THE IMPORTANCE OF DISTRIBUTED STORAGE AND CONVERSION TECHNOLOGIES IN DISTRIBUTED NETWORKS ON AN EXAMPLE OF "SYMBIOSE"

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ABSTRACT

The expansion of distributed renewable energy units drives the existing distribution grids to the limits. One possible solution to avoid exceeding the grid limitations is the integration of decentralized storage and conversion technologies that enable a decentralized coupling of existing energy supply infrastructures (electric-, gas-, and domestic heating grid). This paper presents the work and selected results of the project "Symbiose", which examined whether the integration of decentralized storage and conversion technologies can support the massive integration of renewable generation into the electrical distribution grid. The idea of "Symbiose" was applied on two distributed model regions (urban and rural) with complete consideration of their regenerative potential. In order to examine the importance of distributed storage and conversion technologies regarding the technological requirements of the electrical grid a linear optimization model in GAMS was implemented. The optimization model comprised all three networks with predefined generation and demand elements, and variables of storage and conversion units. The objective function of the optimization model was minimal costs of the implemented energy system. The optimization results showed a violation of electrical network limitations with the installation of the region's complete regenerative potential. Therefore storage technologies were considered in both model regions. The storage demand was reduced when a coordinated reactive power control was applied. Great reduction of the storage size was achieved by allowing the curtailment of electricity from renewable sources. The preferred storage technologies from a technological perspective were decentralized short-term storages (batteries).

INTRODUCTION

The Austrian 2020 climate targets can only be reached with a further penetration of renewable energy units in the electricity sector. Biomass, photovoltaic (PV), wind and small hydro power plants count to those renewable power units. The volatile and uncontrollable generation behaviour of those renewable sources drives existing distribution grids to the limits. Especially, the loading of grid components (existing power lines and transformers) and the voltage have to remain within the allowable limits. Grid upgrades or capping the power production are the common measures to avoid overloading of grid components. Increased voltage levels on bus bars can be prevented by the integration of controllable transformers (on load and off load tap changer) and the integration of PV systems with a coordinated reactive power control. Another possible solution to avoid exceeding the grid limitations is the integration of decentralized storage and conversion technologies. Storing or buffering the decentralized surplus energy could also decrease the energy import of small and grouped consumers (households and community) from higher grid levels. This is especially important considering the fact that the potentials of Austrian large-scaled hydro storage systems are not sufficient for a complete renewable power supply [1]. Decentralized storage technologies could play a big role here in relieving the large scaled storage technologies, thus relieving the higher level grid. The high flexibility of the gas grid including large gas storage capacities could for this matter particularly be considered if the conversion of power to gas is applied.

To determine the role of distributed storage and conversion technologies regarding the technological requirements of the electrical grid an optimization model of examined model regions was implemented. The main goal was to determine the decentralized storage potential of regions with a high share of renewable generation in order to relieve the higher level grid by ensuring a decentralized generation-load balance. The necessity for distributed storage and conversion technologies was also estimated with the consideration of further grid measures such as reactive power control of PV inverters and the curtailment of electricity from renewable energy sources. The following section presents the implemented optimization model and the initial situation for the examined model regions.

METHODOLOGY

The core of the work for examining the presented "Symbiose" idea was a linear optimization model implemented in GAMS. The determination of the ideal storage technology, ideal storage dimension, ideal storage position and ideal storage operation were targets of the optimization model. The objective function for obtaining those targets was minimal costs of the implemented energy system. Following cost components were included for the determination of the technological role of storage technologies: annual installation costs of storage and conversion technologies, costs for energy losses caused by storage and conversion technologies, costs for losses caused by the energy transport in the electrical and thermal network and costs for the curtailment of electricity. The optimization model comprised the electrical grid, a gas and thermal system with the predefined generation and load profiles, and instances of variables for storage and conversion units. The topology of the implemented optimization model is presented in Figure 1 applied to the rural model region. The presented

topology consists of all elements that were considered during the optimization and which influenced the decision process. To allow a long-term operation of storage, a time horizon of one year had to be considered for the optimization model. A workaround had to be implemented to obtain long-term storage operation during the optimization, since the predefined generation and load profiles were just for three characteristic weeks available. The characteristic weeks, in a time step resolution of 15 minutes, were representatives of a winter, a summer and a transitional period. The workaround implied an optimization for a period consisting of only four weeks (winter, transition, summer and transition) with an implementation of correct energy content to pass from one characteristic week to another. The optimization results were then rolled out for a period of one year with following repetition and multiplication of characteristic weeks: seventeen times winter week, nine times transitional period, seventeen times summer week and nine times the transitional period.
Other methods for keeping the grid limitations in parallel to the installation of storage technologies were examined as well to outline the determined role of decentralized storage technologies in distributed grids. Thus, two further scenarios of required storage demand were calculated. The first scenario considered the reactive power control of PV inverters which counteracted the voltage decrease and voltage increase. The implemented reactive power control was the Q(V)-control. The Q(V)-control generates or consumes reactive power depending on the voltage level considering a linear correction curve with a max $cos\varphi$ of 0,95. The second scenario considered the curtailment of electricity from renewable energy sources installed in the examined model regions. The curtailment of electricity means a deliberate decision of not feeding the potential power into the electrical grid. As an example, for PV systems this means moving away from the maximum power point in PV-inverters in order to reduce the electricity production.
Following sections present the initial data for the optimization, the crucial constraints of the energy networks' limits, and the implemented topology elements that influenced the decision process:

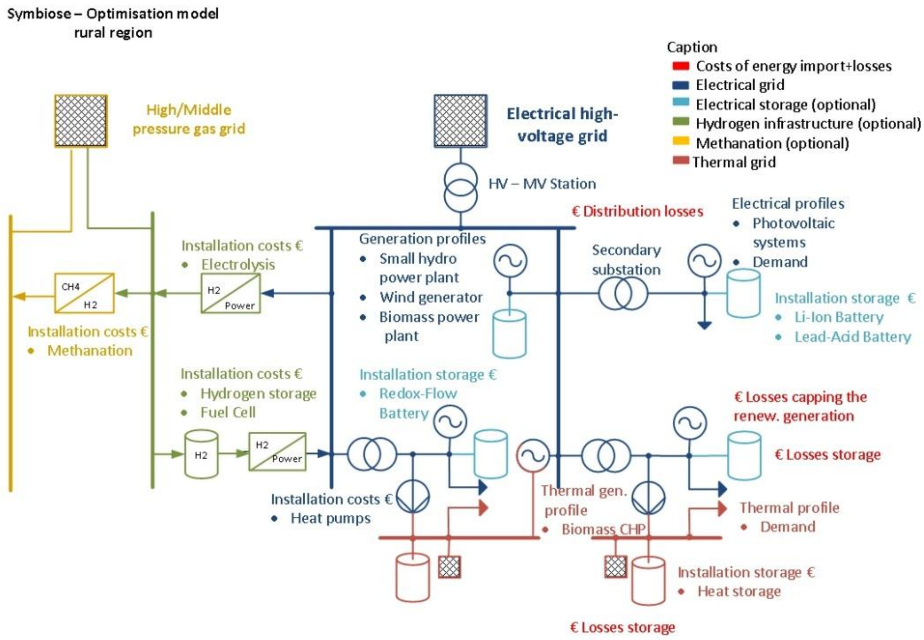

Figure 1: Topology of the optimization model based on the rural model region

Initial situation - input data

The regenerative generation and the energy demand in the examined model regions are the basis for the optimization. A summary of the estimated regenerative generation for both model regions is illustrated in Table 1 and Table 2. The detailed explanation of the perused methods for the estimation of the regenerative potential is given in [1] and [2]. According to Table 1 it is noticeable that the peak power electricity generation in the rural model region exceeded the maximum electricity power demand more than threefold. Therefore it can be assumed that reverse load flow situation in the rural model region could have occurred which could have led to an overload of electrical lines and influenced the installation of storage or conversion technologies. The annual electricity generation in the rural region could have covered almost 99% of the annual electricity demand. The use of own produced volatile energy can only be realized with the installation of storage technologies. The situation in the thermal sector was different. Almost 87% of thermal demand had to be imported. A totally different picture of the initial situation was given in the urban region. Just 15% of the annual electricity demand could have been covered by the photovoltaic systems. Other renewable resources could not have been installed in the urban area. The thermal demand of the model region has almost been completely covered by the imported resources. The most important constraint in the optimization model was the coverage of the energy demand and therefore an

Table 1: Input data for the rural model region

Electricity	Annual energy [MWh]	Peak power [MW]
Demand	**67 590**	**12,12**
Hydro power	9 700	3,2
Wind	14 100	7,7
Biomass and biogas	4 638	0,86
Photovoltaic	38 200	30,2
Total generation	**66 638**	**42,46**
Heat	**Annual energy [MWh]**	**Peak power [MW]**
Demand	**73 743**	**25,4**
Biomass and biogas	**9 831**	**1,79**

equal energy node balance. The energy demand could have been covered by the own produced energy in the model region or it could have been imported. The latter means an energy import from the higher level grid for the electrical grid and regarding the thermal sector, the use of heating systems fired by natural gas or heat pumps.

Table 2: Input data for the urban model region

Electricity	Annual energy [MWh]	Peak power [MW]
Demand	**84 255**	**17,02**
Photovoltaic	**13 046**	**10,3**
Heat	**Annual energy [MWh]**	**Peak power [MW]**
Demand	**86 295**	**30,4**
Waste	**1 787**	**0,204**

Networks

All three radial energy networks were represented in both optimization models in form of different constraints that influenced the decision process. A brief description of these constrains will be given in further sections.

Electrical network

In order to determine the loading of the electrical lines a load flow calculation had to be included in the optimization model. An AC load flow calculation could not have been implemented because of its non-linear character. Thus a DC load flow calculation considering just the active power without any iteration was modelled. The calculation of the lines' reactive power and therefore the calculation of the node voltages and losses could not be determined with this method. The maximum loading of the lines was set by our project partner "Voralberger Kraftwerke AG" which provided the grid data. If an excess of the maximum allowed limit regarding the loading of lines occurred the optimization model started installing and operating storage technologies on critical nodes. The losses of the grid were then linearly approximated based on the calculated active power. The loading of the lines was not the only critical electrical network limitation that determined the installation of storage. The allowed voltage level on nodes and the permissible loading of transformers had to be considered as well. An additional constraint for keeping the allowed voltage level was implemented, because the voltage level could not have been determined with the DC load flow calculation. This constraint included a maximum power limit for each node during the period of reversed power flow (power flow direction opposite of the load direction). This maximum power limit for each node was determined with the AC load flow calculation, executed with the network simulation software tool PSS®SINCAL. This means if the power flow through nodes has exceeded the determined maximum power flow the optimization model started installing and operating storage technologies on critical nodes. An additional set of power limits was determined for the scenario where a Q(V)-control of PV systems was taken into account. A similar equation was implemented for keeping the loading of the transformers in the permissible bandwidth. The only difference was that this equation was valid for both flow directions and that the power limits per node were set by our project partner. Because just a simple method for calculating the loading of the lines and workarounds regarding other network limitations were implemented, the optimized results had to be validated. The validation of results was performed with the AC load flow calculation in PSS®SINCAL.

Thermal network

The constraints for the thermal system were not modelled for both model regions in the same way as for the electrical grid. The rural model region did not contain a thermal grid. Therefore the thermal network was represented by equality constraints which consisted of thermal node elements (demand and supply). The equality constraint implied an equal node balance for each time step. The thermal nodes corresponded to the nodes of the electrical network. The thermal demand could have been covered by different thermal suppliers. The thermal supply options were gas heating systems fired by natural gas, heat pumps and on nine nodes district heating derived from the co-generation fired by biomass or biogas. Thermal storages could have been installed on nodes with the co-generation to store the surplus of thermal energy during the period of low consumption. A thermal exchange between the nodes was not possible. In comparison to the rural model region the urban model region comprised a thermal network that consisted of the same nodes and pipe lengths as the electrical network. The possible thermal suppliers for the urban model region were central district heating station fired by the natural gas and a fixed amount of waste, and decentralised heat pumps on each node. The optimization task for the model regions regarding the thermal system was to choose the ideal thermal supply to obtain minimal costs for the energy system. For the urban model region costs for the transportation losses had to be added to the objective function if the thermal demand was supplied by the central district heating station.

Gas network

A gas flow calculation in the optimization model was not required for either model regions because it did not influence the objective function. Hence, just coupling nodes to the gas network (overall gas balance) that connected gas consumers and gas producers to the gas network were considered. As stated above, one central node in the urban model region and each thermal node in the rural model region were modelled as coupling nodes to the gas network for joining the gas consumers to the network. In consultation with our project partner one coupling node to the gas network in the rural model region and three coupling nodes in the urban model region were modelled for the connection of gas producers to the gas network. The gas producer nodes characterized nodes where an injection of produced synthetic hydrogen and methane using the technology of power to gas could have been injected. An upper limit for the produced hydrogen was fixed according to the real gas capacity of the gas grid in both model regions. This upper limit varied with the examined season.

Storage and conversion technology

The characteristic of the residual load profile influenced the energy flow direction that had to be in alignment with the presented network limits. The residual load profile behaviour could have been changed by the operation of storage and conversion technologies. Hence the residual load profile was the main driver for the installation of storage and conversion technologies. Following technologies could have been installed in the model regions by the optimization: a battery (lithium-ion, lead-acid and redox flow), power to gas with gas grid and hydrogen storage as storage medium, thermal storage (buffer tank) and heat pump.

Storage parameters

Storage and conversion technologies were featured by following parameters in the implemented optimization model: efficiency, for heat pumps by the coefficient of performance factor, for some batteries by the capacity to power (C/P) ratio and installation costs. These parameters were determined by an extensive literature research presented in [2].

Technical parameters: The installed power of lithium-ion and lead-acid batteries depends directly on the installed capacity. This is not the case for the redox flow battery and the thermal storage, because the storage medium and the conversion units of these technologies represent independent storage elements. Therefore a fixed C/P ratio was taken into account for the lithium-ion and lead acid batteries. According to the performed literature research it can be stated that the capacity to power ratio for both technologies varies and is not a fixed value. In order to compare storage technologies with different behaviours in the optimization model, a C/P ratio of 2 for lead-acid batteries and a C/P ratio of 0,5 for lithium-ion batteries was chosen. The conversion technology heat pump was modelled with a coefficient of performance factor and the technology power to gas with two efficiency factors. The first efficiency factor represented the conversion path electricity to hydrogen via the electrolysis process and the second efficiency factor the further conversion path hydrogen to methane. The reconversion of hydrogen to power was realized through a fuel cell. A pre-defined location of possible storage and conversion technologies in the electrical network was set in order to obtain a reasonable size of the optimization model. Lithium-ion and lead-acid batteries belonged to storage technologies that could have been installed after the secondary substation. They described storage technologies for households' PV systems and acted as decentralized storage technologies for the examined model regions. The location of the redox flow battery was set before the secondary substation, since these battery systems are featured with a larger installation size that can store a greater amount of energy and therefore behave as a central storage of the examined regions. The connecting point of other technologies was explained in the upper networks section.

Economical parameters: The implemented costs for the decision process were annual installation costs calculated with the equivalent annual cost method. The considered interest rate for the applied method was 8%. The lifespans of lithium-ion and lead-acid batteries depend on the allowed depth of discharge and the performed annual cycle number. This cycle number was predefined for each battery according to a defined method in [2]. The lifespan for all other storage and conversion technologies was set according to the literature findings. All remaining cost components (installation costs, maintenance / operation costs, periphery costs and inverter costs) were derived from literature sources given in [2]. Results presented in this paper were calculated considering the mean examined annual installation costs. A further variation of annual installation costs was taken into account in the "Symbiose" project. The main parameters that characterized the considered technologies are presented in Table 3.

Table 3: Applied storage and conversion parameters

Storage technology / Conversion technology	Cost components		Efficiency / Rate of performance		Connection to the elc. grid
Variables	Capacity [€/kWh]	Power [€/kW]	Injec-tion	With-drawal	
Lithium-ion	126,3		92,5%	97%	LV
Lead-acid	35,9		90%	91%	LV
Redox flow	20,4	83,27	76%	88%	MV
Electrolysis		131,7	62%	-	MV
H_2 tank (30bar)	1,2		100%	100%	-
Fuel cell		216,3	-	45%	MV
Methantation		158,6	77%	-	-
Thermal storage	0,0198	0,00198	89%	89%	-
Heat pump		399	3,75		LV

Modelling the storage operation

The storage component in the optimization model was described with two storage variables in alignment with the method presented in [2]. These two variables represented separately the accumulated storage of the injection and withdrawal process. They were modelled as monotonically increasing functions. The sum of them represented the actual content of the storage which was limited regarding the installed capacity:

$$0 \leq E(t) = E_{with}(t) + E_{in}(t) \leq E_{inst}$$

The rates of change between two time steps of both storage variables corresponded to the withdrawal and injection power and were limited regarding the installed power. The withdrawal power:

$$P_{el}(t) > 0 \rightarrow -P_{el}(t) \cdot T = \eta_{with} \cdot [E(t) - E(t-1)]$$

The injection power:

$$P_{el}(t) < 0 \rightarrow -P_{el}(t) \cdot T \cdot \eta_{in} = [E(t) - E(t-1)]$$

The parameter T described the time granularity of the optimization. The way of modelling the operation of storage components by using the energy variable and not power variable resulted in an acceptable size of the optimization model and acceptable calculation duration.

OPTIMIZATION RESULTS

The following section summarizes the optimization results which indicate the importance of distributed storage and conversion technologies from the technical perception. The optimization results showed that loading of lines in the urban model region and ensuring the allowed voltage limits in the rural model region are the crucial electrical network limitations. Therefore storage technologies were considered in both model regions. One central storage technology, the redox flow battery with a capacity size of 2,62 MWh and a power size of 0,2 MW was installed in the urban model region on the node with the region's highest energy demand. Several lead-acid batteries were installed on other nodes that supplied consumer groups or large consumers. The entire capacity size of installed lead-acid batteries was 8,8 MWh and the installed power 4,4 MW. The reason for the installation of storage technologies in this region was not the surplus of PV power but the high load demand during the winter period that caused an impermissible loading of lines. The operation of the installed storage technologies resembled a weekly storage so that just 1% of the annual PV production was exported to the higher level grid. The thermal demand was mainly covered by the central heating station. Just 2% of the thermal demand was provided by heat pumps, which was reasonable since the electricity demand during the winter period was already too high to enable an acceptable load flow. The installation of the entire renewable potential and storage/conversion technologies led to a 5% reduction of CO_2 emissions and a 12% reduction of electricity import in comparison to the actual situation. A different picture was noticeable in the rural region. A mix of lead acid batteries and lithium-ion batteries was installed on distant nodes with a high PV production. The complete region's storage demand was 29,8 MWh with a power size of 15,4 MW. The lead-acid battery was the dominant storage technology in the installed mix because of a more suitable capacity to power ratio. The batteries were operated as daily and weekly storages. The costs for the imported energy were not taken into account for the technical perspective; thus the complete thermal demand was covered by the decentralized heating stations fired by gas and by the co-generation. Heating pumps were not needed in this case, because they were featured with additional installation costs. Thermal storages were installed on nodes with co-generation to store the surplus of thermal production. The complete size of installed thermal storages was 207,83 MWh and 1,56 MW and the operation corresponded to a seasonal storage. The installation of almost entire renewable potential and storage technologies in the rural model region led to a 32% reduction of CO_2 emissions and an electricity import reduction of 54% in comparison to the actual situation. Scenarios that considered the reactive power control of PV inverters and the curtailment of electricity were examined only in the rural region, because the storage installation in this region was influenced by a high regenerative production. The optimization results of the first scenario (inclusion of Q(V)-control) showed that storage technologies were still required. A capacity reduction of the installed storage size by 20% was noticeable. This caused a reduction of the regions' self-consumption of 2%. In the second scenario (curtailment of renewable energy sources) a tremendous reduction of decentralized storage size of 85%-97% was achieved by cutting off only 4-5% of regenerative energy production.

DISCUSSION

The results presented in this paper demonstrated that applying distributed storage technologies can avoid exceeding different grid limits. Hence, they enable a massive integration of regenerative generation units in distributed grids. A rather high capacity to power ratio for batteries is preferred for this matter. The required storage operation varies from daily to weekly. The Q(V)-control of PV systems can reduce the storage demand but it cannot completely replace it. The curtailment of electricity from renewable energy sources requires a minimal storage size. Benefits for consumers are noticeable regarding the energy import and CO_2 emissions with the installation of required distributed storage and conversion technologies. The decentralized coupling between the electrical and thermal system through heat pumps avoids transportation losses. Presented results summarize the role of distributed storage and conversion technologies concerning the technological requirements of the electrical grid. The "Symbiose" project examined further benefits of applying storage and conversion technologies which considered a household perception, community perception and community with minimal external energy supply / CO_2 optimal perception.

Acknowledgments

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