Influence of Power-to-Gas-Technology on Unit Commitment and Power System Operation

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***Abstract*—According to the Energy Policy of European Union, renewable energy sources (RES) should supply 80% of the total demand for electrical energy in the year 2050. Due to seasonal intermittency of these production technologies, large-scale penetration of energy storage can be expected. Power-to-Gas (PtG) technology offers a possibility for long-term storage of excess electricity, as well as other advantages that result from the coupling with the gas system. In order to analyze effects of PtG units on the power system, especially with regards to their positioning, a simulation method modeling electricity markets and network operation is presented in this paper. Exemplary results show that PtG units can significantly contribute to the integration of RES energy. Their positioning is however a key factor, as transmission restrictions potentially limit the amount of electricity that can be transported and stored.**

***Index Terms*—Energy Storage, Power system simulation, Power generation dispatch, Power system management**

I. INTRODUCTION

The European power system is foreseen to gain a rapidly growing share of renewable energy sources (RES) in the future. Intermittency of wind and solar energy with long periods of unavailability are increasing the need for energy storage, especially long-term storage with high storage capacity. Furthermore, as the RES are mainly located in rural regions with low demand for electricity, the electrical transmission network has to manage new challenges to transport the electric energy into urban demand centers. The transmission network was primary not designed for this task, which results in a high increase of congestions in future, if no reinforcements are applied. Such interregional congestions can only be relieved by curtailing RES and activating conventional power plants that are located near urban areas. One approach preventing energy wastage is the activation of flexibility potential by coupling different energy infrastructures.

One possible concept connects electrical and natural gas transmission networks via Power-to-Gas-Technology (PtG). Gas infrastructure can be beneficial as it contains high storage potential due to underground reservoirs. PtG units are acting as an extra load in the electrical network as they transform electricity into synthetic gas. Hence, by positioning PtG units in the areas with highly positive power balance (rural areas with high RES generation and low load), it is possible to reduce the network congestions and the amount of curtailed energy due to the limited transmission capacity. In this paper, effects of the PtG units and their locations on the power system will be analysed, especially regarding their influence on unit commitment and congestions in the transmission network.

II. METHODOLOGY

Production schedules of power plants result from trading activities on different energy markets and portfolio optimization. By using this schedules along with the electricity demand forecasts, transmission system operators (TSOs) conduct load flow calculations and prove if any congestions, e.g. violations of current or voltage limits, are present in the grid. If congestions occur, additional operational measures such as adjustment of the market-based power plant schedules (redispatch) are taken in order to ensure operational safety. In order to quantify the effects of PtG units on unit commitment and congestions, it is necessary to simulate wholesale electricity markets and consequently the operation of the power system. A methodological approach consisting of market and network simulation will be presented in this paper.

A. Electricity Market Simulation

The market simulation method is used to determine the cost-minimal production schedule of the power plants to supply a given demand, taking their technical constraints into account. It is based on fundamental data such as fuel prices, electricity demand and technical characteristics of generation units. Simulations are performed in an hourly resolution, with additional constraints such as limited transmission capacity between bidding zones also being considered in each time step. Technical constraints of the power plants comprise their production limits, reservoir levels of hydraulic units, and time-integral constraints such as ramp rates, minimum on/off times as well as emission/fuel constraints. [1]

PtG units, similar to a pump storage, convert electrical energy into another energy type, which is better suited for storage. They are therefore modelled as a pump, e.g. “reverse” gas turbine, taking electric power from the grid and transforming it into natural gas. The PtG units acquire a constant fee for the produced gas, and therefore take advantage of hours with low electricity price to generate

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profits. These profits correspond to the difference between gas and electricity price, taking conversion losses into account. The simulated electricity price is based on the marginal cost of power generation in each market area. Infeed into the gas transmission network is hereby not constrained, as it is assumed that it has been properly dimensioned to accommodate additional infeed of PtG units.

In order to solve the described large-scale optimization problem market simulation method consists of multiple steps. As it includes integer variables and time-integral constraints, performing a full scale optimization would require a long computation time. Fig. 1 gives an overview of the whole process.

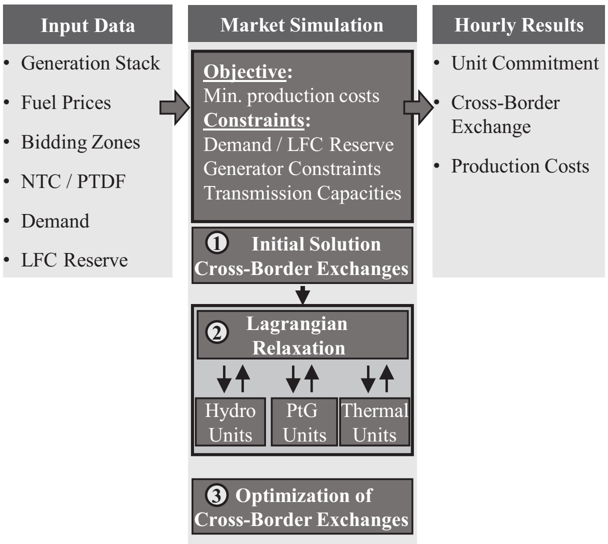

Fig. 1. Market Simulation Overview

After processing input data, method starts by obtaining an initial solution using an LP formulation of the optimization problem, neglecting the production limits as well as the commitment (on/off) decisions. In this way, an approximation of the cross-border flows between bidding zones can be obtained. These are fixed for the next step, in which the commitment of individual units is coordinated in order to determine cost-optimal schedule that complies with their operating restrictions.

This is performed using Lagrange relaxation method. For each bidding zone demand and reserve constraints are relaxed by introducing Lagrange multipliers. Dynamic programming is then used to optimize commitment decisions of thermal and storage power plants (including PtG units). Schedule of interlinked hydraulic groups is determined using successive linear optimization approach.

In the last step, commitment (on/off) decisions are fixed, and the cross-border exchange and production schedule of individual units re-optimized. Based on the obtained production schedule and marginal generation costs for each unit, simulation of network operation is consequently conducted.

B. Simulation of Network Operation

Objective of the network operation simulation is to coordinate remedial actions (such as redispatch, modifications of grid topology or tapping phase shifting transformers) in order to eliminate network congestions that are present in the grid. Congestions arise due to the violation of voltage or current limits on a specific grid element. In addition, it is necessary to consider the operational (n-1) criterion, to ensure the mentioned limits are not violated in the case of a contingency. The flow chart of the network simulation is depicted in Fig. 2.

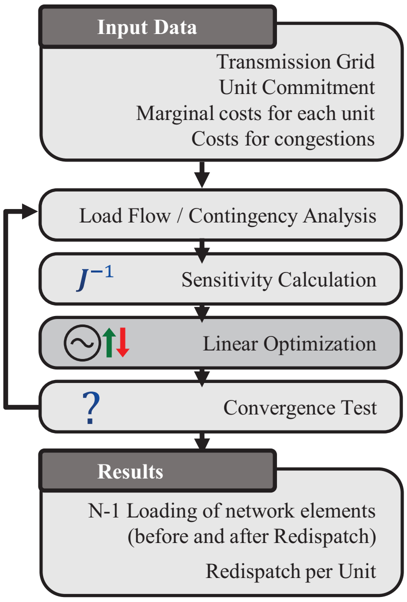

Fig. 2. Simulation of Network Operation

One of the main input data for the network operation simulation is the European transmission grid model, which was developed on the basis of publicly available data (such as grid maps, static grid models). Standardized equipment types were used to model network elements in the case where no additional information on its technical parameters was available. As conducted simulations refer to future scenarios, grid model includes planned expansion projects.

Beside production schedules, marginal production costs are an important parameter for each unit, as the congestions should be relieved at minimal cost. Beside conventional power plants, it is possible to reduce the production of generation from renewable energy sources (RES). However, as a last resort measure, RES curtailment is assigned much higher cost. Loading (or congestion) constraints are formulated as “soft” constraints, introducing a penalty for their violation. In this manner, feasible solution will be found even in the case where the congestion can’t be relieved using available remedial measures.

Simulation method starts with a load flow and contingency analysis, in order to identify the congested elements. In the next step, sensitivities on the load flow are calculated. Node-branch sensitivities quantify the change of the current or voltage over a certain element due to injection additional power on a specific node. Effects of contingencies are considered by the means of branch-

branch sensitivities (LODF).

Sensitivities along with production costs enable formulation of linear optimization problem. Objective is to minimize overall costs of production displacement, while fulfilling current and voltage constraints. Overall power balance should be zero, e.g. power injection on one side of congestion should be compensated by power extraction on another side. As no cross-border dispatch is considered, balance constraint was defined for each bidding zone.

After the optimization, the power plant dispatch is set to a newly obtained value and the load flow calculation is performed again. This is to check if currents and voltages are really within the desired limits, especially due to the potentially high linearization error (sensitivities represent linear approximation of load flow equations). Usually, several iterations are necessary until the linearization error is diminished and the solution converges to a stable value.

Result of this successive linear optimization is redispatch per production unit as well as the new loadings of network elements. [2]

III. EXEMPLARY INVESTIGATIONS

The influence of PtG units was assessed for two scenarios of the power system in the year 2050, based on [3]. In the focus of these scenarios is a power system, in which the renewable energy sources produce enough energy to cover complete demand. The focus of the investigation was Germany. Nevertheless, for the market dispatch the European market was simulated. Both scenarios assume that in such system total capacity of PtG units would amount to 38 GW. This was a result of a techno-economic and profitability analysis. [4] However, scenarios differ in the positioning of the individual PtG units in the grid.

Locations in the first scenario resulted from an optimization process that took costs of connecting the units to gas- and power transmission systems into account (PtG Concentrated). [4] In the second scenario, a simplified approach was conducted, considering only the effects on power system. PtG units were hereby assigned to the network nodes with high RES infeed (PtG Distributed).

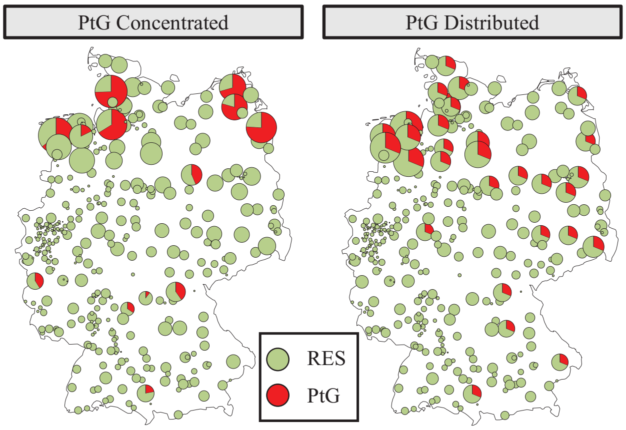

Fig. 3. Spatial distribution of RES and PtG units

As connection points to the gas network are not considered in this scenario, resulting layout is much more distributed in comparison with the first scenario, where most of PtG units were installed in the proximity of gas transmission network. Fig. 3 depicts the differences in the spatial distribution of PtG units between two scenarios.

PtG units were modeled as alkaline electrolyser with an additional methanation unit, with an assumed overall efficiency factor of 84% (to convert electrical energy into methane). As both scenarios assume large scale penetration of PtG technology, mainly consisting of smaller units (each having several MW), efficiency was equal on all network nodes.

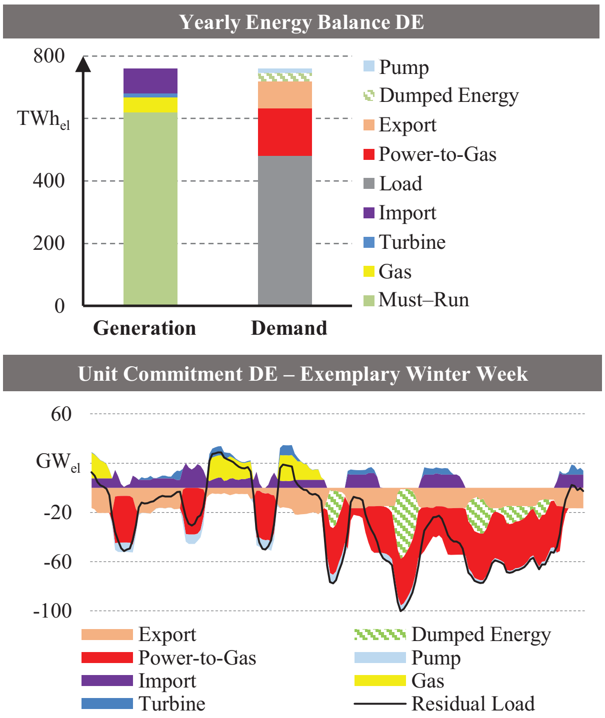

Fig. 4. Influence of PtG on Unit Commitment and Energy Balance

Results of the market simulation for Germany (DE) are depicted in Fig. 4. Since scenarios only differ in the spatial distribution of PtG units and not in the amount of installed power, the market result is not depending on the scenario. As it can be seen from the yearly energy balance for Germany, PtG units consume about 152 TWh, achieving 4000 full load hours. Gas-fired power plants use the gas produced by PtG units to generate 48 TWh of electric energy, completing the storage cycle. The lower graph on Fig. 4 denotes production schedule in Germany for one exemplary winter week. PtG units are mainly activated in the hours with excessive production of RES, while gas power plants operate in the hours with a lack of this intermittent generation. As a long-term storage PtG units mainly make use of seasonal variations in wind and solar power infeed. However, due to limited capacity of PtG units, 25 TWh of excess energy could not be stored into gas, and is thus denoted as dumped energy. PtG units also act as a storage for excess production in neighboring countries. Germany achieves therefore almost equal export and import quantities.

Results of the network operation simulation show that significant overloadings are present in the grid, due to the fact that the transmission grid only includes expansion projects until 2035 (no further grid planning was previously conducted, only the presently available long-term expansion projects were included). Congestion energy will be used to express the amount of overloadings in the system. It is calculated for each network element, it represents the amount to which (n-1) loading exceeds its maximal capacity. As no network expansion was conducted, redispatch costs should not be overestimated due to structural congestions. Redispatch was therefore limited - in order to reduce congestion energy by 1 MWh, it was allowed to conduct 6 MWh redispatch at most.

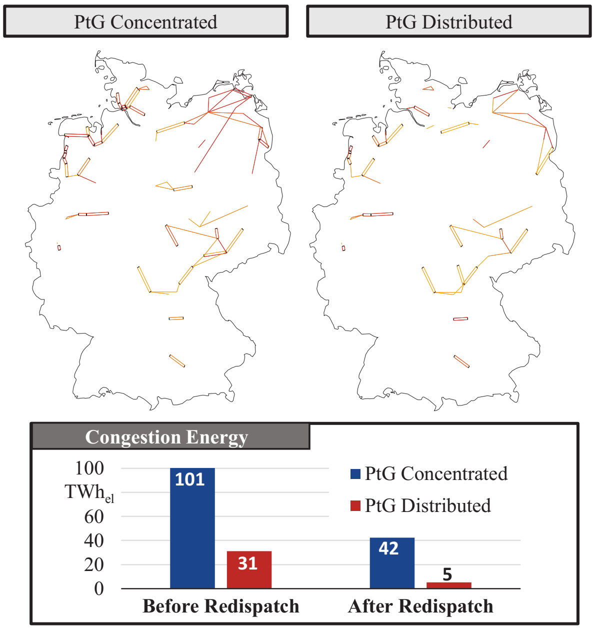

Fig. 5. Congestions in considered scenarios

Fig. 5 and Fig. 6 depict the congestion energy and conducted redispatch in Germany, respectively. In both scenarios, congestions are present in the regions that either have high RES penetration, or lie on the main routes to demand centers. Such examples are connection points of offshore wind parks or transit region between East and South Germany. Additionally, in the first scenario, high concentration of PtG units on several locations in northern Germany induces large amount of local congestions on the surrounding lines. It is often necessary to curtail the operation of PtG units (positive redispatch of 16 TWh) to relieve these congestions. By distributing the PtG units on much more locations and in accordance with RES distribution, congestion energy can be reduced to a third of original value, confirming a significant share of local congestion in the first scenario.

As a consequence of reduced congestions, necessary redispatch decreased from 51 TWh to 26 TWh, which especially applies to the curtailment of RES. Differences are especially visible on the reduction of positive redispatch in western Germany, as well as on reduction of local redispatching in northern Germany. Although the curtailment of PtG units could also be reduced to 11 TWh, PtG units often conduct a positive redispatch (reduction of power of PtG units in grid simulation). This means there is still a need for grid expansion for the proper integration of those new units. More than 40 % of congestions in the first scenario could not be eliminated due to limited redispatch potential.

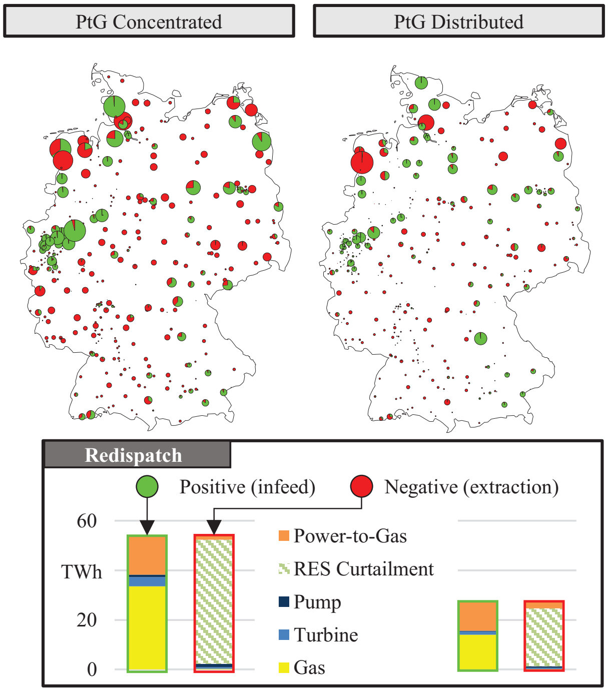

Fig. 6. Redispatch Structure and Spatial Distribution

IV. CONCLUSIONS

The exemplary investigations show that PtG units can significantly contribute to the integration of RES into the power systems, as they reduce the amount of curtailed (dumped) energy by transforming it into natural gas. Excess electrical energy can therefore be used for the gas supply or reconverted to electrical energy at some later point. Furthermore, the importance of the PtG units positioning in the electrical grid was pointed out by comparison of two scenarios. It could be concluded that more distributed arrangement that correlates with the distribution of RES would be highly beneficial, in terms of reducing network congestions and therefore enabling integration of large quantities of renewable energy. However, since this second scenario doesn't consider costs of connecting PtG units to gas system, a trade-off between distributed and concentrated layout should be made. Furthermore, congestions remaining due to limited redispatch potential indicate the need for a network expansion, which should consider the possible positions of the PtG units.

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