OPTIMAL ALLOCATION OF ENERGY STORAGE AND CONVERSION TECHNOLOGIES IN AN URBAN DISTRIBUTED ENERGY SYSTEM

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ABSTRACT

The main challenges in the existing distributed electrical energy systems when facing intensified renewable generation shares are considered to be for grid components (power lines and transformers) and the allowable voltage bandwidth (the voltage has to remain within the allowable limits). The expansion of grid upgrades or curtailments of the power production are common measures to avoid overloading of grid components.

This paper addresses another possible solution to avoid exceeding the electrical grid limitations: the utilization of decentralized storage and flexibility of conversion technologies for the decentralized distributed coupling of existing energy supply infrastructures (electric-, gas-, and domestic heating grid). Therefore, a linear optimization model is developed to solve the multi-domain allocation and positioning problem for different energy storage and conversion technologies in an existing urban energy system considering households and industrial prosumers.

The results show, how an urban energy system with a high share of renewable generation can relieve the higher-level electrical grid by ensuring a more decentralized generation-load balance. The optimal allocation of multi-domain distributed storage and conversion technologies is investigated for different stakeholder viewpoints and show benefits regarding the energy import/export balance and CO_2 emissions.

INTRODUCTION

The intensified integration of renewable energy producers is essential for achieving climate goals, especially after the Paris Agreement [1]. Wind power, photovoltaics (PV) and biomass are the predominant propagating renewable generation technologies. The net generating capacity of wind and solar plants in the ENTSO-E area is continuously rising in the last decade [2]. However, existing electricity grids can face difficulties and were often not designed for the distributed and volatile feed-in of wind power and PV, which are only partially controllable, and therefore face several challenges. The massive integration of renewable generation causes an increase in fluctuations in the electrical energy supply [3]. Nowadays, these fluctuations are dampened by rotating masses of synchronous generators and compensated by large-scale storage systems and the utilization of flexible conventional power plants. With less inertia in the system due to converter based generation, more storage systems, flexible loads and other solutions are needed.

Challenges due to intensified installation of renewable distributed power generators for electric power lines and transformers are usually met by grid expansion or curtailments of the power production. The integration of controllable on-load tap changing transformers and the integration of photovoltaic inverters with a coordinated reactive power control can prevent voltage level violations.

The proposed solution in this paper is based on research project "Symbiose-4-IuG"[4] and investigates the coordinated use of decentralized storage and conversion technologies for distributed coupling of existing energy supply infrastructures (electric-, gas-, and domestic heating grid) to avoid exceeding the electrical grid limitations. Distributed heating grids and the gas distribution systems have the advantage, that they can storage a certain amount of energy within their grid system itself. They can also be operated more flexibly compared to the electrical grid, which does not have this internal storage capacity ability. Large-scale gas and heat storages are usually cheaper, and (dis-)charging power and energy storage size can be chosen independently. With limited potentials of large-scaled hydro storage systems, decentralized storage technologies could play a big role in relieving the large scaled storage technologies, thus relieving the higher level grid [5]. The coupling and coordinated operation of these (existing) energy infrastructures allows a higher share of renewable electrical generation in distributed energy systems. It can provide additional flexibility for the electrical grid by shifting electrical energy to the heat or gas network [6].

To determine the optimal position, size and operation of distributed storage and conversion technologies in the investigated urban electrical grid (with a high share of renewable generation) a linear optimization model of examined model region's energy system is developed. Depending on different stakeholder viewpoints in the energy system (technical, prosumer, municipality and highly energy import independent community), the objective function varies according to their economic and ecologic interests.

The following section details the implemented optimization model, the considered technologies and the input parameters for the examined urban model energy system.

METHODOLOGY

A linear optimization model implemented in GAMS is developed to solve the multi-domain allocation and positioning problem for different energy storage and conversion technologies in an existing urban energy system. The target of the model is to determine the optimal size, position and operation of different storage and conversion technologies in an urban energy system with a high share of renewable electricity generation. The objective function of the optimization is minimal costs of the implemented energy system. Considered technologies are decentralized battery storages (lithium-ion and redox-flow batteries), power-to-gas (H_2 and SNG), combined heat and power units (CHP), heat pumps, heat and hydrogen storages, fuel cells and demand side management (DSM). Following cost components are implemented in the objective function: annual installation costs of storage and conversion technologies, costs for energy losses caused by storage and conversion technologies, costs for losses in the energy transport in the electrical and thermal network and costs for the curtailment of electricity. The optimization model includes the electrical grid, a gas and thermal system with the predefined generation and load profiles and the previously mentioned storage and conversion technologies. The topology of the implemented optimization model is presented in Figure 1. The electrical load profiles for low-voltage customers are obtained from a regional Austrian grid operator. The industrial load profiles (gas and electrical demand) are provided by an Austrian supermarket chain with own food and meat production. PV generation profiles are measured in a previous research project and adapted for the utilization in this urban energy system.

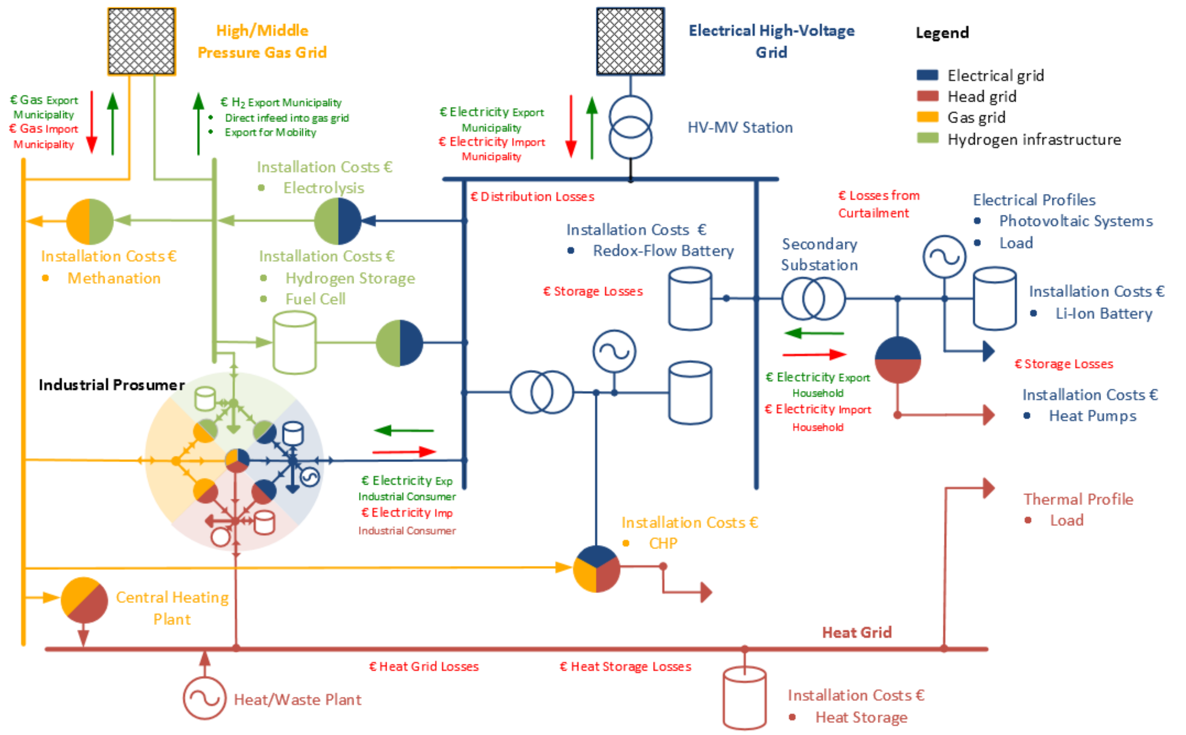

Figure 1: Topology of the optimization model for an urban energy system

To investigate seasonal effects for long-term operation of storages, a time horizon of one year is considered for the optimization model. Simulations with a time step of 15min and 30min were done on local computers using a workaround with only four weeks (winter, transition, summer and transition) with an implementation of correct energy content to pass from one characteristic week to another, similar to [1]. The optimization results are rolled out for a period of one year considering VDEW load profile seasons. In addition, a closed optimization with a time horizon of one year in a time step resolution of 30min is calculated on the Vienna Scientific Cluster supercomputer [7]. This optimization led to similar results. Furthermore, other methods for managing the grid limitations are examined as well: reactive power control of PV inverters (Q(V)-control) and curtailment of PV generation. The optimization model applies in most of the cases curtailment as a cost effective solution, a deliberate decision of not feeding the potential power into the electrical grid.

Different aspects and interests of stakeholders in the urban energy system (technical viewpoint, prosumer, municipality and highly import independent community) are defined and calculated by using different cost parameters for energy import and export over different substation levels. The optimization goal from a technical viewpoint is the minimization of transport losses considering grid constraints. The local self-consumption

of industrial and end prosumers is the driving force for installing storages and conversion technologies for those stakeholders and for the municipality point of view, the energy import export balance is the decisive factor.
Table 1 shows the relevant constraints, cost and revenue parameters for the considered stakeholders in this urban energy system.

Table 1: Constraints, cost and revenue parameters for different stakeholders in the energy system

	Stakeholder	Technical viewpoint	Prosumer viewpoint	Municipality & energy import independent viewpoint
Grid constraints	DC Load flow	✓	✓	✓
	Transformer limits	✓	✓	✓
	Transport losses electrical grid	✓		
	Transport losses heat grid		✓	✓
Costs and Revenues	MV-LV substation import/export		✓	
	HV-MV substation import/export			✓
	Gas (NG, SNG) import/export		✓	✓
	H_2 export		✓	✓
	Storage and conversion losses	✓	✓	✓
	Curtailment	✓	✓	✓

Input data

The urban energy system comprises 65GWh electrical and 142GWh thermal load. In addition, load profiles for battery electric vehicles (BEV) with a share of 40% and 100% of the total mobility demand are generated and implemented as additional load component. A summary of the demand and the estimated regenerative generation for the model region is illustrated in Table 2.
Around 41% of the annual urban electricity demand could be supplied in the base case by PV generators given a maximum installation of its potential. However almost the entire heat demand has to be covered by central heating plant firing the imported gas since local heat generation, the waste plant, is marginal. At the node of the industrial prosumer, a CHP is located with 890kW electrical and 790kW thermal peak power. The decision whether to use the CHP plant for local generation of electricity and heat is made by the optimization.
The urban region depends in any case on the energy import. Considering the electrical grid, the electricity import is be imported from the higher-level electrical grid.
Regarding the thermal sector, the use of heating systems fired by natural gas, waste or heat pumps are possible. The path of the energy import and the export as well as the connection of the energy systems is chosen by the optimization based on the stakeholder's point of view.

Table 2: Input data for the urban model region

Scenario	Basic	40% BEV	100% BEV	Basic	40% BEV	100% BEV
Electricity	**Annual Energy [MWh]**			**Peak power [MW]**		
Demand	65 494	75 315	93 179	10.79	14.75	21.78
PV		26 929			19.65	
CHP					0.89	
Heat	**Annual Energy [MWh]**			**Peak power [MW]**		
Demand		142 703			42.23	
Waste		1 787			0.20	
CHP					0.79	

Energy systems

The three energy systems considered in the model are implemented by linear constraints to influence the decision process of the optimization.
For the electrical system, a load flow calculation has to be included to determine the impact of intensified local renewable generation on the grid. If an excess of the maximum allowed limits regarding the loading of lines and voltage levels occurs the optimization model is required to install and operate storage and conversion technologies on critical nodes. Since AC load flow calculation is based on non-linear equations, a DC load flow approach, a linear approximation method, is used. Hence, only the active power flow can be calculated in a direct way to estimate the loading of the electrical lines in the model. However, the reactive power flow would be necessary for the calculation of the node voltages and line losses. Therefore, the losses of the grid are linearly approximated based on the calculated active power. An AC load flow calculation is carried out separately in PSS®SINCAL, considering the installation of the complete PV potential in the model region, to analyse the node voltage situation. The results indicate no voltage level violations in this model region. Therefore, the optimization model does not to have include any constraints considering the node voltage limitation. Hence, the effect of Q(V)-control is not considered in the end as well.
The thermal network is congruent with the electrical network. It consisted of the same nodes and pipe lengths as the electrical network. The possible options for the supply of the thermal demand in a base case are the central district heating station fired by the natural gas, a fixed amount of waste and a CHP at the industrial prosumers side. The costs for the transportation losses are added to

the objective function in case the thermal demand was supplied by the central district heating station. In addition, the installation of decentralised heat pumps on each node and CHPs on selected nodes are further possible options for the optimization as well. The optimization's objective regarding the thermal system is to select the ideal thermal supply to obtain minimal costs for the energy system of the model region.

A gas flow calculation in the optimization model is not required because it does not influence the objective function. Hence, just the overall gas balance that connected gas consumers and gas producers to the gas network is considered. Connection points to the gas system are at the central district heating node, and the industrial prosumer, where an existing CHP is already located. Additionally, local CHPs can be installed in some scenarios as well. The project partner is already installing a power-to-hydrogen plant on its production facility in real life. Therefore, the optimization has the possibility to install an infeed of produced synthetic hydrogen and/or methane using the technology of power-to-gas. An upper limit for the produced hydrogen is fixed according to the real gas capacity of the gas grid. In addition, a limited amount of produced H_2 can be exported for e.g. mobility purposes.

Storage and conversion technologies

The modelling of storage operations are implemented using the same approach as described in [5]. Main drivers for the installation of storage and conversion technologies for the optimization are grid limitation, economic interests, self-consumption and import independencies. Depending on the stakeholder interests and scenarios, a different technology mix is chosen.

The following technologies and measures are considered:

- electrical battery storage: lithium-ion, redox flow
- power-to-gas (H2, SNG) for an infeed into the gas system, export for mobility purposes and with or without a hydrogen storage as buffer
- hydrogen fuel cell
- thermal storage (buffer tank)
- heat pump
- combined heat and power plant
- DSM and curtailment

Storage and conversion technologies are implemented by the following technical and economic 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 are determined by an extensive literature research presented in [4].

The efficiency (charging or discharging) of lithium-ion batteries were 94.9% and for redox flow systems 80.6%.

DSM is modelled for households and the industrial prosumer separately [4]. For households a 2% shift over a period of 5 hours is assumed. The DSM potential of industrial prosumer is modelled in more detail and specific production line operations are investigated. Depending on the day or night shift 4.8kW or 3.8kW (around 7% of the total energy demand of the production line) can be utilized. For heat pumps, a coefficient of performance (COP) of 3.75 is assumed given different types of heat pumps and limited heat depots potential. CHP plants has an electrical efficiency of 0.45 with a ratio of 1.13 between electrical and heat production. The heat storage has a charge and discharge efficiency of 0.95%.

The power-to-gas technology efficiency is implemented with 70% for hydrogen and with 80% for hydrogen to SNG production. The fuel cell efficiency is set to 45%.

The implemented economic parameters are based on installation costs calculated with the equivalent annual cost method. The lifespan of lithium-ion depends on the allowed depth of discharge and the performed annual cycle number, which is predefined for each battery according to a defined method in [6]. The lifespan for all other storage and conversion technologies is set according to the literature findings. Installation costs, maintenance and operation costs as well as periphery costs and inverter costs are all derived from literature sources given in [4, 6]. Results presented in this paper are calculated considering the mean examined annual installation costs.

OPTIMIZATION RESULTS

From a technical viewpoint, the loading of lines and transformers are triggers for installation of flexibilities since the goal is to minimize transport losses in the energy systems while keeping the grid limits. Without an increase in the share of BEV only the utilization of DSM and curtailment are chosen to minimize losses. When high shares of battery electric vehicles (40%, 100%) are considered as additional loads in the energy system, decentralized storages and flexibilities became necessary to avoid grid upgrades. In case of a 40% share, lithium-ion batteries with a total of 0.7MW with 1MWh are required and distributed over the network on critical nodes. The curtailed PV generation can be reduced with storages from 404MWh to 248MWh. When a share of 100% is assumed, battery storages with 8.9MW with 17.6MWh are installed and no PV generation is curtailed.

For end prosumers the installation of heat pumps ($3MW_{el}$), decentralized storages (0.8MW with 1.5MWh), and DSM are preferred. In addition to that, the industrial prosumer also favors the installation of power-to-H_2, if an export of hydrogen to the gas grid was possible and a fraction of the produced hydrogen could be sold for mobility applications for a higher price. The central heat plant with a 27MWh heat storage is predominant for the heat supply (73%) with low shares from heat pumps (13%) and CHPs (14%). The self-consumption of PV generation is 69%. The increase of BEV shares leads to a reduced battery storage demand and curtailment. However, a 100% BEV share leads to more battery storages (3.2MW with 5.2MWh) and CHP plants ($4.8MW_{el}$) in total.

From a municipality viewpoint, decentralized storages are substituted by heat pumps, which are also dominant in the heating sector with a share of 55%, compared to the heat plant (31%), waste plant (1%) and the CHPs (13%). A heat storage with 40MWh is installed to support the CHP of the industrial prosumer along with the waste plant. Furthermore, 75% of the decentralized generated PV power is used locally. Higher BEV shares lead to a reduction of heat pumps with more battery storages installed (3.2MW and 5MW).

For a highly energy import independent community 156 MW with 116.5MWh of decentralized storages are required along with a 7.9MWh heat storage and $31MW_{el}$ of heat pumps. The total share in the heat sector for heat pumps is 84%, for CHP 15% and 1% for the waste plant. Therefore, there is no gas import for the heat plant required and no export of PV generated power. In total, the import independency of the urban energy system can reach up to 58% compared to 16% without any measures. Increased BEV shares are met with more import from the electrical grid but with similar batteries storage sizes and heat pump installations compared to no electric vehicles.

Regarding CO_2 emissions, a reduction of up to 9% is estimated from an end prosumer point of view compared to the scenario without storages and measures. The municipality stakeholder can save up to 50% and concerning the highly energy import independent community a maximum of 77% can be achieved. Taking car traffic and a higher share of battery electric vehicles into account, the reduction of CO_2 emissions is significantly higher.

DISCUSSION

The decentralized coupling of the existing energy supply infrastructures especially between the electrical and heat system allows an increase of the energy import independency and the self-consumption of energy generated in the model region. In addition, they enable a massive integration of renewable generation units in distributed energy grids. Benefits for industrial and household prosumers (increase of the self-consumption, additional revenues through H_2 production) and the community are noticeable regarding the energy import independency and therefore CO_2 emissions with the installation of distributed storage and conversion technologies. Especially in the heat sector, a high share of sustainability can be established by shifting (renewable) electrical energy from the electrical grid to the heat grid.

Therefore, a combined consideration of electricity and heat infrastructure in a city makes sense. The coupling of existing energy infrastructures on the industrial and end-user side makes it possible to reduce the overall energy consumption from higher network levels significantly.

Industrial and commercial customers play an important role in coupled energy networks to increase sustainability. The results with consideration of industrial and commercial customers confirm and reinforce the statements of the predecessor project "Symbiose" [6], especially regarding the improvement of the sustainability and the reduction of energy import in distributed energy grids.

Decentralized electrical storage and conversion technologies favor a more even utilization of existing energy networks with a high share of decentralized generation. High BEV penetration, even with controlled charging and relatively low energy increase, leads to a significant increase in power of the low-voltage grid and requires grid-friendly measures.

Presented results summarize the role of distributed storage and conversion technologies in an urban energy system concerning the technological requirements of the electrical grid and different stakeholder interests.

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