Design and assessment of energetic agility measures in factories based on multivariate linear regression

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Abstract

Industrial power supply systems have to adapt to the impending turbulence on the energy market as well as the agility of the influences on the manufacturing systems. Furthermore, developments such as e-mobility or interlinking different energy sources provide challenges to the industrial power supply. The design and assessment of possible measures addressing these changes is a challenging task for planners of industrial energy systems. The presented method first introduces a stepwise procedure of designing agile measures for the factory’s energy system. Following the designing phase, the benefit assessment method based on multivariate linear regression analysis in combination with Monte Carlo simulation is described. Finally, a case study demonstrates the usability of the overall method and shows first benefits of an agile energy system. Therefore, the presented method is suitable for evaluating measures that promote agility despite planning uncertainty.

1. Introduction

The increase of volatile energy in the electricity grid due to the energy transition poses risks for industrial energy supply. In addition, the demand for further electrification of the consumed energy in production and the saving of fossil fuels in order to achieve the climate protection goals are constantly rising. This leads to uncertainty about the secure of supply [1-3] and the development of the energy prices [4]. As part of a reorientation of the price models for electricity, a general dynamization of the electricity tariffs as a function of the temporal energy usage will take place. Parallel trends like the CO2 reduction and cheaper technology for producing electricity renewable may force the energy cost for natural gas at an equal level compared to electrical energy. The World Energy Outlook 2017 forecasts a doubling of gas prices until 2040 [5]. At the same time, for example, the electricity production costs of PV systems are halved. For all forecasts, there is a high level of uncertainty about policy and emerging trends, such as the electrification of thermal processes in industry. In addition, technical and ecological developments such as the transformation towards electro mobility burden the planning reliability with regard to the requirements of the energy supply system of a factory [6]. The agile design of the energy supply in the factory provides one possibility for dealing with planning uncertainties [7, 8]. The energetic agility enables the power supply to respond to the turbulence from the external environment and internal production through organizational or technological changing reactions. The ability to make these changes quickly and cost-effectively outside of the systems planned and normal flexibility describes the ability of energetic agility. Since the energy supply system is closely linked to the production layout and the building [9], the fundamentals for adaptability must already be set within the framework of factory planning.
2. Agility measures in the energy supply

The planner has to make decisions for a certain technological solution during the planning process. Doing that, he has to take measures into account that are capable of transforming the energy supply system in case of the entrance of a relevant agility driver. The following model of a process for designing an agile energy supply system was developed to guide the planner (Fig. 1). The model is divided into two sections: the selection of the relevant agility measures (agility enablers) and the subsequent assessment of the use of the agility enablers, considering future developments.

Fig. 1. Procedural model to assess agility measures in energy supply.

Wiendahl derives five general agility properties of systems: mobility, modularity, compatibility, universality, and scalability [10]. As far as possible, these properties should also apply to the agile subsystems of the factory’s energy supply system (as energy agility enablers). The task of the energy supply system is to meet the energy demand of production through external energy procurement, the generation of own energy or the use of storage under temporal, qualitative, quantitative and economic criteria [11, 12]. Building on that, three basic technological principles can be formulated for the energy agility measures: onsite generated energy, the flexible use of different energy forms and the storage of energy [13].

2.1. Onsite energy generation

The possibilities of onsite power generation can be divided into power plants, the singular use of regenerative energy sources or the coupled generation of energy, in which several forms of energy are generated in a quasi-fixed ratio [14]. Power plants, which only generate electricity, are not considered further, as they are rarely relevant for use in individual manufacturing companies. These power plants are mostly used in the public power supply system. The coupled generation of energy is typically based on combustion processes in which heat or cold and electricity are generated together. These coupled generation processes use renewable energy sources (e.g. biogas, biomass) or fossil energy sources (e.g. natural gas or diesel). The different technologies differ with regard to their agility. Photovoltaic (PV) systems are modular. The expandability is bounded to the limits of the usable area. The universality exists for the generated energy form of electricity, but does not apply to the system itself. Combined heat and power plants (CHP) are more universal in this context, as they allow different driving styles in addition to the coupled generation of multiple forms of energy. Furthermore, these systems can be designed in a modular design and are thus both restricted in mobility and scalable due to the interconnection of several systems.

2.2. Usage of different energy forms

The concept of sector coupling (coupling of electricity, heat and cold) as well as bivalent production plants show possibilities for using different energy forms in a flexible way [15]. Depending on availability or price, the energy form can be substituted by another one. Modular power-to-heat systems can be extended or reduced. The universality of the systems is given in principle by the flexible use of the energy form, but limited by the technical implementation, for example, the achievable heat level. Bivalent manufacturing machines are not modular, extendable or reducible due to the integration of the energy conversion in the machine in terms of energy conversion capability. The universality is given by the change of the energy carrier.

2.3. Energy storage

There are a variety of energy storage technologies, which differ by the underlying forms of energy, the amount of energy, the charging and discharging speed as well as the lifetime and reliability. These technologies lead to different concepts of energy storage systems that may partly limit the ability to change the energy supply system in general. Therefore, only those storage systems that are modular and scalable should be considered in the further discussion. Such storage systems can be used close to production. The storage system is universal in the sense of a functional neutrality. This is not aimed at the function of saving, but at the functions resulting from the application of the storage system. For example, there is the functional possibility of using the storage system for load balancing, bridging short-term interruptions or marketing as a flexible load on the energy market. In addition, electricity storage can be classified universally by the versatile uses of electricity.

2.4. Agility enablers in the context of agility drivers

For a preselection of the right agility enabler, these have to be set against the agility drivers. In this case, the agility property serves as a link. In order to do so, the agility enablers were assessed in terms of their support for the agility properties of mobility, modularity, compatibility, universality, and scalability, based on the assessment of the agility of assembly systems [16]. The effects of the agility drivers are influenced by the same agility properties. If the valuations are combined in the final analysis, then an evaluation of the agility enabler results from the perspective of the agility drivers.
drivers. Figure 2 illustrates the approach for the PV system with respect to the response to the driver of the declining energy demand in production. The PV system would have a weighting value of 14. A CHP would have a higher value due to the possibility of a mobile solution and better scalability as well as higher universality. Thus, the CHP plant would be better suited to respond to the agility driver. This evaluation approach can be applied to new technologies, e.g. the use of a chemical looping energy demand system (CLES).

<table>
<thead>
<tr>
<th>Agility property by the agility enabler</th>
<th>Approaching</th>
<th>Achieving</th>
<th>Achievement</th>
<th>Degree of influence of the agility driver through agility properties [0.2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>photovoltaic system</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>2 declining energy demand in production</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>modularity</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mobility</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>scalability</td>
</tr>
</tbody>
</table>

\[ \Sigma 14 \]

Fig. 2. Agility enabler weighted by the agility driver.

The agility enablers can be evaluated for their versatility of agility properties. A coupled onsite energy generation, power-to-x systems as well as production-related power storage systems have the highest degree of agility. Other technical solutions have only individual agility strengths.

Agility drivers can be identified by workshops with experts of the individual manufacturing company as well as studies on energy supply megatrends [17]. Complemented by the company-specific weighting and concretization of the agility drivers, the planner can work out the agility enablers who are most effective for the company.

In addition, it is important for the planning process to not only know the target-oriented agility enablers, but also to analyze their influence on production over the course of time as part of an initial assessment.

3. Monte Carlo-based multivariate linear regression

Simulation is a suitable method for analyzing the dynamic interactions between the agility enablers, the production and the energy supply system. Jeon and Shin already apply the Monte Carlo simulation on a System Dynamics model for the technology assessment of PV plants [18]. They rate the combination of System Dynamics with Monte Carlo simulation as the most suitable method for analyzing dynamic and complex models, taking into account uncertainty. Wangdee and Billinton use the Monte Carlo simulation to analyze the availability of power distribution networks [19]. In addition to considering uncertainties in the analysis, they emphasize the possibility of being able to specify the probability distribution of the target variables.

In the generated model, the production is modeled in the form of individual energy exchanging agents. The energy pool, which connects all these agents, contains the energy storages and ensures the balance between external energy supply, the onsite energy generation as well as the energy demand of the production and energy transformation processes. Onsite energy generation, divided into volatile and controllable generation, as well as energy transformations are connected to the energy pool (Fig. 3).

The simulation model is implemented on an agent-based basis to analyze the benefits of the agility enablers as a function of their severity and thus to assess the benefits of adaptable structures as a possibility for agility [7]. The agents that build up the energy supply system are adapted in their behavior to the company-specific requirements by means of parameters and control algorithms. Control algorithms are, for example, the basic load distribution between different energy stores.

During modeling of the energy supply system, the parameters that are subject to change by agility drivers and enablers and thus influence the supply system must be identified. Cause chains aid in the identification of these parameters. Doing so, based on the evaluation target, the influencing chain is built backwards (Fig. 4).

If a parameter is identified as an agility-influencing property, then this is included in the scenario description vector. Examples of such parameters are the development of the energy efficiency of production processes through technological advances, different characteristic energy demand profiles of production machines caused by technological or strategic development, the change in price.
dynamics or the increasing energy supply for electro mobility. The characteristics of these parameters are estimated in their time course. It is important to include not only the expected value, but also the variance and the minimum and maximum value of the expression. If there is no indication of a specific distribution, the triangular distribution is to be assumed. In a simple way, this forms the possibility of both specifying the limits of the characteristic expression and specifying an expected value. The comparison of results of a triangular or logarithmic normal distribution shows that the regression coefficients vary slightly in terms of their values. Their relative importance and the positive or negative influence on the target size is independent of the distribution. The same applies to the use of correlating and non-correlating parameters [20].

At point of time \( t_u \) at which the parameter development changes significantly - a so-called agility milestone - simulation studies for agility are to be carried out and evaluated in accordance with the procedural model. Due to the complexity of the interaction of the different agents, the partially stochastic influences and the nonlinearity of the decisions, it is not possible to work out the functional relationship analytically as a closed expression. To estimate the functional relationship of the target value to the output values, the multivariate linear regression is applied [21].

3.1. Collection of scenario data using Monte Carlo simulation

A Monte Carlo simulation provides the database for the regression analysis [18]. Stochastic influences, resulting of the simulation in a previously defined range of characteristics, are recorded. In order to be able to derive a functional relationship between agility enablers, future scenarios and the objective function over the entire possible parameter range, a large number of simulation experiments are required. In order to ensure the applicability of the method in the planning process a shortened computing time is necessary and thus, the number of simulation experiments has to be reduced. First of all, quasi random numbers are used from the Sobol sequence. The second step of reducing the amount of simulation experiments has to be concentrated on times of agility milestones (Fig. 5).

3.2. Multivariate linear regression

The regression analysis is used to analyze the statistical relationship between a dependent variable and an independent variable. The most important model is linear regression. The target size \( y \) can be described as the sum of the parameter \( \beta \) weighted explanatory variables \( X \) and the error \( \varepsilon \) \( (1) \) [21].

\[
y = X\beta + \varepsilon
\]

The parameters \( \beta \) are estimated upon knowledge of a set of data points. The resulting error in the form of the deviation of the estimate of \( y \) from the actual \( y \) of the data point is attempted to be small. The method usually used is calculation of the least squares (LS). This method proves to be efficient because the LS estimator has the smallest variance.

If the data from the Monte Carlo simulations is available at different times, the cost function can be generated using the configurable characteristics of the technical system. The planning restrictions, which under certain circumstances lead to a lower limit of the technical design, must be taken into account. Comparison of the cost functions at different analysis times shows the effects of a possibly changing nature of the agility drivers as well as the options to react on these changes with the help of the agility enablers. If this cost difference is greater than the measures for conversion capability, then an investment, for example in a more flexible infrastructure, would be worthwhile.

4. Case study

A plastics processing company operates 20 injection molding machines to manufacture their products. Today, refrigeration compressors and free coolers are used to cool the tools. The company wants to know how far the cooling system can be converted to a combination of adsorption chiller with CHP. In order to prevent a bottleneck in cooling process, an additional refrigeration compressor has been added in the model. This compressor starts when the chillers and the storage are not providing sufficient cooling. In this context, it must be examined to what extent such an investment in CHP and chiller makes sense even under changing environmental conditions. At the beginning, the model was created and parameterized with the cooling and power requirements of the injection molding machines. In a first simulation study, the effect of system sizing on the expected energy costs for electricity and gas was investigated. Table 1 shows the results of this study and compares the correlation today with the estimated correlation in future after taking the agility drivers into account.

The regression coefficients indicate the dependence of the variable to be explained (the energy costs) and the influencing
variables. A negative value indicates an opposing trend. The p-value indicates the probability that the null hypothesis (regression coefficient = 0) would be correct [22]. A small p-value (less than 0.05) proves a clear significance of the influence on the variable to be explained. Thus, these independent variables are to be preferred in explaining the influence. The coefficient of determination R² indicates the quality of the regression. The coefficient of determination can be between 0 (no correlation) and 1 (complete functional quality of the regression). The coefficient of determination can only slightly vary.

The result of the simulation runs point out that a cluster of smaller CHPs has a decisive influence on energy costs nowadays due to its performance flexibility. Small individual CHPs combined in a cluster should be preferred. The same correlation applies to chillers whose influence on costs is significantly lower. The intermediate storages for heat and cold have no significant influence, so they must fit in their dimensioning to the overall system. The capacity of the cold storage moves in the middle level in the simulation runs with the lowest overall energy costs. The capacity of the heat storage is very different.

During a workshop, the agility drivers - mainly the increase in the price of fossil energy, the flexibilization and dynamization of electricity prices - were identified and forecasted accordingly in their future development. At the same time, effects of energy efficiency enhancement were considered. Again, simulation runs were performed. The multivariate regression showed that the influence of the average power of the CHPs and chillers has increased. The development of the relations of the coefficients of the agility drivers with a low p-value (W1 - W4) show the technology agility strategy. While W1, W2 and W4 coefficients are increasing, the W3 coefficient is decreasing. An increasing value above 1 (base value of today’s cost impact) leads to a disinvestment strategy or otherwise this leads to higher operating costs in the future scenario. A decreasing value below -1 points out an area of future development. A value between 1 and -1 indicates a reduction in the importance of the agility driver to the cost target variable (Fig. 6).

Table 1. Result of the multivariate regression today and in a future state.

<table>
<thead>
<tr>
<th>independent variables</th>
<th>regression coefficient today</th>
<th>p-value</th>
<th>regression coefficient future</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1: number of CHPs</td>
<td>22.59</td>
<td>1.16E-13</td>
<td>148.62</td>
<td>6.01E-22</td>
</tr>
<tr>
<td>W2: average heat power per CHP [kW]</td>
<td>7.41</td>
<td>1.02E-305</td>
<td>36.12</td>
<td>5.51E-280</td>
</tr>
<tr>
<td>W3: number of chillers</td>
<td>-7.06</td>
<td>0.0222</td>
<td>-14.29</td>
<td>0.346</td>
</tr>
<tr>
<td>W4: average cooling power per chiller [kW]</td>
<td>4.49</td>
<td>1.97E-65</td>
<td>18.19</td>
<td>2.15E-45</td>
</tr>
<tr>
<td>W5: heat storage capacity [kWh]</td>
<td>5.17E-02</td>
<td>0.571</td>
<td>-0.68</td>
<td>0.135</td>
</tr>
<tr>
<td>W6: cool storage capacity [kWh]</td>
<td>-1.77E-02</td>
<td>0.946</td>
<td>-0.69</td>
<td>0.596</td>
</tr>
<tr>
<td>X1: stretching power curve (electricity)</td>
<td>733.84</td>
<td>9.154E-24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X2: Increase performance price (electricity)</td>
<td>-37.08</td>
<td>0.605</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X3: increase efficiency (electricity)</td>
<td>-4642.99</td>
<td>7.26E-27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X4: expectation of short-term interruption</td>
<td>6.78</td>
<td>0.842</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X5: Ratio price gas to electricity per kWh</td>
<td>4949.17</td>
<td>4.33E-113</td>
<td></td>
<td></td>
</tr>
<tr>
<td>coefficient of determination R²</td>
<td>0.831</td>
<td>0.816</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The independence of the variables in the model is given by the derivation of the cause chains, which are used to identify the variables. Nevertheless, the variables cannot assume any value. They are subject to the technical restrictions in the model. For example, a defined, minimum heating power is necessary. This can be split into any number of CHPs. An increase in overall heating performance is also possible to analyze the effects of peak loads in conjunction with the storage. In addition, it was shown in [20] that even with correlating and therefore non-independent values, the regression coefficients only slightly vary.

In this case study, this means, that the number of CHPs and the average heat power of these CHPs should be lowered in the future. Or in other words, in a cluster with different sized CHPs today, the strongest ones should be removed first. The same applies for the average power of the coolers. But the number of coolers should be raised. This means an overall decrease of the cooling power but an increase of flexibility in the cooling power.

Under the given margins, the simulation runs with the lowest energy costs derive to today’s favorable technical system configuration consisting of 8 CHPs with a capacity of 34 kW each and 9 chillers with a capacity of 18 kW each. In addition, there is a heat storage of 175 kWh and a cold storage with 57 kWh. This system configuration would mean, under the influence of change, possible additional energy costs of about 40 %. An increase in the price of gas in relation to the
price of electricity will increase the cost of the CHP relative to an electric refrigeration compressor. The strategy for the company should be a system of several small plants that can not only be operated flexibly but also be reduced in line with environmental development. In addition, there is a need to change the energy source for cooling from heat or gas to electricity.

In this example, only the impact on energy costs was considered. For a profitability analysis, further costs have to be considered. In addition to the investment costs, these costs also include the operating costs beside the energy costs, conversion costs of the energy system and sales proceeds for not anymore needed systems. For this, it is necessary to transfer the identified, meaningful scenarios into a development path. The results of the simulation assist in the selection of the meaningful scenarios and the definition of the development paths. In addition, the simulation estimates the energy costs and thus the part of the operating costs that is significant for the energy system and thus provides decision support. Other risks, such as production disruptions due to an insure energy supply, can also be estimated using the model and included in the calculation.

5. Conclusion

In summary, the presented method allows the assessment of agility measures relating to the planning of production energy systems. To this end, the most important agility drivers and relevant agility enablers are identified. In an agent-based simulation model, the mutual influences can be examined. They form the basis for the multivariate linear regression analysis. An example has shown that the change in the refrigerator system can achieve significant cost savings in the future. Another analysis, examining the effects of a battery storage system considering an increase in electro mobility [23], formulates a strategy for a company’s storage expansion. In that case, the company should first increase the stationary storage. With increasing electro mobility, it makes sense to reduce the storage capacity. With increasing dynamization of electricity prices, however, the storage should be expanded again. These studies show, on the one hand, the need for a study of the agility of the energy system against the background of a turbulent development of the energy market. On the other hand, the examples show that the presented method offers a possible approach for assessing different technological scenarios and thus supports strategic planning.

The limits of the agile energy supply lie in the costs of providing agility as well as in the still slow changes in the field of energy. An agile design is subject only to the energy system components, which can be assumed to be used much longer. Short product and technology life cycles increase the dynamics in the energy system. With regard to the costs, it is necessary to estimate the additional costs which result from an agile design. These costs must be compared with the possible benefits, especially energy cost savings and savings of production loss due to energy disruption.

References