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Integration and Interaction of Energy Flexible Manufacturing Systems within a Smart Grid

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Abstract

The need for clean, safe and inexpensive energy provision is driving many countries in the transition towards renewable energies. Due to the characteristics of solar and wind power, a volatile energy provision and therefore an increasing instability of the grid can be observed. Hence, a fast and efficient communication and interaction of energy providers and energy consumers within the grid is necessary. Manufacturing companies can enable the efficient integration of renewable energies to the grid and can additionally gain a competitive advantage through the concept of energy-flexibility. This paper presents findings of the future interaction of factories and an approach for integrating manufacturing systems into a smart grid environment.

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Keywords: energy efficiency; energy-flexibility; manufacturing systems; production planning and control

1. Motivation

In December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) agreed on a global climate agenda, in order to limit the global warming due to manmade green-house-gas emissions [1]. Therefore, an annual decrease by 1.9 % of energy related CO_2 emissions between 2013 and 2040 is strived for, so as to reach the set 2 degrees Celsius agreement. Besides efforts to use energy efficiently, the goal is to steadily substitute fossil fuels by increasing the share of renewable energies to 30 % [2]. This forces economies worldwide to change their current energy supply towards a higher share of renewable and CO_2 neutral energies within their energy system. As an example, Germany is shifting the public electricity supply strongly towards a sustainable energy provision, and at the same time opts out of nuclear power generation [3]. By the year 2050, Germany aims at an 80 % share of renewable energy source in the country's electricity generation, mostly using solar and wind power plants [4]. Due to the volatile provision of these energy sources, the German power grid is facing an imbalance of electric demand and supply and is becoming increasingly instable [5]. This results in rising power grid infrastructure costs [6], redispatching efforts [7] and a need for demand response alternatives, in order to control these imbalances [8]. In the past, the power distribution by the grid can be described as unidirectional [9]. Therefore, imbalances were stabilized by the power suppliers. As the supply side is currently facing the volatile electric feed in, bidirectional approaches, e.g. demand response, are needed in a so called smart grid environment [10].

Besides households and commercial consumers, the industry can contribute significantly to the effectiveness and elasticity of demand response by adapting its electricity demand towards the gird [8]. This concept is defined as energy-flexibility, which describes the ability of a manufacturing company and its manufacturing systems to adapt the production to short-term changes in the energy provision with as little loss in time, effort, costs and performance as possible [11, 12]. In order to realize these load adaptions, manufacturing systems need to be integrated into a smart grid with a short-term communication approach.

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Thereby, manual or automated changes in the load profile can be performed between the grid and the production within an immediate timeframe. Thus, energy-flexibility in production has the potential to contribute to the power system's stability. Currently, the German energy system is facing an organizational change, called energy-market 2.0, which will impact future market designs and regulation [13]. The importance of demand-response is clearly expressed, but the conditions and implementation is still not defined. Therefore, this paper presents findings from expert panels how energy-flexible manufacturing systems can be integrated to a smart grid approach and how a possible interaction can be technically realized.

2. Integration of energy-flexible manufacturing systems

2.1. Current situation in Germany

The possibilities of a factory to provide energy-flexibility to the grid can be divided into long-term and short-term markets [14]. For the increasing demand-response-applications, short-term markets are focused. In Germany, these markets consist currently of a *Spot Market* and a *Control Power Market*. The Spot Market is divided into a *day-ahead market* and an *intraday market*, where electric demands can be traded one day before or during the day on a public exchange. Therefore, the load adaption can be made shortly before the physical energy provision. The Control Power Market is an auction-based system, which aims to balance the power grid whenever an imbalance occurs. Therefore, the request for flexible loads is unknown and uncertain for the company and is requested during the production process. At the moment, the market structure and regulation design in Germany is not sufficiently adapted to the consumers' flexibility potentials that are already available or yet to be developed. This is the reason why the consumers' participation that could be beneficial for the system is limited by hindrances and market entry barriers at present [15]. Main obstacles for manufacturing companies are the requested high loads, the fixed bidding and holding periods as well as the limited reimbursement potential [16]. To ensure that industrial companies are able to offer and market their loads appropriately, such hindrances, e.g. distorted price signals on the Spot Market, need to be reduced. Furthermore, market entry barriers that are caused by the design of tender procedures need to be revised [16, 17]. As the regulation and demand response market are in an undergoing change process, expert groups were surveyed in order to gain knowledge about future developments.

2.2. Expert groups surveys about future electricity market developments in Germany

In 2015, two expert groups were surveyed about the future developments of the German electricity market with the focus on industrial demand response. The first group consisted of production companies, which were interviewed and surveyed in collaborative workshops alongside the joint research project FOREnergy [16]. The second group consisted of pre-selected German market experts and was surveyed in individual in-depth interviews. The scope of the interviews contained the current and future power grid situation in Germany in general as well as for industrial companies. Table 1 summarizes the two surveyed groups.

Table 1: Surveyed expert groups in Germany

Group	n	Sectors	Method
Production experts	8	Chemical, metal production, metal processing, mechanical engineering, electronics, food processing	Research Workshops
Market experts	9	Government, research, consulting, association, utility	Selective Interviews

The production expert group generated insights about their capabilities to provide energy-flexibility to the power grid. The market expert group was surveyed about the future developments in order to market the flexible industrial loads to the grid.

2.3. Production group survey: Assessment of possible market options

In two consecutive workshops the production companies evaluated the options to provide their flexible loads to the *Spot Market* as well as to the *Control Power Market*. In collaboration with utility companies and research institutes, the results were summarized in advantages and disadvantages [16].

2.3.1. Integration in the Spot Market

The Spot Market is an attractive option for manufacturing companies to adapt themselves to a given energy market situation [16]. The crucial factor is the signaling effect of the electricity price and the related individual opportunity costs of each consumer. As a result, there are additional revenue potentials for the consumers if they adapt their demand temporarily and voluntarily. Therefore, companies need a direct access to the Spot Market or an indirect participation option, e.g. via a utility company through real time pricing contracts (RTP) [16]. The group stated three advantages of the Spot Market integration. Table 2 summarizes the results of the workshops.

Table 2: Results of the Spot Market and RTP assessment

Spot / RTP	Advantages	Disadvantages
	- Leveraging low and negative prices - Integration in production planning and control - Plannability of costs	- Price risk - Collision with load-maximum agreement

At first, low and negative prices are accessible for the production and can be transformed into value creation. Secondly, the integration in conventional planning and control process is possible, because the adaption is made before the energy provision and the start of production. As a result, the plannability of the energy costs is seen as an advantage. On the other hand, two disadvantages can be observed. The price risk is transferred from the utility company to the production company, compared to a Time-of-Use model with an annual fixed energy price. In addition, flexible consumption is not in line with load maximum agreements between the grid operator and the company, which can lead to penalty payments.

2.3.2. Integration in Control Power Market

Participating in Control Power mechanisms is as well attractive for manufacturing companies as the Spot Market or RTP option. Especially negative control power, where excess energy is provided at no cost or even for a reimbursement, can be transformed into additional value creation within manufacturing processes [16]. Another advantage is the possibility of an automated control of an energy-flexible manufacturing system by the grid operator or utility company, in order to shorten activation times. Within the workshops, the companies stated that continuous processes, e.g. oven-processes, are eligible for this automated control, if the quality of the product is not influenced. Discontinuous processes, e.g. assembly systems, are complex to control in a short time period and therefore a disadvantage in an immediate load adaption scenario. Therefore, the application in a Control Power Market is described as challenging, because of the set activation and holding times. The activation time describes the time span between the request from the grid and the realization of the manufacturing system, e.g. 15 minutes in the tertiary control market. The holding time describes the time span the load adaption needs to be executed, e.g. between 1 minute and 4 hours in the tertiary control market [16]. As both activation and holding time are not known, the energy amount, costs and benefits of a participation in the Control Power Market are not plannable. Table 3 provides an overview of the workshop results.

Table 3: Results of the Control Power Market assessment

Control Power	Advantages	Disadvantages
	- Automatic control continuous process possible - Transforming excess energy in value creation	- Manual control for discontinuous processes - Set activation times - Holding times - No plannability

2.4. Market expert group survey: Future market development in Germany

Besides the workshops with the production experts, pre-selected energy market experts were interviewed. In addition to general questions about the changing energy market, the experts were exposed to questions about the future development of industrial demand response in Germany. Therefore, three hypotheses were formulated and follow up questions defined. Table 4 shows the results of the hypotheses.

Table 4: Hypotheses of the future application of energy-flexibility in Germany

Hypothesis	Description	n (N:9)
1	Energy-flexibility will be provided exclusively to the Spot Market	0
2	Energy-flexibility will be provided exclusively to the Control Power Market	0
3	Energy-flexibility will be provided to both markets	9

When asked about the future application of energy-flexibility, all respondents unanimously opted for a mixed version, meaning the future marketing will take place on both the Spot Market and the Control Power Market. The next questions asked about the share between the two market options. The experts had to choose on a scale of 1 to 5. 1 representing a full market share of the Spot Market and 5 a full market share of the Control Power Market. Figure 1 illustrates the experts' answers on the future market shares of the Spot Market and the operating reserve electricity market

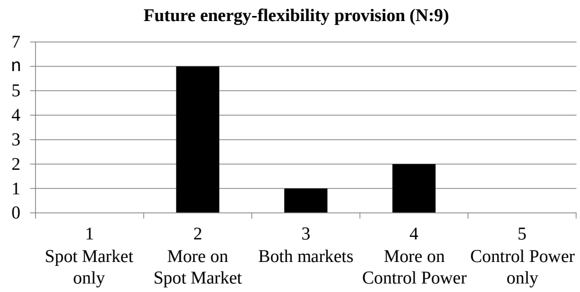

Figure 1: Result of the expert assessment about the future application of energy-flexibility

According to the experts, energy-flexibility is currently provided to a large extent to the Control Power Market. This is due to the insufficient price signals on the Spot Market. The experts assume that in five to ten years the Spot Market will show price signals that make marketing on the Spot Market more attractive and profitable than on the Control Power Market. As a consequence, an equal division on both markets in five years, with a continuously growing share of the Spot Market, is expected. This tendency is also predicted by the experts' answers on the advantages and disadvantages of both markets. Although at first the Control Power Market seems more attractive because of a basic reimbursement, it comes with the prequalification and related higher requirements, resulting in extra efforts and additional costs compared to participating on the Spot Market. Furthermore, market participants are able to offer their services individually and short-term because they can choose their offer period as well as the delivery duration based on their own needs. On the other hand, marketing on the Spot Market does not draw significant profits at the present. Moreover, the potential of flexible production loads cannot be provided for a longer time in the majority of cases. Market participants will face the same problem on the Control Power Market as well, since participants commit themselves to long-term offers here. Eventually, the experts conclude, that companies should prefer the marketing on the Spot Market as soon as there are acceptably higher prices spreads. Figure 2 shows this trend as a qualitative illustration.

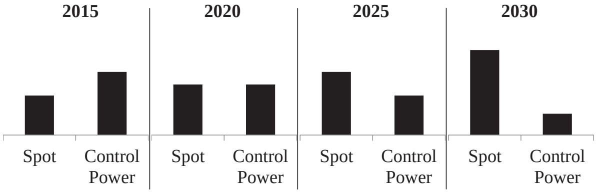

Figure 2: Qualitative illustration of market shift of future energy-flexibility application according to the experts' expectations

In the interviews, several experts attached the expected higher price signals to the increasing share of renewable energies and the shutdown of conventional base load capacities as a consequence thereof. Because of this, there can be temporal shortages on the electricity market, resulting in higher electricity prices. This will make the energy-flexibility marketing more attractive. Some experts see the chance for establishing a whole new market on a regional level. Such a new market would be particularly reasonable in terms of redispatching if there is a focus on the topic of dealing with shortages caused by the increasing German energy generation north-south gap and the linked danger of system instability.

3. Interaction of energy-flexible manufacturing systems with a Smart-Grid

3.1. Evaluation and implementation in production planning and control

Most manufacturing companies know little about the available measures for shifting electrical loads. Hence, not all potentials are used for adapting the load profile. In addition, the companies' decision-makers cannot evaluate investments leading to a higher grade of flexibility. Lacking a data basis, there is no benchmarking in cooperation with other enterprises. Due to these reasons, a documentation and evaluation of potentials for energy-flexibility needs to be performed. These records should be kept in a way that allows the production planning and control to use them for production [18]. Figure 3 shows an approach including the identification, categorization and evaluation of the technical potentials and of the costs for each measure. Following the evaluation, the production planning and control is provided with a catalog of measures that can be integrated into the sequences of planning and control.

The first step of a potential analysis for energy-flexibility in manufacturing systems is a method of identifying and analyzing measures of changing the performance within defined operational states in a positive or a negative manner. The results of this step are potential measures, which are then categorized and evaluated with regard to their economic efficiency and sent to the production planning and control (PPC) as a catalog of measures. In addition, state changes' effects on the building services in order to identify possible additional performance variations, such as shutting down the air conditioning, can be added to this catalog. After identifying and categorizing each of the measures, the production planning and control collects the relevant data [14]. Developing such an evaluated catalog of measures aims at providing the production planning and control with the data required for realizing the flexibility potentials. The economic tradeoff of a load adaption depends on the current price signal on the various markets that are to be included into the production planning and control. By means of system-specific functions regarding the revenues and the costs, the production planning and control can calculate the optimum duration of a certain measure as well as its beginning and end. The result is an energy-orientated production plan and control strategies in the production process.

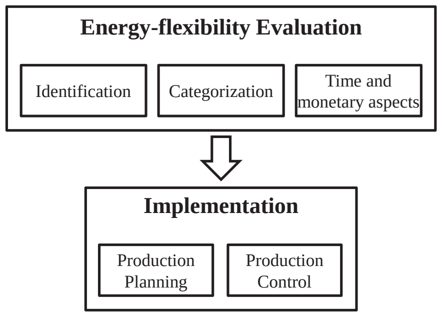

Figure 3: Evaluation and implementation of energy-flexibility in manufacturing companies

Figure 4 shows how production planning and control act on different time scales with regard to the energy markets. Incorporating long-term markets into the planning process, the capacity planning can find an economic balance between the production plan and energy prices. This plan can be detailed further within the scheduling process to synchronize energy supply and energy demand due to manufacturing. Subsequently, the production control ensures the execution of this detailed production plan. If deviations from this plan arise during the manufacturing process, e.g. delays, breakdowns or even demand response events, the production control will implement short-term load management measures.

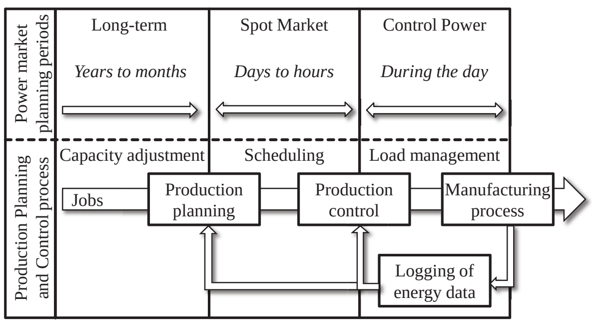

Figure 4: Planning periods of an energy-orientated production planning and control

3.2. Communication approach between a Smart-Grid and manufacturing systems

In order to utilize the aforementioned strategy for energy-orientated PPC, the communication loop with facilities on the shop floor has to be closed. Since measures for load shifting are dependent on the operating states of machines and their components as well as on their energy consumption, this data should be monitored continuously and communicated to the production planning and control level.
As shown in Figure 5, one efficient way to gather the required data is to upgrade a machine's programmable logic controller (PLC), which serves as the pivotal data node for this machine. Modern PLCs, which are connected with each component of the machine, include or can be expanded by measuring terminals. Thereby, the energy consumption and component states can be logged continuously. As part of a low-level controller within the PLC, this data can be monitored to identify load peaks and to implement counter-measures instantaneously.

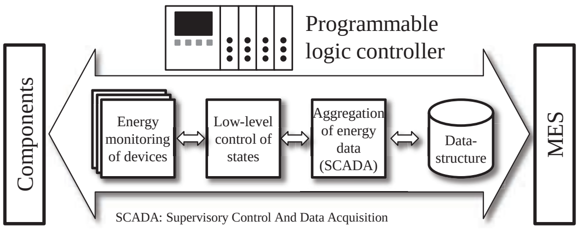

Figure 5: Architecture of an interface for energy monitoring and management on the shop floor

Furthermore, the energy data of all components can be aggregated, e.g. using SCADA, and converted to a data structured, which can be communicated to a supervisory Manufacturing Execution System (MES). For modern IT systems, OPC UA is a very suitable protocol to handle this machine to machine (M2M) communication since it is non-proprietary, scalable, object-oriented and shows good performance in regard to the transfer rate.

However, the communication via OPC UA between PLC and MES is not conceived as unidirectional. The MES, which is the preferred software system to implement a high-level production control, can use this interface to send commands related to energy consumption to the machines. For example, such a command might be that a single machine should decrease or increase its energy consumption by switching to a different operating state for a period of time. This command then serves as an input for the low-level control within the PLC operating the various components. On the power grid level, OPC-UA is as well discussed for a possible M2M protocol [10]. This development may result in a standardized communication from the power gird to the manufacturing systems.

In order to clarify how the interaction of planning, control and PLC work within energy-orientated PPC, Figure 6 describes the consecutive tasks performed on these levels using load management as an example. The procedure for production planning acts according to price or control power signals, e.g. via OPC-UA, which are received from the energy supplier. Following the detailed scheduling of orders, an energy schedule can be calculated, which specifies total consumption thresholds for each measuring interval, e.g. 15 minutes the standard German peak load interval. At the beginning of each interval, the production control starts to read out the consumption data continuously monitored by the PLC. Using this data, the production control calculates a forecast for the remaining part of the 15 min interval. If the forecast predicts an exceedance of the threshold set by production planning, a command is send to the PLC of a machine to adapt energy consumption, e.g. by reducing the power demand. The reduction is then executed by the low-level controller by switching operating states of single components, e.g. switching off of a hydraulic pump or

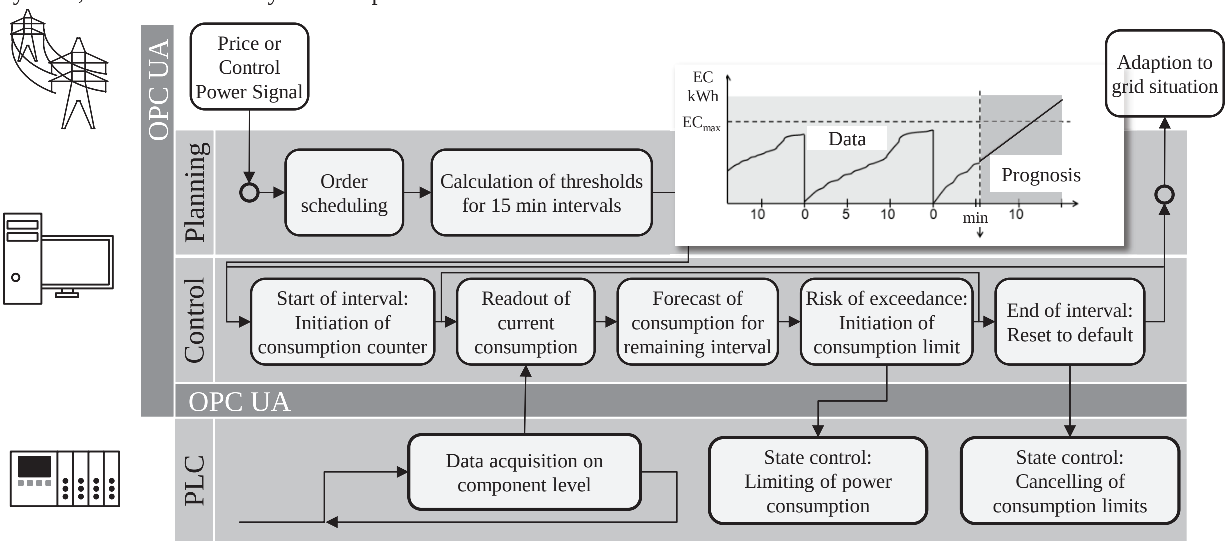

Figure 6: Exemplary procedure for load management within an energy-orientated PPC

reducing feed rate. The production control runs through this process until the end of the 15 min interval is reached. By that time, all states may be reset to their default value and the next interval begins possibly with a different threshold, which is set to the information of the power supplier. Therefore, a planned and controlled load adaption of a factory can be realized, according to the current situation in the energy grid.

4. Summary and Prospects

The rising energy prices and the increasing need for demand response measures are the reason for companies to introduce the concept of energy-flexibility in production. Besides saving energy costs, a flexible energy consumption of the industry is a promising lever to integrate renewable energies efficiently to the power grid by avoiding cost intensive energy storage systems or grid development projects. Therefore, this paper assesses future developments how to integrate energy-flexibility to a smart grid. Therefore, expert panels were surveyed and the aggregated results presented. In addition, a communication approach was introduced, which links market signals via planning and control systems to the machines.

The provided findings present, how industrial companies are interacting with the different energy markets. In addition the different market options were evaluated and a future energy-flexibility application estimated. Using the generated results from industrial companies in Germany, the authors derived an approach to integrate the different market options into the PPC process. Main objective is to include and handle power market and grid signals within the PPC in order to enable energy-flexibility through an organizational approach, e.g. by adapted job scheduling and adjustable load management. In order to increase the industrial demand response potential, benefits for the industry need to be implemented to the market options, e.g. higher price signals in the Spot Market or shorter holding times in the Control Power Market.

The interaction with a smart grid requires new communication approaches between utility companies, the grid operator and the company. Standardized concepts and protocols, e.g. OPC-UA, yet need to be developed. Within the factory, planning and control systems can realize load adaptions from the internal company grid level to the machines. The identification and evaluation of flexible loads need to be performed, in order to access more energy-flexible potential and therefore increase the demand response elasticity. In the future, further developments in market design and regulation will strongly influence the economic feasibility and thereby the technical exploitation of more energy-flexible potentials in the German industry.

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