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Economic and environmental cost of self-sufficiency - analysis of an urban micro grid

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Abstract

In this paper, we analyze the economic feasibility as well as the environmental ramifications of operating a renewable energy based micro grid for achieving ultimate self-sufficiency. Results show that ultimate self-sufficiency is neither economically feasible nor environmentally viable due to large overcapacities in storage and generation. Based on the results we motivate the thesis that economic viability as well as ecological effectiveness of a local micro grid can only be achieved by an optimized combination of storing, curtailing and feeding-in of excess renewable power, all of which should be considered in a new reform of the German Renewable Energy Act (EEG).

Keywords: *micro grid, self-sufficiency, EEG, multi-objective optimization*

1 Introduction

The latest reform of the German Renewable Energies Act (EEG 2017) will take effect in 2017. The reform remains to disadvantage partial self-sufficiency of local energy systems by applying EEG levy for small systems and entirely eliminating the option of self-sufficiency for larger energy systems looking to receive a market premium. According to §61a of the EEG 2017 storage operators are exempted from EEG levy as long as the energy is completely fed into the grid in terms of intermediate storage. As soon as energy is used for self-sufficiency for the whole energy that is taken out of the storage system the levy has to be paid according to §60(1) and §61(1) EEG 2017. This also applies for energy that is produced and stored by renewable energy power plants exceeding 10 kW nominal power which belong to the storage operator (§61(2) 4 EEG 2017). Thus, in consideration of §60 (2) 2 EEG 2017, one of the alternative concepts appears to be that of complete self-sufficiency in which operators are exempted from EEG levy if they are not directly or indirectly connected to the grid. In this paper, we analyze the economic feasibility as well as the environmental ramifications of installing and operating a renewable based local energy system for achieving ultimate self-sufficiency, using the example of the urban micro grid “EUREF Campus” in Berlin.

Within the framework of the *Micro Smart Grid – EUREF* project as one of the 30 *International Showcase Electromobility Berlin Brandenburg* core projects the mentioned urban micro grid has been significantly extended. The main objective of this project was the installation and operation of a micro grid consisting of various types of renewable energy generators and storage systems to provide local consumers with locally produced renewable energy. Besides providing energy to the buildings the project focuses on the supply of the growing demand of energy for electric mobility. It is seen as a drive train to install micro grids using storage systems to cover high peak in the energy demand. A particular feature in this project is the possibility to do research on the feasibility of a micro grid which is completely disconnected from the utility grid and provides 100 % self-sufficiency. These circumstances enable the following studies and discussions of the economic feasibility and ecological effectiveness of micro grids under the regulatory conditions of the new German Renewable Act.

2 Methodology

In order to identify how an urban micro grid like *Micro Smart Grid EUREF* can be supplied with energy sustainably and cost-efficiently while at the same time mitigating stress on the grid, the micro grid's real components (see figure 1) were simulated based on physical modelling and real-life parameters. A computer model is employed to assess and optimize the system's performance regarding levelized cost of electricity (LCOE), local autarky as well as life cycle greenhouse gas emissions (LCE). Due to the anticipated conflict between these objectives, the result of optimization is expected to be a multi-dimensional optimal pareto curve which identifies the trade-off decision makers should be aware of during the design of the micro grid and its components.

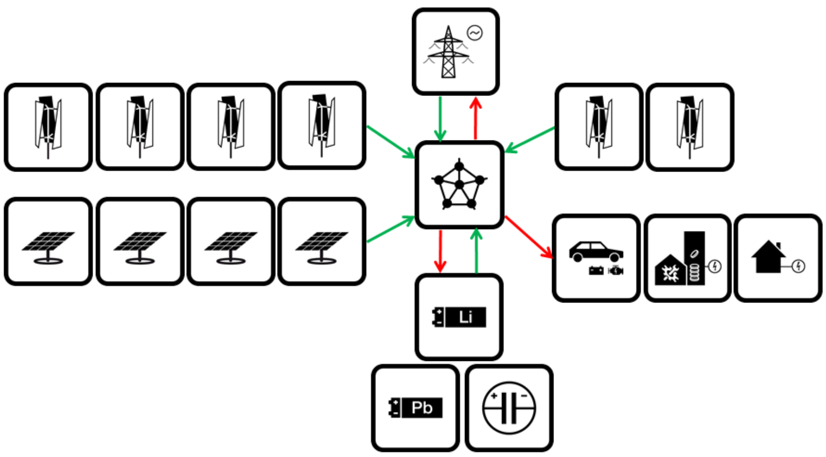

Figure 1: Topology of Micro Smart Grid EUREF

2.1 Simulation model

For the modelling and simulation of the microgrid RLI's simulation framework *SMOOTH* (*Simulation Model for optimized operation and topology of hybrid energy systems*) was employed [1]. It aims at modelling the power flow between the mircogrid's components. In this case it was used to solve the energy balance with a one hour time resolution over one year to anticipate the system's performance for a planning horizon of 20 years. Meteorological resource data is based on NASA SSE data (Surface Meteorology and Solar Energy SSE Release 6.0) [2]. The original data was converted to hourly resolution by the German Aerospace Center [3]. Data for component parameterization is based on data from the real system and listed in table 1. To synthesize an electric load curve for the microgrid's buildings and electric vehicles actual measurement data from the location was employed, completed by standard load profiles where necessary (e.g. office buildings). Lifetime of a battery is determined using the post-processing model of cycle counting [4], which associates the battery's cyclic lifetime to the energy throughput at certain depths of discharge throughout the simulation time. Thus, the overall lifetime of a battery can be estimated using both the cyclic and calendaric lifetime.

2.2 Optimization approach via key performance indicators

Optimization was conducted using RLI's multi-objective evolutionary algorithm [5] with the aim of simultaneously and equitably minimizing the key performance indicators of life cycle emissions and levelized cost of electricity by determining the optimal combinations of the microgrid's major topology and operational design parameters: nominal power of PV generators, number of small wind turbines (SWT), nominal capacity of storage technologies, curtailing or storing of excess renewable power. Optimization was executed with a population size of 80 over 100 generations.

2.2.1 Levelized cost of electricity (LCOE)

Levelized cost of electricity in this paper describe the cost per electrical energy unit used by the microgrid's total load and takes into account all capital and operational expenditures (levelized over all years within the planning horizon) of all components that are part of the optimization process [6].

$$LCOE = \frac{\sum_i An_i}{\sum_{8760h} E_{load}} \quad (1)$$

2.2.2 Time-based autarky (TA)

Time-based autarky describes the degree of self-sufficiency of the microgrid and is determined according to the overall time span in which power is neither taken from nor fed into the overlying electricity grid level.

$$TA = \frac{\sum_{j=1}^{8760h} t_j(P_{grid}=0)}{8760h} \quad (2)$$

2.2.3 Life cycle greenhouse gas emissions (LCE)

Life cycle emissions consider all greenhouse gas emissions associated with the production, installation, operation and recycling of the microgrid's components. LCE are normalized with the overall load demand.

$$LCE = \frac{\sum_i(\sum^{20a} Em_{fix} + \sum^{20a} Em_{var})_i}{\sum^{20a} E_{load}} \quad (3)$$

Table 1: Parameterization of system's components

			PV				**small-scale wind**		**CHP**	**PtH**	**storage**			**grid**
			Car-shelter	**Green Garage**	**Grey Garage**	**Haus 4**	**Gaso-meter**	**Haus 1+4**						
technical	number	-	1	1	1	1	2	4	1	1	1	1	1	
	type	-	Mono-CSI	Mono-CSI	Mono-CSI	Mono-CSI	Amp. VK-58	Amp. VK-58	Smart-blocks	immer-sion	Li	Pb	Super-Cap	
	lifetime	*a*	20	20	20	20	20	20	20	20	12.5 (cal.)	6.5 (cal.)	20 (cal.)	
	η_{el}	%	13.9	13.9	13.9	13.9	97	97	38	99	95	83	98	
	P	kW_{el}	60	19.9	22.62	23.4	1	1	22	10				
	height	*m*	20	20	20	40	80	28						
	azimuth	°	180 (S)	180 (S)	180 (S)	136 (SE)								
	tilt	°	15	15	15	18								
	c-rate	*1/h*									1.54	0.18	5	
	capacity	*kWh*									78	90	3	
	$SOC_{lim,u}$	%									50	10	0	
	$SOC_{lim,l}$	%									100	90	100	
	$P_{standby}$	*kW*	0	0	0	0	0	0	0	0	0.6	0.15	0	
economic	CapEx	*€/kW$_{el}$,*kWh*	7000	1500	1500	1500	13529	11454	66000	50	2500*	500*	30000*	
	$OpEx_{fix}$	*€/a, *€/kWh*	1500	498	588	608	324	275	660	50	1000	486	375	0.25*
	r_{equity}	%	40	40	40	40	40	40	40	40	40	40	40	
	r_{debt}	%	60	60	60	60	60	60	60	60	60	60	60	
	i_{equity}	%	3	3	3	3	3	3	3	3	3	3	3	
	i_{debt}	%	8	8	8	8	8	8	8	8	8	8	8	
ecol.	LCE	*t CO_2-eq. /kW$_{el}$, *kg CO_2-eq. /kWh$_{(cap)}$*	1.5	1.5	1.5	1.5	4.1	4.1	1.5	0.01	75*	59*		0.535*

3 Results

Due to the optimization's multi-dimensionality, the presentation of results is split into two parts according to economic and ecological aspects.

3.1 Economic cost of self-sufficiency

Optimal configurations of the micro grid could be successfully identified regarding the system's LCOE as well the TA. Figure 2 shows the results of two optimization versions (curtailing of excess renewable power allowed (OV1) and not allowed (OV1). Both versions demonstrate the kind of conflict between cost and self-sufficiency which can be expected: Increasing autarky generally leads to higher costs, more so for high degrees of autarky. This can generally explained by the fact that a higher local energy supply for the demand requires larger battery capacity. Table 2 shows the according topology parameters of the marked solutions in figure 2.

Up to a TA of around 40% the installed battery capacity is at a lower level, because most of the energy demand can be supplied by PV systems with their power output during day time. As a storage technology lower cost lead acid battery is prioritized while lithium ion technology is generally needed only to supply load peaks for higher autarky. When TA passes 75 % LCOE exceeds 2.5 €/kWh (MSG 3). At this point the micro grid's configuration includes cost-intensive small wind turbines to provide energy during night time and in the winter. Additionally load shifting has to be provided by larger battery capacity. Very high autarky, therefore, is only possible with expensive lithium ion technology, whose performance ensures highly dynamic power supply peaks.

Cost can generally be reduced, however, by switching the operational strategy and rearranging the topology, such as could be shown through the results of OV2. Within the micro grid larger capacities for renewable energy generators can be installed and their power partly curtailed according to demand to avoid feeding into the grid, which would decrease autarky. This approach allows mitigating the need for battery capacities and reduces the costs at a comparable TA level by 25% as shown in figure 2 with MSG 1 to MSG 2 at an economically relevant level.

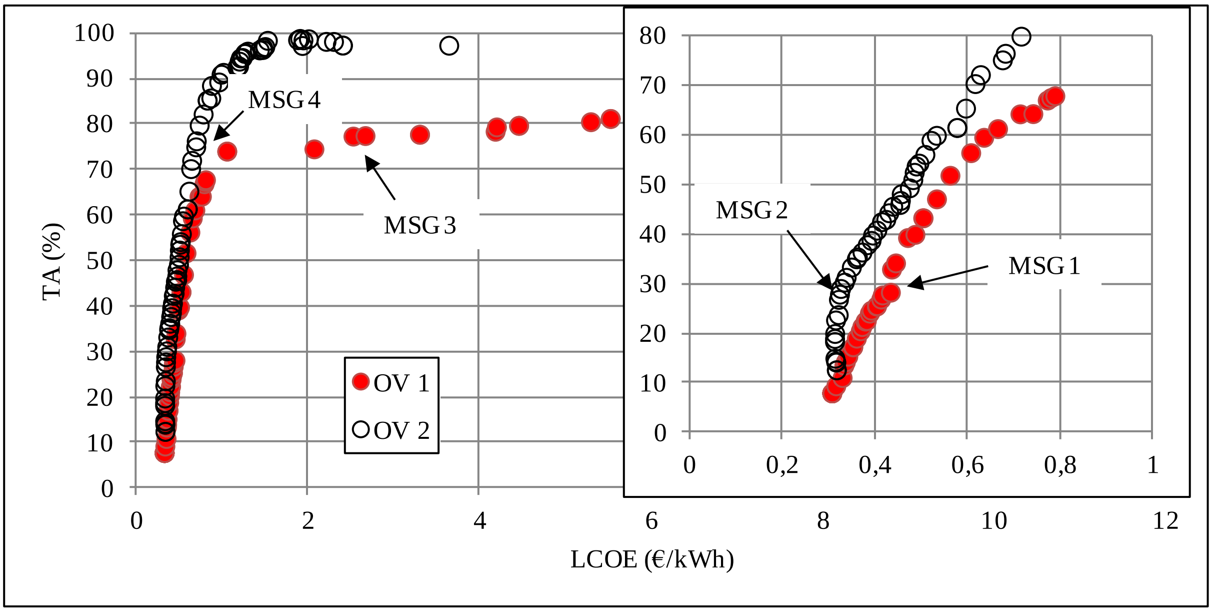

Figure 2: LCOE can be reduced without decreasing TA by installing and curtailing larger capacities of renewable generators, thus substituting cost-intensive battery capacity.

Table 2: optimal micro grid configurations for different operational conditions

	LCOE	*TA*	P_{SWT}	P_{PV}	Cap_{Pb}	Cap_{Li}	*LCE*
	EUR/kWh	*%*	*kW*	*kWp*	*kWh*	*kWh*	*g CO2-eq./kWh*
MSG1	*0.43*	*28.3*	*20*	*235*	*219*	*0*	*167*
MSG2	*0.33*	*29.0*	*0*	*257*	*0*	*0*	*180*
MSG3	2.65	77.7	*32*	*308*	9749	4	268
MSG4	0.72	80.0	*27*	*625*	727	0	146
MSG5	2.28	98.4	*0*	*3487*	3452	10	520
MSG6	2.28	98.4	*0*	*3487*	3452	10	85

3.2 Ecological cost of self-sufficiency

When analyzing the optimization results of OV2 and OV3 regarding the system's LCE, it can be observed that curtailing excess renewable power can be ecologically advantageous to storing it. Table 2 shows a LCE decrease of over 40% by switching from solution MSG3 to solution MSG4. However, curtailing of excess power does not always effectively reduce emissions. At first, increasing renewable-based autarky on low levels shows to help mitigation of greenhouse gases by substituting high-emission grid-supplied energy (535g CO_2-eq./kWh in 2016). At a TA of around 85% higher capacities of renewable energy generators are needed, however only serving the rarely occurring load peaks and are therefore underutilized. Consequently, the micro grid's components cause higher overall LCE while generating only reduced power output. Full autarky can thus only be reached at the cost of LCE leveling with those of the overlying grid (e.g. MSG 5 at 520g CO_2-eq./kWh).

The operational strategy OV3 represents the option of feeding in the surplus energy output from the micro grid into the overlying grid level thus avoiding the vast curtailing of renewable energy. As shown in figure 3, LCE doesn't increase, because all energy generated within the micro grid is either used to serve local loads or to supply the main grid.

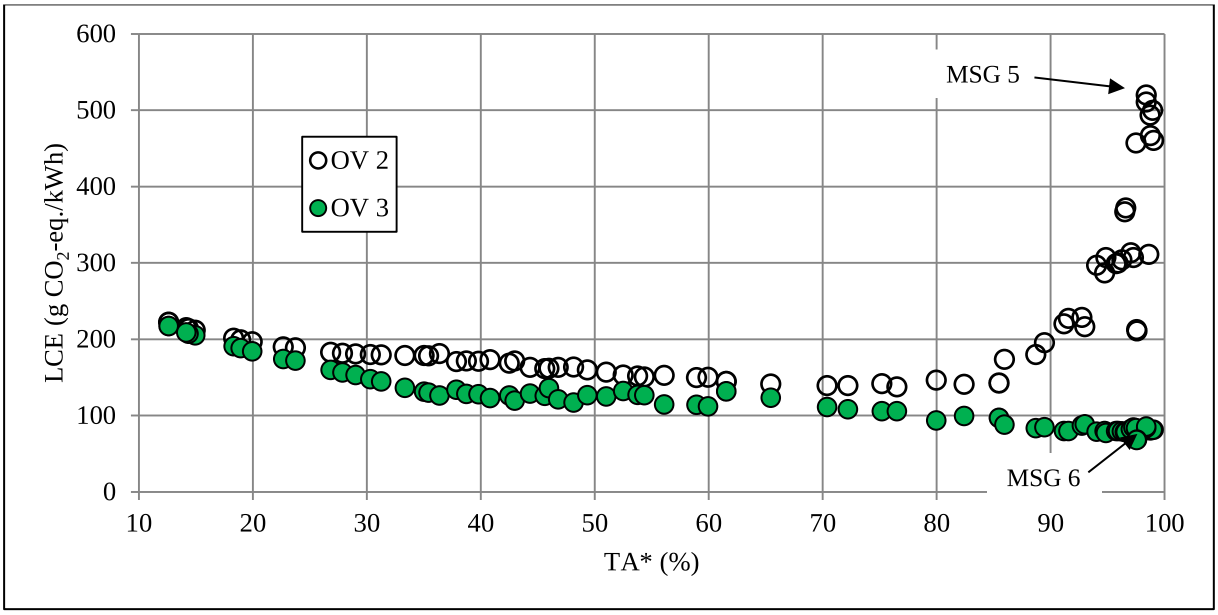

Figure 3: Curtailing of excess renewable power can lead to overall LCE comparable to those of the overlying grid level electricity (OV 2). Controlled feed-in effectively reduces LCE (OV 3). *for better readability TA of OV3 is not reduced by power feed-in.

4 Conclusion

Multi-objective optimization of the according micro grid demonstrated that ultimate local self-sufficiency is neither economically feasible nor environmentally viable because of the need for large overcapacities of storage and generation. While the curtailing of excess renewable energy generation can help replace parts of cost-intensive battery capacity and thus decrease the levelized cost of electricity, the overall life cycle greenhouse gas emissions of the system can become comparable to those of the overlying electricity grid level. Based on the results we motivate the thesis that economic viability as well as ecological effectiveness of a local micro grid can only be achieved by an optimized combination of storing, curtailing and feeding-in of excess renewable power. Setting the objective of ultimate self-sufficiency for the design of a micro grid without load management can be counterproductive in this matter.

According to the above stated thesis the currently applicable German Renewable Energy Act (EEG 2017) is deficient and should be refined for multiple reasons. Firstly, it remains to disadvantage partial self-sufficiency of local energy systems by applying EEG levy for small systems and entirely eliminating the option of self-supply for larger energy systems looking to receive a market premium. Furthermore it does not account for the fact that curtailing instead of storing excess renewable power in decentralized systems can be an economic alternative for mitigating stress on the grid while at the same time mitigating greenhouse gases. For future reform considerations a new version of the EEG should not penalize and at best motivate topologies and control strategies of micro grids which optimally combine the storing, curtailing and feeding-in of excess renewable power as to achieve economic viability as well as ecological effectiveness while mitigating stress on the grid.

Acknowledgments

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