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System Efficiency Rating of Industrial Utilities in Electricity Grids with a high share of Variable Renewable Energies

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System Efficiency can help to reduce greenhouse gas emissions significantly, because this approach offers the opportunity to integrate a higher share of renewable energies. This paper focuses on industrial utilities and gives a proposal to how a System Efficiency rating of utilities can be done. The dilemma of System Efficiency is that interactions between efficiency and flexibility can be intersecting or contrasting. This affects the greenhouse gas emissions and the profitability of utilities. Those effects have to be considered in the ratings to find an optimum solution. The purpose of the paper is to have a sufficient collection of technical and economical properties to describe System Efficiency. Therefore, a model defining the abilities that a utility must have to be system efficient is described. From the model single technical properties, that support future ratings, are derived. For economical rating, useful properties are listed and approaches for rating and presentation methods are suggested.

1. Introduction

In 2018 the Intergovernmental Panel on Climate Change (IPCC) published a report which emphasizes better to fulfil a 1.5 °C warming limit compared to the pre-industrial age (IPCC, 2018). The report was important to linked research fields like greenhouse gas (GHG) emission reduction, efficient power generation and usage and the very important field of renewable energies. A result of IPCC climate modeling for the 1.5 °C limit is that the GHG emissions have to be net zero until the year 2050. The national climate change objectives in the energy sector for the same year in Germany is to deliver 80 % of the electricity by renewable energies (BTBRD, 2011). The challenge with the energy transition is the controllability of renewable energies. Due to geographical circumstances, Germany's renewables predominantly consist of wind and solar power. These two types of energy are under the influence of the weather and accordingly volatile at a high rate. A fast, time-critical integration of a high share of variable renewables (VRE) into Germany's demand controlled energy system is a difficult task. If the amount of fluctuating power generation gets too high, the guarantee of power supply is in danger. Therefore, a transformation of the system is additionally necessary. This has to be changed to a supply controlled system.

Because the group of industrial power consumers requires 47 % of the whole electricity usage (BDEW, 2018), this group promises success by smoothening the volatility of the overall system. The industry also shares 29 % of the final energy demand (AGEB, 2018). This leads to the idea coupling the different forms of energy consumption, electricity and heat, and combine the existing methods of demand response and energy efficiency. Since those two standalone methods are in interaction together a new approach that is combining these two aspects called System Efficiency (SE) has to be developed (Schumm et al., 2018).

The overall question is, if energy efficiency or VRE integration in future systems has a stronger effect on GHG emissions reduction or both can be combined for an optimum solution (Philipp et al., 2016). To answer this question, conditions for more intense investigation on the approach of SE (Philipp et al., 2017) have to be set.

In this paper, the research focus is on the demand side of the system, especially on the level of industrial energy conversion units. Those industrial utilities have to be rated in terms of their abilities to provide energy to or to

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reduce power demand from the electricity grid to equalize VRE volatility. Previous contributions giving properties that describe the flexibility of utilities date back to the times of conventional fossil or nuclear power plants. These property sets were extended during the energy transition. The rating has to secure that the properties of the utilities match the requirements of the grid. In addition, the rating has to be a decision criterion for industrial corporations in which system efficient utility it is more profitable to invest.

2. Description of system efficiency

2.1 Overview of state, lack of research and novelty

Current research findings provide approaches to describe flexibility (Müller et al., 2017) of utilities more precisely (Hentschel et al., 2016). One approach is the definition of aspects of flexible energy generating units (Holzhammer, 2015) or a list of performance indicators for power generation (Dotzauer et al., 2019). These are based in the main on the description of the flexibility of biogas plants.
For future ratings of SE this state of research shows the following deficits:

- Not all technologies on utility level have been rated yet. Those few, who have been rated (e.g. biogas CHP), were rated isolated for itself.
- There is no method existing to compare different technologies as existing approaches were developed only for biogas plants.
- Flexibility is considered only as an isolated criterion. To describe SE as a combination of efficiency and flexibility in full, interactions between the two parts have to be considered as well.
- Only technical but no economical properties are set. For an overall evaluation of a technology for use as an industrial utility and the comparison of several, economic criteria have to be defined more precisely.
- Existing methods rate only single utilities. It is important that ratings in terms of combined utilities or utility networks are possible due to hybrid utility systems can increase SE.

Regarding these deficits in research, this paper will prepare fundamentals to describe interactions between efficiency and flexibility in quantified ways, especially for the synergies and discrepancies that will result when combining them to SE. For that, it will take a closer look on the requirements set by the electricity grid and have to be fulfilled by a utility. The purpose of the paper is to have a sufficient collection of technical and economical properties to describe SE of isolated and combined technologies. The collected properties from researching will be listed after evaluating whether they match the challenge with SE and minimize the described deficits. Therefore, in some cases, conformations have to be made or terms and properties have to be redefined. In addition, a presentation method for the comparison of the profitability of a technology is recommended.

2.2 Requirements and overlapping model

In the following sections, existing and newly developed methods are described to deliver a sufficient collection of properties. First, the requirements have to be defined. As the paper focuses on preparing fundamentals of SE rating, the requirements for energetic and ecological efficiency, that come from the industry, have to be united with the flexibility required by the electricity grid.

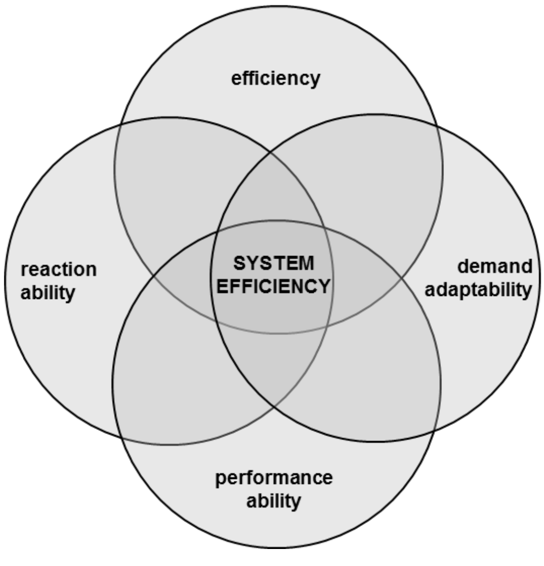

Figure 1: Overlapping Model illustrating the single abilities completing the approach of System Efficiency

Referring to the mentioned approach of aspects by Holzhammer in section 2.1, Figure 1 shows a new approach of an expanded overlapping model. The expansion includes the efficiency dimension to complete SE, while the referred aspects only include flexibility requirements. It also includes a renaming of sets, because the requirements all address the abilities of utilities and further to have a consistent terminology. Finally, the model includes the following four sets: efficiency, performance ability, reaction ability and demand-adaptability.

2.3 Abilities and properties

The single abilities are defined more precisely by a chosen selection of properties. Efficiency can be defined either by energetic properties or by ecological properties. Energetic ones are the secondary energy input as well as the final energy output and the resulting efficiency factor or alternatively another type of performance coefficient. As it is seen that these properties are dependent on the energy source and the energy converting technology itself, these are often necessary, but not always the best indicators to compare a high number of utilities. Because of that circumstance this paper gives the advice to focus on an ecological rating, and also because of the overall question of reducing GHG Emissions (see section 1) (Philipp et al., 2016). This can be done by the property emission. It has to be pointed to the fact that the parameters for emission reduction are hard to calculate, because the interdependencies of efficiency and flexibility affect the emissions directly.
Flexibility can be defined by some properties clustered by abilities as pictured in the overlapping model.

Table 1: Definition of selected system efficiency properties clustered by abilities

Ability	Property	Definition	Symbol
Efficiency	Secondary energy input	Energy input of an energy source treated for direct conversion	E_{in}
	Final energy output	Energy provided for conversion into useful energy for a final consumer	E_{out}
	Efficiency factor	Ratio of final energy output to the secondary energy input	η
	Performance coefficient	Other specific type of efficiency index depending on conversion technology	ε, cop, etc.
	Emission	Global warming potential of a system efficient operating utility	GWP
Performance ability	Installed power	Installed and absolute maximum of power that can be provided by a utility	P_{inst}
	Maximum rated power	Maximum annual average power a utility can provide	$P_{r,max}$
	Minimum rated power	Minimum annual average power a utility can provide	$P_{r,min}$
Reaction ability	Power change velocity	Ability to change provided power from current value to a target value during the period from a signal to achievement of the target value (Dotzauer et al., 2019)	m_P
	Activation velocity	Ability to change the provided power from zero to a minimum value during the period from a signal to achievement of the minimum value (Dotzauer et al., 2019)	m_{Pon}
	Reaction velocity	Ability to process a signal during the period from the signal to the start of the process (own definition)	t_{act}
Demand adaptability	Minimum power	Absolute minimum of power that a utility can provide, mostly technically limited	P_{min}
	Part load ability	Bandwidth of provided power that maximum can be provided (Dotzauer et al., 2019)	ΔP
	Provision ability	Ability to provide the demanded power over a maximum period (Müller et al., 2017)	t_P
	Activation frequency	Number of technically maximum possible activations to provide power during a period (Müller et al., 2017)	f_{start}

Performance ability:
This ability is defined by the technical power dimensions of the utility. For flexibility reasons, it can make more sense to design a utility not the conventional way. The more the design overachieves the own consumption of the company the more flexible a utility can act.
Some state-of-the-art properties were developed applying to biogas plants and to calculate grid charges. Varying parameters that do not fit for technically exact definitions are used for calculations here. Some even increase correlating with an increasing flexibility, which is just the main aim. Hence, some properties are not useful to describe and compare a high number of different utilities and have to be changed or replaced.

It also has to be taken into account that additional situations are faced. The existing properties all describe generation units that are only energy market and grid oriented. The new situation on a production site includes the utility additionally has to satisfy the needs of the producing company itself. While production facilities of the company can provide flexible power demand itself (Selleneit et al., 2018), the complexity of the company's flexibility rises to a higher level. Another situation is that a utility is installed to use electric power, e.g. a consuming technology like a heat pump.

For an industrial utility rating, following suggestions (see Table 1) consider all these aspects (company's requirements – electricity and heat, generating or consuming, combined utilities) and give all future approaches and research tasks a solid and comprehensive base. During future research, it may be necessary to add or customize some properties according to circumstances. It is advised to use signs for all power values which display the power direction of the grid and the provided power of the utility from grid perspective (electric sink: "-" for low VRE production and consuming utility; electric source: "+" for high VRE and producing utility).

Reaction ability:

This ability is defined by the time a utility needs to accomplish a task. In most cases, the tasks can be described by processing a signal, e.g. given by the grid that includes the information of power demand. Power change velocity and activation velocity are well defined yet. To complete this ability an additional property reaction velocity is suggested to describe the duration a technology needs to start the power generating process.

Demand adaptability:

This ability summarizing is defined by the potential of a utility to adapt the power demand of the grid. This includes the range of power it can provide, switching more or less continuously between minimum and installed maximum power and for how long it can hold. To complete this ability an additional property activation frequency is suggested. This one considers the pause times a utility technically is limited until it can restart its generating process. By adding this parameter, it can be described how often a utility can provide a demand.

Most but not all of the properties can be described more detailed by mathematical parameters or formula. Some of the parameters are directly measurable. Properties P_{inst} and P_{min} coincidentally are parameters. P_r is in correlation with full-load hours *flh* and is calculated as follows:

$$P_r = \frac{P_{inst} \cdot flh}{8760\ \mathrm{h}}\text{, for } P_{r,max} \text{ using } flh_{max} \text{ and } P_{r,min} \text{ using } flh_{min} \qquad (1)$$

Dotzauer defined m_P, m_{Pon}, ΔP and t_P (Dotzauer et al., 2019) and Q_P correlating with P_r. Notice that the power changing velocity defined over the slope of power change m_P can be positive or negative according to which direction the power changes. The reaction velocity t_{act} can consist of more periods of utility significant start sections. E.g., the fuel of a CHP plant has to be preheated and the engine drives ineffective until generating electric power. t_{act} usually ends with the beginning of the activation velocity m_{Pon}. Notice that provision ability can be min or max according to P_{min} or P_{inst}. Activation frequency f_{start} is best when high, which means when the period between two activations is short. This period is the sum of all time slices during a start-stop procedure including minimum continuous power provision t_P, minimum t_{act} and maximum m_p or m_{Pon}. All selected properties are illustrated in Figure 2.

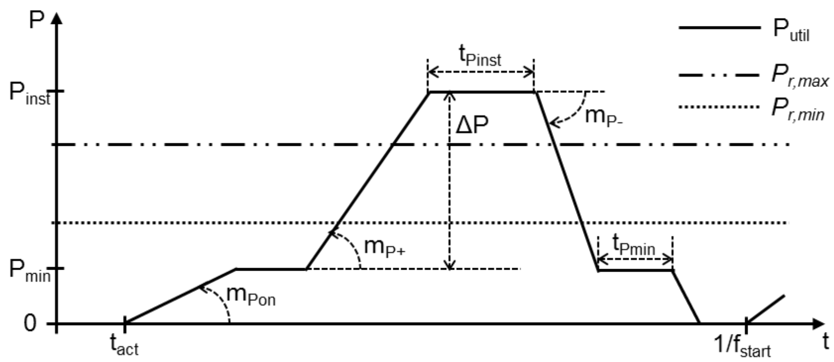

Figure 2: Selected properties illustrated in a power change diagram

From this paragraph, the following important points should be recognized. Flexibility abilities do not interact among themselves. After adding Efficiency to the model, it gets a more complex and dynamic model, because flexibility abilities and efficiency do interact. For all the further researching, it has to be taken into account that efficiency properties can be influenced by some flexibility properties. To give a simple example, shifting the partial power of a utility to fulfill a shifting grid requirement causes a change of the utility's efficiency factor. When rating industrial utilities, property values will be different depending on purpose of use and energy demand. This has to be differentiated.

2.4 Economic properties

In consequence of the different design and the different operating mode of utilities for flexible or SE usage, the investment costs and the operating costs are different, too. In Table 2 all costs for an economic rating and investment decision for utilities of a conventional calculation (complying with VDI standards 2067, 6025) are listed. To complete the economic rating of SE, costs for flexible utility operating are added. All listed expenditure can consist of several cost parameters depending on utility type, plant location and other company circumstances. Detailed parameters cannot be discussed in the limits of this paper.

Table 2: Capital and operational expenditure of system efficient utility

Capital expenditure		Operational expenditure	
Utility hardware	Heating system	Substitution heat supply	Standby costs
Thermal storage system	Facility building	Restart energy costs	Storage operating
Regulation technology	Removal	Benefits of time shifted selling	Fuel savings
Additional infrastructure		Costs/Savings tax, fee, charge	Maintenance costs
			General overhaul

Capital expenditure:
For the example case the utility is a combined heat and power technology and supplies heat to the company, additional capital costs can incur. Addition or expansion of thermal storage capacities might be necessary when the utility's operating mode gets more flexible regarding electric energy. If the thermal energy demand remains unaccomplished, an additional peak heating plant has to be installed. For these additional capacities regulation technology and infrastructure (e.g. a more powerful grid connection or extended heating system) has to be adapted.
Operational expenditure:
According to reaction abilities standby costs can occur when the flexibility of a utility has to be increased by reducing the reaction velocity. For combined heat and power technologies additional storage operating costs and heat supply costs have to be added. In contrast are fuel savings for heating in times of low ratio of VRE and the residual power of the utility is high as well as when thermal storage capacity is in use. The additional costs for secondary energy input in consequence of a higher count of starts has to be taken into account. Maintenance and overhaul costs also rise with that count of restarts. The time shifted energy selling and income or savings from taxes, fees and charges are the benefits of the electric power generation by grid requirements and the electricity market. To refer back to the technical interactions described in section 2.3, they affect operational expenditure. To continue the example, interactions shifted partial power of a utility can have monetary benefits whereas the reduced efficiency factor during partial operating point reduces the benefits.

3. Conclusion and outlook

System Efficiency rating and the difficulty with its dilemma of interactions should be solved more precisely with the presented approaches in this paper. The expanded overlapping model, derived abilities and customized properties of utilities give a solid base for SE rating including technical, ecological and economical properties. The approach is also able to make ratings in terms of combined utilities or utility networks. This is very important due to SE of such hybrid utility systems can vary decisively versus single utilities. These defined properties are able to indicate the variation.
For the next research phases of rating utilities the prospect of some methods under development are presented. Especially a missing methodology for the technical rating will be applied, following the steps in Figure 3. In step 1, properties for a useful SE rating have to be defined as we just did in this work. Additionally, the relations between the single properties have to be set in the second step in preparation for the step 3 sensitivity analysis.

Figure 3: Methodology for the technical rating of utilities

The sensitivity helps to weigh the relation in step 4. The weighting is the major challenging step of the rating procedure, because it is influenced by the requirements of the energy system. The requirements vary with progressing time of the energy transition and VRE ratio and are not defined for future scenarios. After the weighting the properties can be rated and technologies can be compared in steps 5 and 6.
For the comparison of utilities regarding economic properties an approach for a presentation method is under development. The planned illustration has to represent the specific capital (CAPEX) and operational expenditure (OPEX). The relation between these two quantities has to be shown for every utility to guarantee economical classification and comparison. This is not an easy task, because relations also depend on technical properties (see also section 2.4). The specific quantities are indicated by €/kW for CAPEX and by €/kWh for OPEX. A utility can be marked in the illustration with its calculated typical expenditure. Those might not be possible to be calculated exactly so that the representation of a utility could include the variety of calculation. It should be differentiated if the utility technically is more of an efficient or flexible characterized technology. One result can be the characterization by low total costs which can help for an investment decision. In practice the characterization can be intersecting with the investment budget.
Thinking of power and heat integration technologies, an electric boiler usually can react flexible but is not efficient, and is characterized by low CAPEX but high OPEX. Compared with this can e.g. could be a heat pump which is a less flexible but higher efficient technology characterized by low OPEX and high CAPEX. Although the heat pump technically seems to be the better decision for most of applications, in some example case the investment budget may be too low. Then the company might invest in the electric boiler, if a low CAPEX and the technical demand for flexibility overweighs other criteria.

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