APPROACH FOR MULTI CRITERIA OPTIMIZATION AND PERFORMANCE MONITORING OF A VIRTUAL POWER PLANT WITH URBAN STRUCTURES

Alexander HOBERT
Wuppertal University – Germany
alexander.hobert@uni-wuppertal.de

Heiko SCHROEDER
Wuppertal University – Germany
heiko.schroeder@uni-wuppertal.de

Marlon KORALEWICZ
Wuppertal University – Germany
marlon.koralewicz@uni-wuppertal.de

Björn UHLEMEYER
Wuppertal University – Germany
bjoern.uhlemeyer@uni-wuppertal.de

Markus ZDRALLEK
Wuppertal University – Germany
zdrallek@uni-wuppertal.de

Dirk ASCHENBRENNER
Wuppertaler Stadtwerke Netz GmbH
dirk.aschenbrenner@wsw-netz.de

Lena SEEGER
Wuppertaler Stadtwerke GmbH
lena.seeger@wsw-online.de

Pascal BIESENBACH
Aufbruch am Arrenberg e.V.
biesenbach@klimaquartier-arrenberg.de

ABSTRACT

In this Paper a simple approach for modelling a multi criteria optimisation is described which includes the three relevant politic targets for energy-systems. Furthermore the optimization results are evaluated with a Key-Performance-Indicator model. Both models are developed for a local energy-system with urban structures and enables an objective measurement of performance monitoring.

INTRODUCTION

Within the context of the transition process of the German power system known as “Energiewende”, the energy-system is redesigned in respect to the characteristics of loads, feeder and the geographical dispersion of these assets. In the initial phase of the electricity supply, there were many decentralized power plants. From the middle of the 20th century onwards, larger power plants were built near load centers and a unilateral flow of energy was established. Since the year 2000 a trend towards decentralized units, which obtain their energy from renewable sources, has been observed [1]. The next transition step will be the installation of distributed energy resources (DER) like photovoltaic systems (PVS) and distributed generators (DG) like combined heat and power (CHP) in urban energy-systems in urban districts [2]. This process step induce the need for new concepts of supply and demand strategies, a bidirectional energy flow is created. In the project “Virtual Power Plant” (VPP), such a strategy is developed for the energy supply of an urban district in Wuppertal [3]. The optimization of this urban energy-system entails DG, e.g. with fuel cells, load management and energy storages such as battery systems (BS) as virtual power plant [4]. This project uses the cellular approach [5] which aims at the balancing of micro grids and different energy sectors (e.g. natural gas and electricity). Furthermore the cellular approach can be used as a planning- and operation-tool [6]. This paper is placed in this context and demonstrates a multi criteria optimization which includes a wide view of energy economic goals. Furthermore, the monitoring of results and their aggregation in standardised key performance indicators (KPI) including all of these aspects as well as the correlation between the different aspects is performed.

DESCRIPTPTION OF THE OPTIMIZATION MODEL

For an optimization of local energy-systems there are three fundamental optimization objectives [7].

1. Economy efficiency
2. Environmental sustainability
3. Security of supply

These three goals represent the target triangle of the German “Energy Economy Law”. An additional dimension which is often added in this context, is the acceptance by the end consumer. In this case these are the occupants of the urban district. There are two options to consider the target triangle in an optimization calculation. The first option is the mapping of the objectives with constraints. One example for this is to fix a maximal exhaust of carbon or a minimal self-sufficiency. The second option is to use a multi criteria optimization. In VPP, two frameworks for energy-systems modelling are used, whereby the optimization concept must comply with these frameworks conditions and bounds. The used frameworks are “oemof” [8] and “pandapower” [9], which both apply the coding language python. The first framework are used for the portfolio optimization and for the creation of the timetable of the asset portfolio (CHP, Storages etc.). The following optimization objective for a linear optimization is used (Equation 1):

$$MIN \sum_{t \in T} \left(\sum_{(s,e) \in E} \sum_{i \in I_1} c^i_{(s,e)}(t) \cdot w^i_{(s,e)}(t) \cdot \tau \right) + \sum_{t \in T} \left(\sum_{n \in N} \sum_{i \in I_2} c^i_{(s,e)}(t) \cdot w^i_{(s,e)}(t) \cdot \tau \right) \quad (1)$$

In this model, the energy-system is mapped as a node-edge-model. Each node represents an energy sector and the edge the energy flow between DER, DG, loads, storages and the slack node to the energy sectors. The slack-node represents the energy flow through the local power station for the active energy compensation with the higher-level electric grid. The model minimize the marginal costs for the energy flows between each Bus. The second framework is used for the state calculation of the grid. The optimized timetable will be used to determine an AC load flow. The components in the mapped grid (energy converters and storages) will be parameterized with the timetables. In case a limit violation in the grid is identified, the second framework is deployed. With the optimal power flow (OPF) of "pandapower", the grid conditions for any object in the energy-system will be recalculated. That means the objects adjust with new maximal or minimal power values. This values will be used in an iterative recalculation in the "Energy-System-Modell". The optimisation's program sequence and the interaction between the two models are illustrated in Figure 1.

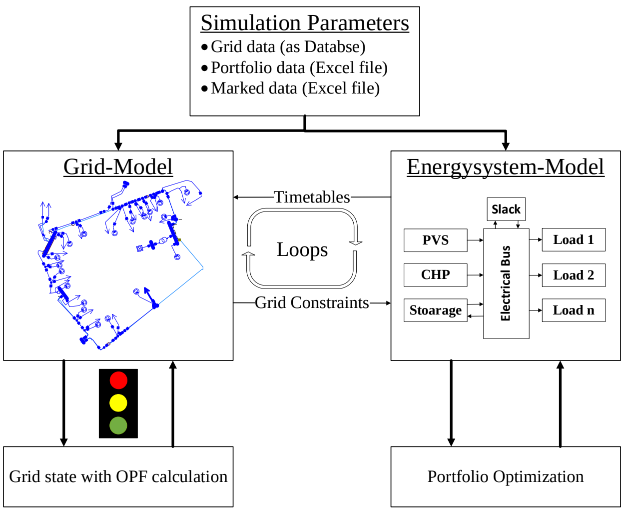

Figure 1: Optimization Model

To apply a multi criteria optimization, the optimization objective needs some further adjustments. These contain the change of the optimization value, which needs to be transformed from a financial value to an abstract value without any unit. In the following, this value will be referred to with the term "Optimization Value" (OV). The OV is calculated with Equation 2 and Equation 3.

$$OV = V_{Economy} \cdot F_{Economy} + V_{Ecology} \cdot F_{Ecology} + V_{Security} \cdot F_{Security} \qquad (2)$$

$$F_{Economy} + F_{Ecology} + F_{Security} = 1 \qquad (3)$$

"*V*" represent the relative Value to the other options in the energy-system. This way, the options are normalized, e.g. in terms of costs with regard to the most expensive option. This way, the most expensive option obtains a value *V* of 1, the cheaper options <1. The values regarding ecology and security are defined analogously.

F is a weighting factor. All weighting factors sum up to the value 1. With this procedure, the order of the options in the energy-system is adapted and the priorities within the optimization can be adjusted. This way, the relative relevance within the optimization of the financial aspects, of the ecological factors or of the local components can be increased. The behaviour of the OV is demonstrated with the following components of an exemplary energy-system (Table 1).

Table 1: Components for a test simulation

Components	Parameters
Households	Installed Power $P_{Load} = 250\ kW$ with synthetics timetables
PVS	Installed Power $P_{Peak} = 308\ kW_{peak}$ Number of PVS $n = 19$
CHP 1	Installed Power $P_{CHP} = 40\ kW_{el}$ Operation-Costs $C_{CHP} = 0{,}08\ €/kWh$ Exhaust-Factor $EF_{CHP} = 317\ g/kWh$
Solar accumulator	Number of Accumulators $n = 17$ Capacity $C_{Acc} = 5\ kWh/n$ C-Rate = 0,3

The results for the OV calculation with a focus on the financial aspects are given in Figure 2, the slack node is the most used option, due this has a low value.

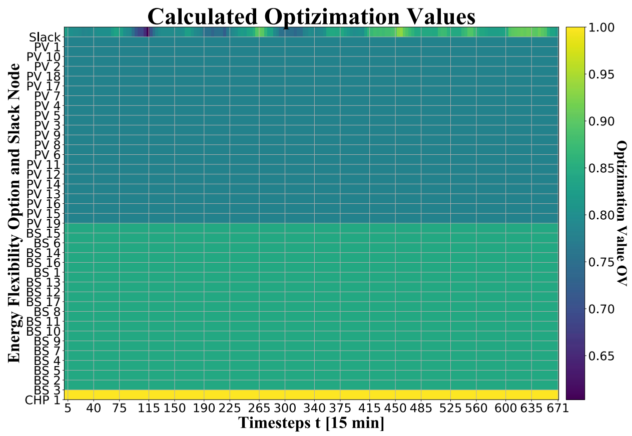

Figure 2: OV calculation

It can be seen that the slack node has a low OV, it would be primarily used in a simulation (Equation 1). The PVS are not object of the optimization but feed in automatically. The CHP has the highest OV and is thus not utilized in the optimized system. In the next chapter, the timetables and the use of the single components will be presented.

OPTIZIMATION OF AN ENERGY-SYSTEM

For an exemplary application of the optimization model, the test area of the VPP-Project “Arrenberg” is used. The low voltage grid of this Area is illustrated in Figure 3.

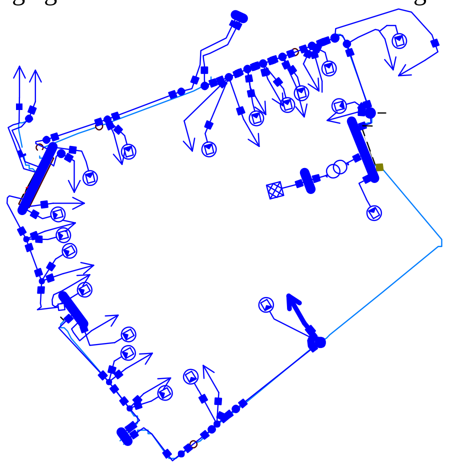

Figure 3: Grid of the urban district “Arrenberg”

In actual status is the used grid a low voltage load-depressed distribution grid without feeder or other aggregates that could be used as flexibilities. For the simulation, additional components are added, which are listed in Table 1 with the respective parameters. When the optimization model is parameterised with a focus on economic values, the model will give the most cost-efficient component combination at each time step. The costs that occur at the slack node are dependent on the market price and therefore contain a certain fluctuation (bottom plot in Figure 4). Thus, in times of low market prices the optimization results in higher power flows through the slack node compared to high-price times in which instead the storage is utilized more extensively. The CHP is in this scenario too expensive and is not used at all. The PVS feeds in automatically and unaffected of the optimization.

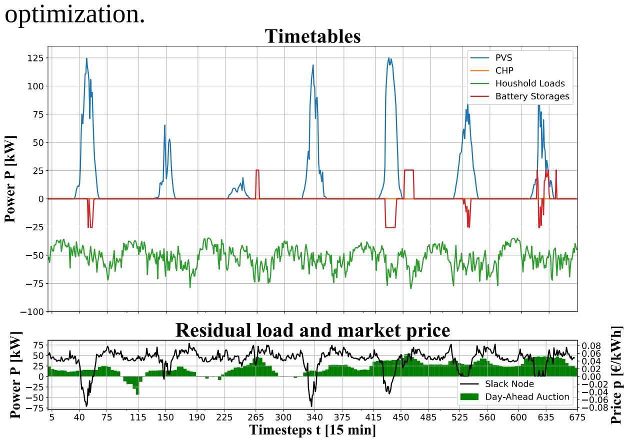

Figure 4: Portfolio economic optimization

When the OV weighting factors are adjusted to force a higher number of decentral components, the CHP and the energy storage will be used more used extensively, as illustrated in Figure 5.

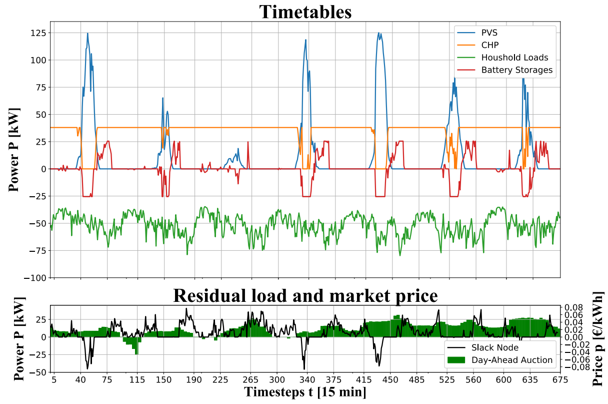

Figure 5: Portfolio security optimization

The weighting factors for the second optimization are *Ecology* = 1/10, *Economy* = 2/10 and for *Security* = 7/10. Another central question is arising after the optimization: How do the different operation kinds affect the state of the grid. The results of both scenarios are shown in Figure 6 and in Figure 7. The figures show all 15-minutes situation of one week of the simulation in a 3D-axis with the ratio load, feed and the use of flexibilities (CHP and storages). In both cases, there are no violations of constraints in current and in voltage.

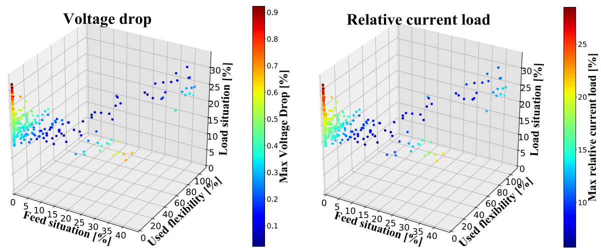

Figure 6: Grid states in the economy scenario

In Figure 7 an increased utilization of flexibilities can be observed. This results in a significant reduction of the load situation and the voltage drop.

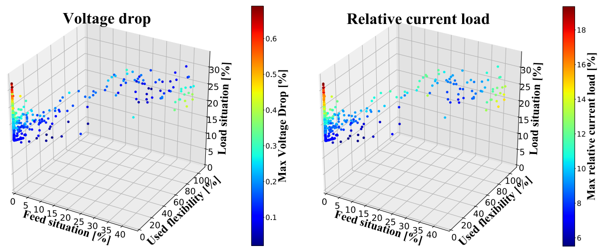

Figure 7: Grid states in the security scenario

MONITORING OF ENERGY-SYSTEM PERFORMANCE WITH KEY-PERFORMANCE INDICATORS

The performance monitoring of energy-system optimizations is nowadays usually performed with a simple one point of view indicator like efficiency of the distribution network or with the reliability. A more detailed analysis on low voltage level grids of the different goals of energy economies is not common. In this chapter, the first conception steps towards a holistic assessment are presented (Figure 8).

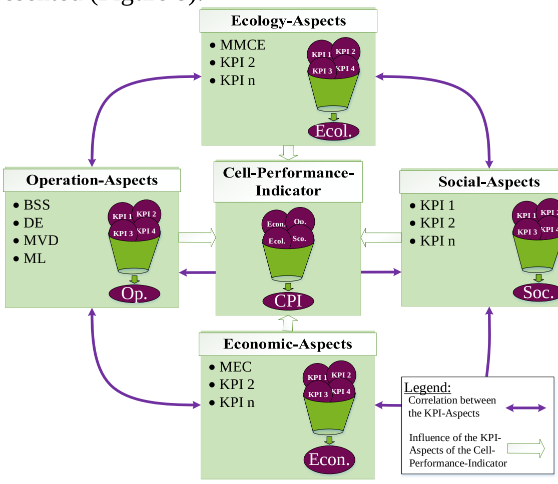

Figure 8: KPI-System

The results are evaluated with parameters which can be divided into the four aspects operation, ecology, economic and social. The exact definition of this KPI's are listed in Table 2.

Table 2: KPI for energy-system monitoring

KPI	*Equation*
Balance Self-Sufficiency (BSS)	$\frac{\sum_{t=0}^{T}\sum_{n=0}^{N} P_{feed,t,n}\cdot 15\min + \sum_{n=0}^{N} P_{DG,t,n}\cdot 15\min}{\sum_{t=0}^{T}\sum_{n=0}^{N} P_{load,t,n}\cdot 15\min}\cdot 100$ *[%]* (4)
Distri-bution Efficiency η_{Dis} (DE)	$\frac{\sum_{n=0}^{N} P_{load,n}}{\lvert P_{Loss}\rvert+\sum_{n=0}^{N} P_{load,n}}\cdot 100$ *)[%]* (4)
Mean carbon emission (MCE)	$\frac{\sum_{t=0}^{T}\sum_{n=0}^{N} EF_n\cdot P_{n,t}\cdot 15\min}{\sum_{t=0}^{T}\sum_{n=0}^{N} P_{n,t}\cdot 15\min}$ [kg/kWh] (5)
Mean Marginal Electric Energy Cost (MMEC)	$\frac{\sum_{t=0}^{T}\sum_{n=0}^{N} C_n\cdot P_{n,t}\cdot 15\min}{\sum_{t=0}^{T}\sum_{n=0}^{N} P_{n,t}\cdot 15\min}$ [€/kWh] (6)
Max Voltage Drop (MVD)	$\max\left(\begin{bmatrix} \lvert\Delta U_{n=0,t=0}\rvert & \lvert\Delta U_{n=0,t=1}\rvert & \lvert\Delta U_{n=0,t=T}\rvert \\ \lvert\Delta U_{n=1,t=0}\rvert & \lvert\Delta U_{n=1,t=1}\rvert & \lvert\Delta U_{n=1,t=T}\rvert \\ \lvert\Delta U_{n=N,t=0}\rvert & \lvert\Delta U_{n=N,t=1}\rvert & \lvert\Delta U_{n=N,t=T}\rvert \end{bmatrix}\right)$ [%] (7)
Max Load (ML)	$\max\left(\begin{bmatrix} \lvert I_{n=0,t=0}\rvert & \lvert I_{n=0,t=1}\rvert & \lvert I_{n=0,t=T}\rvert \\ \lvert I_{n=1,t=0}\rvert & \lvert I_{n=1,t=1}\rvert & \lvert I_{n=1,t=T}\rvert \\ \lvert I_{n=N,t=0}\rvert & \lvert I_{n=N,t=1}\rvert & \lvert I_{n=N,t=T}\rvert \end{bmatrix}\right)$ *[%]* (8)

t: Count of timestamps
n: Count of elements (node or lines)
P: Power in kW
I: Current in ampere
U: Voltage in volt

BBS is the autarchy of the local grid, it is the ratio between local feed energy and demanded load, it is evaluate in percent (operation). The DE is a measurement for the efficiency of the grid and evaluate the local distribution losses (operation). MCE and MMEC is the mean of the marginal cost of the energy options and the mean of the carbon output of this (economy and ecology). Another KPI of the local grid is the MVD and the ML (operation), both evaluate the maximal voltage or current that appear in the simulation.

ENERGY-SYSTEM ANALYSIS WITH THE KEY-PERFORMANCE-INDICATOR ON THE EXAMPLE WUPPERTAL

In this chapter, a city district (Figure 3) is analysed with the explained optimization approach. Also, the performance of the grid is monitored with the KPI from the previous chapter. It uses the configuration given in Table 1 (CHP, the PVS and the storages). A few weighting factors and results for the simulations are illustrated in Table 3, this illustrate an exemplary list of results of the simulation. The other simulations are working with this scheme. These contain the extreme cases of weighting factors focusing on one objective only (e.g. 1-0-0) and few trade-offs. This case apparently cause one KPI to have a good performance e.g. the first scenario which has a low MEC.

Table 3: Simulation results with different objectives

OV			KPI					
Economy	Ecology	Security	BSS [%]	DE [%]	MCE [g/kWh]	MMEC [€/kWh]	MVD [%]	ML [%]
1	0	0	20,30	98,57	490,08	0,03	0,68	28,51
0	1	0	88,58	98,79	300,31	0,07	0,42	19,35
1/2	1/4	1/4	86,46	98,77	308,40	0,07	0,42	19,35
0	0	1	88,55	98,79	300,29	0,07	0,42	19,35
1/4	0	3/4	88,92	98,79	300,49	0,07	0,42	19,35

The correlation between different objective functions and the influence of the KPI are illustrated in Figure 9 and in Figure 10. In Figure 9 the minimal energy price is at 0.03 €/kWh. With decreasing focus on the economy objective, the price increases. This effect is shown in the left and in the right figure. In both figures, a negative correlation between the objectives is given.

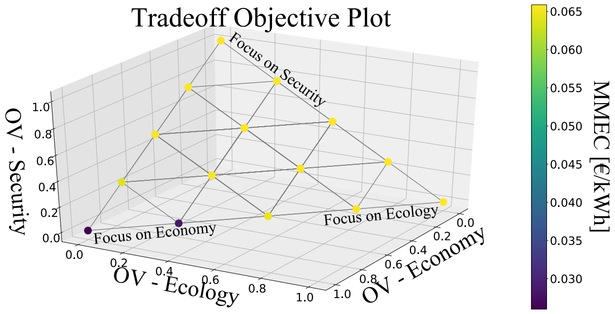

Figure 9: Influence of MMEC due the objectives

This situation is different from the correlation between ecology and security. In Figure 10, there is a positive correlation between both objectives. This demonstrates that a higher focus on ecology raises the utilization of the local DER and DG while the use of energy from external sources via the local power station is decreasing.

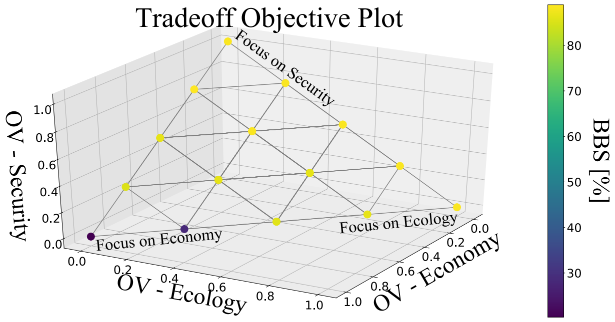

Figure 10: Influence of BSS due the objectives

CONCLUSION

According to the simulation results, an environmentally friendly energy supply in city districts with urban structures is possible. In the simulation, a typical city district is evaluated under technical, ecologic and economic aspects. Each aspect can be similarly optimized by laying the focus on one of the objectives or by a trade-off between the goals. If the focus is solely on financial aspects, the energy supply with only local energy sources is not possible because the electricity demand is met with a supply from the extern grids. When the focus is on the environment, requirements a trade-off between profitability, local energy generation and environment (at currently regulation). The investigation of the correlation between the objectives results in a positive correlation between environment and ecology. The correlation between environments was positive, which implies a high security result in a more environmentally friendly energy supply. The next steps for VPP are split in two tasks. The first task is to advance the outlined monitoring tool with more detailed KPI like cash value or KPI for single objects like full-load hours for CHP. The second topic is to analyze the effect of the use of demand response on the KPI. The demand response will use a non-direct control approach and indirect controlling signals for the households. Research questions arising in this field are e.g. the optimal capacity of a battery storage when demand response is deployed in this approach. In addition, the decrease of the residual load and consequently the BSS is to be evaluated.

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