Impacts of Energy Flexibility on Energy Efficiency of Hybrid and Bivalent Facilities

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Abstract

The increasing share of renewable energy sources such as photovoltaic or wind turbines have an impact to the grid stability – the grid is more difficult to stabilize. The cost for grid usage and measures to keep the grid running were growing in the past years. There are chances for companies to participate in the regulation markets and generate additional revenues by powering up or shutting down their facilities and supporting the stabilizing efforts of the grid operator. In particular, hybrid and bivalent facilities cover a high flexibility potential. Another matter of interest for companies is to reduce their energy costs by increasing their energy efficiency. However, energy flexibility from hybrid and bivalent systems and energy efficiency have an impact on each other and, therefore, on the energy costs. For companies there are many issues to consider if they want to participate in the flexibility market. One of them is to identify the right time to change the energy carrier and which factors need to be considered. The Institute of Energy Efficiency in Production EEP at the University of Stuttgart created a method for hybrid and bivalent facilities to provide a guideline for companies. It indicates, which parameters to consider, if companies want to change the energy carrier of their processes and how to determine the right time to change, depending on energy efficiency, feasibility and the revenues of the energy market.

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1. Introduction and state of the art

Energy efficiency and energy flexibility are getting more important these days. In November 2018, the energy production supplied from renewable energy sources of the OECD Members were at 27 %, in Germany at 32.5 % [1]. The increasing share of renewable energy sources in the electrical grid does effect the grid stability. The frequency of the grid has to stay between certain borders. The stability of the frequency is ensured, when energy supply and energy demand are matching, otherwise a black-out might occur [2]. Energy production from renewable sources endangers the electrical grid, due to the fluctuating and uncertain prediction of energy quantity.

The stability of the grid can be ensured by switching off regenerative plants (feed-in management), providing control reserve energy and shutting down energy plants and facilities. Participants of stabilizing the grid are compensated for call-offs or shutdowns. In 2017, the costs for redispatch measures with market and grid reserve power plants rose up to 901 million Euro in Germany [3].

Furthermore, electricity prices for the German industry increased up to 15.17 ct/kWh for companies with an annual consumption between 500 MWh – 2,000 MWh [4]. This confirms the importance of using resources rationally. The standing of electricity prices and renewables can also be seen from the World Energy Issue Monitor, where those two issues are in many countries, among others, action priority topics [5].

Every intervention in production has an influence on the energy efficiency of systems. Energy efficiency in industrial processes can become a decisive competitive factor. Depending on the economic sector, the energy intensity can be more than 32% and due to the advancing globalization and the increased competitive pressure, advantages can be achieved compared to the competition. [6] In addition to reducing the energy costs, investing in energy efficiency can have other positive effects, such as reducing downtime, increasing the life cycle of the plant, or reducing cleaning and maintenance requirements [7].

The Institute for Energy Efficiency in Production (EEP) of the University of Stuttgart developed a method that enables companies to evaluate energy efficiency and, thus, the energy costs of hybrid and bivalent facilities. On the basis of the efficiency evaluation of both processes in combination with the energy market, a decision concerning the change of energy carriers can be made wisely.

With fluctuating energy sources on the rise, attention must be paid to the use of energy and its production. There are already some methods and guidelines that describe factors of energy waste and identify energy efficiency potentials [8–12]. Some also show, which energy flexibility parameters have to be considered regarding the flexibility markets [13–16]. There are also tools and papers for evaluating the impacts of offering energy flexibility [16–20]. Nevertheless, there are no tools or methods to identify the right time to change the energy carrier considering energy efficiency and feasibility of hybrid and bivalent facilities. The developed methodology shows, which efficiency and flexibility parameters have to be considered and which steps have to be made in preparation to change the energy carrier.

The following section describes in general, which energy flexibility measures are available and why hybrid and bivalent facilities are relevant when it comes to the fluctuation of renewables in the grid. Furthermore, a classification of present hybrid and bivalent facilities according to the degree of support and the reason for use will be carried out. This is followed by a section that describes the relevant factors to execute an energy efficiency and feasibility analysis. Before summarizing this paper and presenting an outlook of the future works in section 5, section 4 delineates the assimilated parameters of section 3 and characterizes the developed method to evaluate the energy efficiency of hybrid and bivalent facilities.

2. Energy flexibility

Energy flexibility is the ability to adjust to the changes of the energy market quickly and with few financial expenses [21]. Due to the regenerative energy feed into the grid, the residual load between renewable energy generation and energy consumption can change very quickly into the positive as well as to the negative [22].
However, these deviations have a strong influence on the trading of energy – especially to electricity prices. In the day-ahead market, 185 hours of negative electricity prices were recorded in 2017 [23]. However, in the same year, several hours were priced at over 100 €/MWh, so that the volatility of the energy market prices is at a high level [24].

In order to address this volatility, the demand side of the energy system must become more flexible. There are many measures and markets, which have to be considered. They will be introduced in the following section.

### 2.1. Energy flexibility measures

Companies have nine different types of measures available, which can be implemented in the short, medium or long term and realized more or less quickly and flexibly. Figure 1 shows these categories and their implementation level [25, 26].

When renewables have an average proportion of power generation, many of these measures are enough to ensure the stability of the grid. However, if the generation of renewable drops for a longer period of time – also called a Dark Doldrum – this condition threatens the stability of the electrical grid [27]. Depending on the individual process, the structure of the company and the quality requirement, many of these measures cannot be activated more often than five times a day. In addition, many of the measures for flexibility have a shorter call duration than five hours [28]. Due to this restriction, hybrid and bivalent facilities are getting important. Therefore, the following sections will especially consider the flexibility measure of the dynamic change between energy carriers.

### 2.2. Bivalent and hybrid systems

A bivalent process can switch between two energy carriers. The restriction to the two energy carriers of electricity and gas is also called hybridization. Multivalent processes can switch between more than two energy carriers. The interpretation of bivalent (industrial) processes is not new. In the heating circuits, bivalent processes can often be found. The more favorable energy carrier provides the basic load and the peaks, which should not occur frequently, are covered by another technology (redundant) or another energy carrier (bivalent). A thermal bivalent design that is often depicted in industry is the use of a heat pump for the basic load supply with an additional heating boiler for peak loads. If the additional demand for the heating energy of the heat pump is compensated by electrical current, it is also referred to as a mono energy heat pump system.

Depending on the requirements of the thermal process, e.g. temperature, call-up speed, amount of energy, transmission speed, the energy demand can be supplied by using different energy carriers and technologies. [29] Figure 2 shows different possibilities of energy supply within a factory. Depending on the number of energy carriers, the number of facilities used and the intended use of the second energy carrier, the system can be assigned. [29–33]
A process with only one energy carrier and one facility is monovalent. There are already facilities, which regulate their power consumption for a short time in dependency of the electricity market. A subsidiary redundancy is at hand, when there are at least two facilities, regardless of the number of energy carriers. Some companies in the glass industry have mixed melting systems implemented, where they can provide 20% of the necessary energy with electricity to reduce emissions or increase their melting power [32]. A homogeneous redundancy is usually in use, when the process is too important to fail, such as compressed air supply, where there is at least one additional compressor. A dynamically controlled process which can switch between two energy carriers depending on the energy market is called diverse redundant. There are bivalent processes, which can switch between gas and oil to provide the necessary heat demand – like in glass production – depending on energy prices [31]. A hybrid system can be integrated in one facility or can be totally separated [33]. The most common combination of a heat pump and a boiler is called hybrid [33] but also bivalent [30]. In this paper it is defined, that a hybrid system consists of two facilities whereas a bivalent system is integrated in one facility.

Due to their flexibility, bivalent or hybrid production plants can minimize energy costs and have a positive effect on the company’s results [16, 29]. Furthermore, hybrid and bivalent processes can increase the production quantity without harming the quality of the product. [32]

3. Method to identify economic changeover times

The change from one energy carrier to another always has an impact on energy efficiency and on energy costs. Hence, the impacts on energy efficiency have to be tracked down, when considering a change of the energy carrier. Besides, there are also factors regarding the machine. It is not always possible to change the carrier. The factors that prevent a change of energy carrier on the machine side must also be identified and evaluated.

The method to identify the right time to change the energy carrier introduced here, has four steps (figure 3, left). It starts either with a control energy call, or with a change of energy prices on the exchange market (figure 3, left). The grid operator may impose the conditions of call duration. It is assumed that facilities counteract within a virtual power plant, where the prequalification requirements can be fulfilled. Since all the demands from the energy market, such as ramp up gradients, prequalification tests, call duration, etc. have been widely discussed they are not considered in detail here [16, 26, 34, 35]. In addition, it is assumed that a request from the virtual power plant operator can also be rejected. This is the case in the research initiative “SynErgie”, which implements flexible IT-platforms to synchronize energy demands with volatile market [36].

All four steps have to be completed before a decision can be made whether or not to change the energy carrier. If the energy carrier has not changed, the method can be started from the beginning – either with a new energy exchange price, which is usually renewed every 15 minutes, or with a new control energy call. If the energy carrier has been changed, some recovery time must pass until the energy carrier can be changed again.
3.1. Analysis of operating conditions

The first step of the evaluation is to figure out the operating conditions during changing the energy carrier (figure 3, right). Those operating conditions are, on one hand, the conditions of the process, which is operated in a hybrid or bivalent manner, e.g. stand-by, ramp-up, production, etc. However, on the other hand, it is also important to incorporate the interaction of the following and previous processes, for example, for the possibly recovered heat energy, which could be used.

Figure 3b shows the necessary use energy of a furnace, the assumed recovery energy which is needed and can be used within factory and also the three operating conditions of the furnace heat-up (1), stand-by (2) and production (3). The recovered energy, which could be used, becomes necessary with the start of the production (3).

Depending on – for example – the length of a control energy call \( t \), other operating conditions have to be considered in the following steps. Therefore, different level of power can be provided. In this case, if the control energy call lasts up to \( t_1 \) the control power provided would be 33 kW, if the call is up to \( t_2 \) the offered control energy power would decrease to 10 kW.

3.2. Feasibility analysis

The next step would be checking out, whether a change of an energy carrier can be fulfilled, with the appliance installed. Figure 4a shows the process flow chart for the feasibility analysis. A control reserve call is the energy, which is offered for the grid operator to stabilize the electrical grid.

Regarding the conditions, which are determined in the first steps, the first checkpoint would be, whether the use energy of the different operating conditions of the hybrid machine can be started. For example, a combined heat and power plant (CHP) cannot run at every partial load. If certain operating conditions are not guaranteed with one carrier, it can be inspected, if they can be approached with the support of the other appliance, which uses the other energy carrier. The first condition in figure 3b shows the ramp-up stage, where the material in the furnace is melted. It is possible that a technology cannot provide the total power on its own, but possibly with the support of the second appliance. A change of the energy carrier cannot be executed, if one of the operating conditions cannot be executed on its own or with the support of the other energy carrier.

If the operating conditions can be approached, it should be checked, whether the connected load of the factory, e.g. transformer, solar thermal, gas pipeline, etc., is sufficient to provide the required power. If this is not the case, a change of the energy carrier is not possible. The last two checkpoints on the feasibility analysis regard a control reserve call. If the energy carrier should be changed, due to a control reserve call, it has to be checked, if the regulations of the energy call can be fulfilled with the technology installed. As already mentioned, those regulations like ramp up speed, minimum of power supply, etc. will not be discussed here.
3.3. Energy efficiency analysis

After the feasibility analysis is successfully done and there are no reasons not to change the energy carrier due to the criteria mentioned in 3.2, the energy efficiency analysis must be performed (figure 4b). In order to assess energy efficiency, it is necessary to identify a method that can be equally applied to all processes, whether main or peripheral processes, cross-sectional technologies or supporting functions. For example, a method that specifically aims at assessing the energy efficiency of refrigeration systems cannot be used to assess the efficiency of heating systems. The energy value stream method is particularly suitable for assessing the energy efficiency of flexible and especially hybrid systems. Since it does not only consider the entire energy value stream in general, but also energy recovery. [12] The hybridization or expansion of a plant with a second energy carrier is especially relevant for thermal processes.

In order to assess the energy efficiency of a process, it is not only necessary to determine the efficiency of the process, but the entire process chain within the factory – from conversion, via transport to the use of energy [12]. Transportation losses might be different when changing the energy carrier. If the heat supply for a process is generated electrically directly on site at the facility or if the necessary energy is provided by a boiler in the cellar, transport losses can change. The use energy for the process is always the same. The efficiency of the conversion can also vary widely dependent on the energy carrier and the technology used. Another parameter be considered, is “startup losses”. The required energy for ramping up also has to be calculated. The ramp-up can take a while and needs energy, which in some cases cannot be used. In doing so, the corresponding energy losses must be determined along the process chain.

Despite those losses, there is one other factor, which has to be considered. Following [12] losses due to bad adjustments, like over-dimensioning, also have to be considered and are summarized as machine state losses. If the upcoming operating conditions are not in the most efficient operating point of the technology, those efficiency losses have to be taken into account and is summarized in machine state losses. The energy losses have to be calculated for every operating condition. How many operating conditions have to be considered is dependent on $t$ – the duration of a control energy call or the recovery time between two energy carrier changes.

The accumulated energy losses give the total losses for the process (see formula 1 and 2). The conversion, transport and machine state losses have to be calculated for the whole time $t_n$, where $t_n$ is the duration of the operating condition. Startup losses for the operating appliance can be ignored. If the machine is not running and has to be switched, the
startup losses for both appliances have to be considered. The startup losses only occur while ramping up \( (t_{\text{ramp}}) \) and can be calculated as seen in formula 3.

\[
E_{\text{losses}}(t) = E_{\text{conversion losses}}(t) + E_{\text{transportation losses}}(t) + E_{\text{machine state losses}}(t) + E_{\text{startup losses}}(t)
\]

(1)

with:

\[
E_{\text{conversion losses}}(t) = (1 - \eta_{\text{conversion}}) \int_{t_n}^{t_{\text{ramp}}} P_{\text{use energy}} \cdot dt
\]

(2)

and:

\[
E_{\text{startup losses}}(t) = \int_{t=0}^{t_{\text{ramp}}} P_{\text{startup losses}} \cdot dt
\]

(3)

Transportation and machine state losses can be calculated according to formula 2, with adapted corresponding efficiencies. The efficiency of technologies can vary between the operation condition. Therefore the varying efficiency of every operation condition have to be taken into account.

\[
t_{n-1} \leq t < t_n : \eta_{\text{machine state } n-1 \rightarrow n}
\]

A compressors with variable speed drive have their highest efficiency between 40-80% of its load. Below above this range the motor is less efficient. [37] The efficiency of partial loads is strongly technology dependent. Transport losses can also have different efficiencies in different operation conditions.

After this, the energy process consumption has to be calculated again including the use energy for every operating condition (formula 4).

\[
E_{\text{process consumption}}(t) = E_{\text{losses}}(t) + E_{\text{use energy}}(t)
\]

(4)

The potential of waste heat recovery in thermal processes is substantial [38]. If energy from the process can be recovered for other processes, this has to be taken into account. The recovery energy has to be subtracted from the cumulated energy consumption. In step I the operating condition of the possible energy recovery was identified (figure 3b). Regarding the reserve energy call duration or the recovery time \( t \) (before changing the energy carrier of the hybrid again) the possible waste heat recovery has to be considered. Whether or not the used recovery energy can be made available is depends on the technology. Figure 3b shows the use energy of a furnace. This energy could be supplied by – for example – using gas burner or resistance heaters. While the exhaust gas from the gas burner could be used at temperatures of up to 1100°C and for other processes, where, in contrary, there is hardly any usable waste heat (heat between 40-80°C) in the exhaust air from electrically heated systems. Hence, the energy recovery needed in the factory could be supplied by a gas burner, but not with electric heaters. [39] Since this factor significantly affects the energy efficiency of a process, the implemented energy recovery concepts must be considered in an energetic assessment of hybrid and bivalent facilities (see formula 5).

\[
E_{\text{consumption}}(t) = E_{\text{process consumption}}(t) - E_{\text{recovery}}(t)
\]

(5)

The energy consumption of the operating machine has to be compared with the energy consumption of the possible machine and the economic analysis can be done.

3.4. Economic analysis

The previous section presented the analysis of the energy efficiency of hybrid and bivalent systems while changing the energy carrier. To compare the energy consumption of two different technologies in order to evaluate, whether to switch the energy carrier or not, there has to be an economic analysis. Due to different prices for energy carriers, the determined energy consumption of both appliances have to be multiplied with the specific energy costs (formula 6).

\[
\text{energy costs} = E_{\text{consumption}} \cdot \text{specific energy costs}
\]

(6)
After the energy cost gap between those two energy carriers is identified, the revenues of the energy markets, like control reserve or energy exchange, have to be considered. Also some additional expenses may occur need to be considered:

- costs for exceeding the peak load
- penalties due to increased consumption
- additional operating expenses

The change from one energy carrier to another always increases the current load. If the limit of the peak load is exceeded due to the change of the energy carrier, the additional costs must also be included. Penalty payments due to breaches of energy contract because the agreed purchase quantity was exceeded must also be taken into account. By switching from one energy carrier to another, additional operating costs, such as increased cooling costs (e.g. additional cooling of the engine oil in a CHP unit), additional oxygen costs for O2 burners, additional oil consumption, increase in maintenance costs due to change of energy carrier, etc. have to be taken into account and priced by (see formula 7).

\[
\text{costs}_{\text{total}} = \text{energy costs} + \text{peak load costs} + \text{penalties} + \text{operations expenses} - \text{revenues} \quad (7)
\]

If the revenues from the energy markets compensate the higher costs due to energy efficiency losses and the additional expenses, then the energy carrier can be changed.

4. Outlook

Hybrid and bivalent facilities will play an important role in the development of renewable energies. In this paper, the application areas of systems with dynamic changes of the energy carrier were shown and a classification according to the degree of support and the reason for use was carried out.

Furthermore, a method for determinate the economic changing time from one energy carrier to another was develop in dependency of energy efficiency and feasibility of hybrid and bivalent systems. It was illustrated that the following machine conditions, the regulations of the control market, energy supply limits, the different energy losses, like conversion, startup, machine state and transportation losses and the energy recovery have to be taken into account, when assessing energy efficiency and feasibility. Continuative work has to analyze, which parameters are important to identify significant operating systems. Additionally, the ecological and economic effects of hybrid and bivalent processes to companies and, furthermore, for the environment have to be investigated.

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