therefore, the "standard" surrounding scenario of 2030 is set in [35]. The installed capacity of power plants in Germany in 2030 is made up of 23.2 GW coal-fired plants and 34.2 GW natural gas-fired generators. The renewable capacities consist of 73.8 GW onshore wind power, 15 GW offshore wind power, and 75 GW photovoltaic power. The regionalisation of RES is carried out as shown in [39]. The annual energy demand is set to 496.2 TWh_{el}, comprising the conventional load, the demand from heat pumps and the energy demand of the electro-mobility sector. Altogether, the share of RES accounts for 61 % of the final electrical energy consumption.

5. Results

Considering the framework conditions, the gathered cross border flows in Chapter 2.4 and the defined surrounding scenario in Chapter 4.2, simulations of the unit commitment in 2030 are conducted for the market area Germany and Austria. First, a simulation without any GOM is computed and taken as the reference scenario for comparisons with further simulations. Thereafter, several GOMs are implemented for following simulations: two different configuration levels of 'Overhead Line Monitoring' (OLM 1 and OLM Max; 256 km and 23,621 km), a scenario of 'Grid Expansion' (GE; 507 km), a scenario with 'Power-to-Heat' elements and a scenario with 'Demand Response'. The main findings of those simulations are given in the following.
The reduction of redispatch and curtailment are two major criteria when assessing the benefits of a GOM. Compared to the reference scenario, the reduction of redispatch is 0.12 TWh and 0.59 TWh for the two different stages of OLM, the decrease of curtailment amounts to 0.18 TWh and 0.31 TWh (see **Figure 5**).

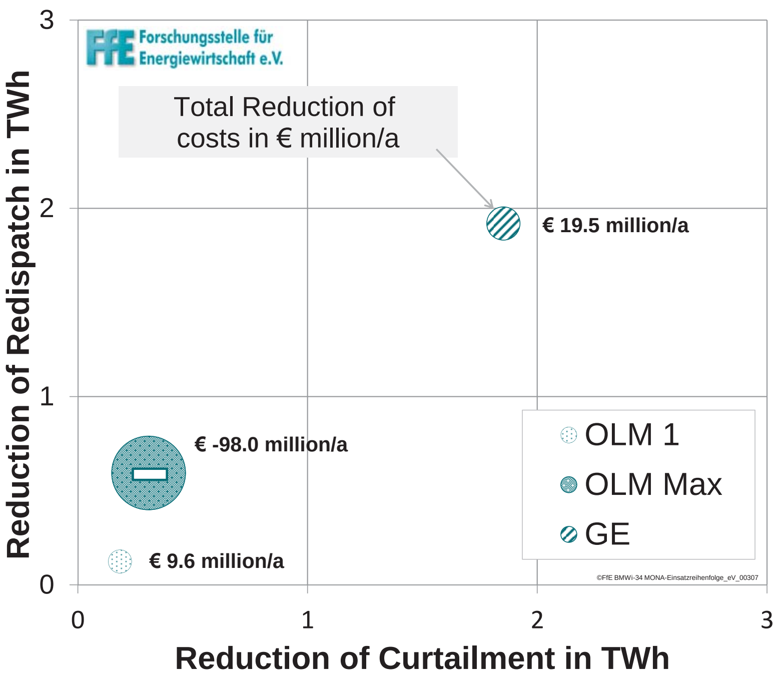

Figure 5. Reduction of redispatch, of curtailment, and diminution of total costs for different GOMs.

With a reduction in redispatch by 1.8 TWh and a decrease of curtailment by 1.9 TWh, the 'Grid Expansion' scenario achieves a greater benefit than OLM. Even the maximum possible equipment with OLM cannot benefit the transmission grid as much as the 'Grid Expansion'-scenario. The decrease of redispatch and curtailment consequently leads to reduced power plant commitment costs due to a more reasonable power plant dispatch and higher integration of RES. Considering the annual

costs for the construction of the GOMs, in **Figure 5**, the annual benefits of the measures can be examined. OLM 1 and 'Grid Expansion' come with a reduction in total cost[11] of € 9.6 million and € 19.5 million, respectively. The measure OLM Max causes an additional total cost of € 98.0 million to the system. An intensive expansion using OLM is neither beneficial for the total cost nor for a significant reduction of redispatch and curtailment.
Figure 6 depicts the reduction of curtailment of the GOMs 'Power-to-Heat' with 1.5 TWh and 'Demand Response' with 0.1 TWh. DR has a limited potential to integrate surplus energy from RES due to a restricted shift potential of industrial production processes. However, PtH can permanently integrate excess energy to the heat sector. The reduction in power plant commitment costs due to the GOMs, shown in **Figure 7**, is at € 69 million for PtH and € 49 million for DR. Considering the costs for construction and the total reduction of costs, DR (€ 46 million savings) is more profitable than PtH (€ 11 million). Here, the transfer of load demand to dates with a high share of RES and therefore low prices leads to lower unit commitment costs. Due to the unfavourable spatial arrangement and the restricted shift potential of DR the impact on the network loading is modest.

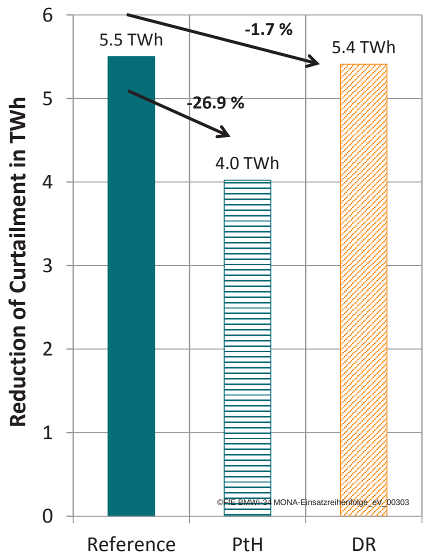

Figure 6. Reduction of curtailment for the measures PtH and DR in comparison to the reference scenario.

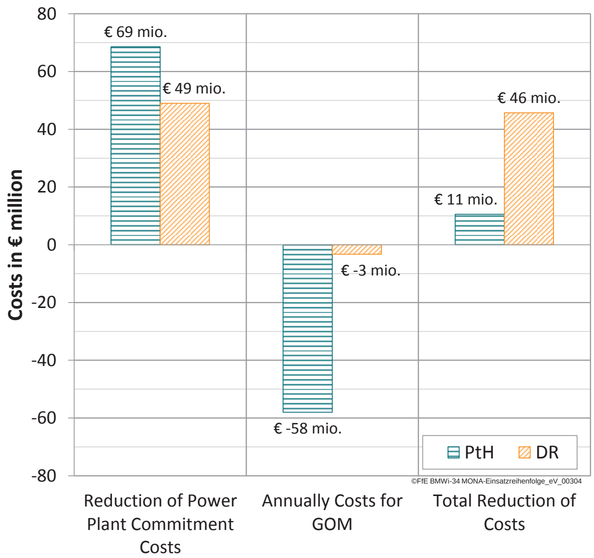

Figure 7. Reduction of unit commitment costs, annuity costs for construction, and reduction of total costs for the measures PtH and DR in comparison to the reference scenario.

6. Conclusion
This paper describes the extension of the ISAaR model with a linearised grid model, enabling a holistic assessment of grid optimisation measures and providing comparability among them. Grid data is gathered from sources of grid operators and open-source data, based on Open Street Map. Different OSM-based toolkits help to achieve a reasonable grid representation.
Within the research project *MONA 2030* (Merit Order Grid Expansion 2030), the ISAaR model is applied for evaluating the grid optimisation measures 'Overhead line monitoring', 'Power-to-Heat', 'Demand Response', and conventional 'Grid Expansion'. In Chapter 5, first results and findings are shown, while further outcomes are supposed to follow from the mentioned project.

[11] Total costs are the costs of one year for the dispatch of power and heat plants minus the annually costs for construction of Grid Optimising Measures.

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