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An optimization-based approach for the planning of energy flexible production processes with integrated energy storage scheduling

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Abstract

Due to the fluctuating energy supply of renewable energy systems, electricity prices on the markets are becoming increasingly volatile. This offers manufacturers opportunities to reduce costs by adapting production processes to the energy supply. So-called energy flexible factories are thus a decisive competitive factor and at the same time a solution component for a successful energy turnaround. The implementation of energy flexible factories requires energy-oriented production planning that makes appropriate use of flexibility measures. Energy storage systems supplement companies' flexibility options. In order to be able to use them cost-optimally, interactions with flexible production processes must be taken into account and planned. This paper introduces an optimization-based approach for the integrated planning of flexible production processes and battery storage scheduling.

Keywords: energy flexibility; production planning; cost-efficient scheduling; battery storage; sustainable manufacturing

1. Motivation

In order to achieve the climate goals of the Paris Agreement from 2015 [1], the Federal Government of Germany submitted a climate protection plan in 2016. It describes targets for various sectors in order to be largely greenhouse gas-neutral in Germany by the year 2050. Of central importance is the energy sector, with a planned reduction of 358 tons of CO_2 equivalents in 2014 to a maximum of 183 tons of CO_2 equivalents by 2030. [2]. To achieve that, the so-called brown coal commission has recently issued a recommendation for phasing out lignite-fired power generation by 2038 [3]. These power plants are mainly replaced by wind turbines and photovoltaic systems, which use sustainable primary energy, but lead to weather-dependent feed-in fluctuations [4]. Demand side management (DSM) offers a high potential for balancing the electricity consumption with the volatile electricity generation by renewable energy sources. DSM originally consists of several activities to influence customers' use of electricity [5]. With 47 percent of Germany's annual energy demand, industry presents a relevant element to equalize energy production and energy consumption [6]. Various current studies investigate how the energy consumption of production processes and production infrastructure can be adapted to a fluctuating energy supply [7–10]. Essential measures can be subdivided into categories, such as the shift of process starts, changes in machine occupancy and the use of battery storage [11]. Energy-oriented production planning is necessary to implement these measures. Here it is important to consider relocatable orders and the use of available storage capacity in order to achieve the cost-optimal plan. This contribution presents an approach to schedule both flexible loads and energy storage. Section 2 will introduce energy-oriented production planning and applicable battery storage systems. Section 3 presents the state of research. The approach is introduced and applied in section 4, followed by a summary and an outlook in Section 5.

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2. Energy storages in energy-oriented production planning

2.1. Energy-oriented production planning

Production planning can be described as the coordination of production orders within certain planning horizons. It performs lot size planning, capacity planning and scheduling tasks. The result is released to the production control, which executes the production processes according to the plan [12].

On the one hand, the target parameters of production planning include high delivery reliability and short delivery time. On the other hand, there is the financial aim to lower production costs and capital commitment costs [13]. According to costs, energy efficiency has been the subject of production research for several years [14]. Energy flexibility is gaining in importance as part of the energy transition and as a possibility for energy cost reduction for companies by taking advantage of fluctuating electricity prices [15].

Due to the high complexity of planning problems and the new cost aspects caused by the importance of the resource energy, simulations or mathematical optimizations should be used to support the production planning tasks [16]. Optimizations based on the classic cost, time and quality objective of production are common. Short, medium and long-term planning can be distinguished [17]. The adjustment of consumption to price signals of the day-ahead market requires planning within the day before, as the electricity products are traded one day before delivery [18]. With this timeframe, the planning tasks with day-ahead market prices as the input size belong to operational production planning [17, 19].

2.2. Energy storage use in manufacturing companies

Energy storage technologies can be classified by the physical form of stored energy. Electrical storages are suitable for storing energy on short notice by means of coils or capacitors. Mechanical systems store energy in the form of potential or kinetic energy. Electrochemical storage, as a subgroup of chemical storage, holds the energy in the form of chemical compounds. This includes the widely used lithium-ion batteries [20]. Energy storage systems offer solutions to the problem of the integration of fluctuating energy sources. For example, they can be used to stabilize energy grids in peak hours or to store the surplus production of photovoltaic systems in households [21].

Energy storages are also applied in the industrial sector. A study by the German Chamber of Commerce and Industry [22] determined that in 2018 nearly 20 percent of German industrial companies used energy storage or planned to purchase it. The study also notes that 43 percent of companies have planned or already implemented measures in the field of electromobility. The use of electric vehicle storage within a company's charging infrastructure has been tested in several case studies as an alternative or supplement to stationary battery storage [23, 24]. According to simulation-based studies, this so-called vehicle-to-factory approach has the potential to support the energy procurement of manufacturing companies [25, 26].

Different fields of storage application exist in the industry. In addition to the technical applications like emergency power supply and uninterruptible power supply, batteries are applied in the field of energy procurement [27]. Industrial companies are able to lower production costs through a reaction to the price signals of the European energy exchanges and the integration of companies' own generation facilities, such as photovoltaic and combined heat and power plants [28]. In addition, the use of electrical energy must consider contractual conditions in order to reduce energy costs. Examples are the reduction in absolute power consumption, the shift of electricity demand from high-tariff to low-tariff periods as well as the increase in the reliability of the electrical load profile to avoid penalties. In addition, revenues can be generated if switchable services are agreed on with suitable contractual partners. On the reserve power markets, targeted load adjustments or even the provision of this potential change in performance can be placed as a product [15].

Due to the required storage time of a few hours, lithium-ion batteries are currently being used in particular. Especially if multiple benefits can be realized, the operation of the storage systems is economical. A typical use case is minimizing peak loads combined with optimizing self-consumption [27].

2.3. Interactions of flexible loads and battery scheduling

The use of energy storage makes it possible to adjust the load profile of a company, without directly affecting production processes. Since certain processes can be influenced with regard to consumption, the planning of these processes should be carried out together with the scheduling of the energy storage in order to achieve a cost-optimal overall. Figure 1 shows an exemplary production plan and battery scheduling. While production processes must include not only energy prices but also logistical target figures, the loading and unloading processes can be used to tailor the total load to specific volatile prices.

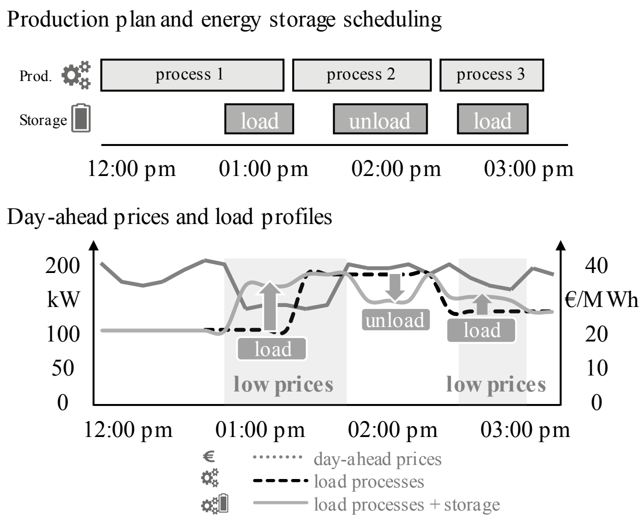

Figure 1: Scheduling of production processes and energy storage according to the day-ahead prices

Hereinafter, relocatable processes refer to energy-flexibility measures. [11] distinguishes energy flexibility measures in the industrial sector in line with the classic flexibility of production according to [29]. In the present approach, the measures "adjustment of process starts" and "interruption of processes" are taken into account. These take place in the context of the scheduling prior to the release to the production control and thus form classic measures of operational production planning.

3. State of research

In the following, the state of research with a focus on the industrial environment will be explained. As flexible loads and energy storage systems are established in grids and households, relevant approaches in these areas are also presented.

3.1. Load shifting and battery scheduling in grids

With the target of minimizing energy costs in micro grids [30, 31] apply mixed-integer linear optimization (MILP) based on predicted loads and decentralized generation. Balancing energy demand and the generation of renewable energy in the local distribution network can reduce the need for grid expansion. For that, energy flexibility options play a decisive role; using DSM especially provides significant cost saving potential.

[32] consider a collective of consumers with a shared renewable energy generation system and an energy storage system. By alternately solving two sub-problems, both the total cost and peak load minimization as well as the consumer decisions of the individuals are met.

A game theory approach is applied by [33], regarding an energy supplier and several households, each with its own photovoltaic (PV) system in combination with battery storage. A Nash Equilibrium provides the optimal energy consumption and storage capacity for every consumer.

[34] describe a quadratic optimization to minimize the energy costs of all participants of a smart grid while avoiding rebound peaks: the emergence of new peaks caused by multiple consumers responding to price signals and thus shifting their schedulable devices to low price periods.

Implementing two metaheuristics within a comparable problem, [35] achieve a reduced peak average ratio (PAR): peak load divided by mean load. Electric appliances are categorized according to their flexibility in use: power-shiftable, time-shiftable or non-shiftable.

3.2. Load shifting and battery scheduling in households

In the field of households, the combination of a photovoltaic system with battery storage to increase self-consumption is often investigated. [36] test mathematically optimized controllers compared to standard controllers. [37] optimize battery control by applying a genetic algorithm. The exemplary simulation of the months January, April, July and October shows savings potential in April and July.

This topic is also discussed by [38], who additionally integrate an electric vehicle into consideration. According to simulation results, a significantly higher energy demand can be covered by the PV system with storage compared to without.

A detailed use analysis of energy storage in households is designed by [39]. Interactions of PV self-generation with stationary and vehicle battery storage are shown, whereas shifting flexible loads is not. The capital value method implemented in MILP allows for implicit battery sizing.

Minimizing electricity procurement costs in residential buildings is also performed by [40]. Flexibilities through energy storage as well as flexible loads are used to avoid buying electricity in periods of high electricity prices.

Volatile self-generation in building energy management is also considered by [41]. A two-stage optimization (medium and short term) is applied. The simulation results for use in a hotel with a PV system and battery storage show cost savings.

[42] present a method for predicting the energy demand for a building planned for construction. Based on this, energy management with battery storage usage and variable electricity prices is simulated. By evaluating the respective profitability, the generated buffer for emergency power supply and space limitations, a suitable storage capacity can be determined.

3.3. Load shifting and battery scheduling in factories

In [27] the use of stationary energy storage as a flexibility option in companies is investigated. Among other things, lithium iron phosphate batteries are evaluated to reduce peak loads in small and medium-sized enterprises. Isolated and considered only for this single application, the investment shows no profitability.

Some approaches utilize simulation algorithms to reduce dependence on the power grid through the energetic flexibilization of production systems. For this purpose, [43] mainly uses indirect energy stores in the form of buffers or warehouses for (intermediate) products, while [44] examines battery storage.

[45] uses sequential planning in the form of MILP to improve productivity and synchronize self-generation and loads of order processing. [46, 47] develop an evolutionary algorithm to lower peak loads as well as the amount of required final energy through the appropriate machine layout planning. These studies also achieve a decrease in emissions by saving on the primary energy demand. Battery storage is not considered.

A concept for short-term, energy-oriented production control with situational load adaptation is designed by [48, 49]. With the aim of synchronizing the production load with volatile self-generation, electrical energy is treated as a limited production capacity. A key part of the program is demand monitoring based on information management.

[18, 50] develop a holistic methodology for energy supply-oriented order planning. MILP generates an exact solution in quantity planning, while after that, heuristic methods are used for order planning and tested in a case study. Energy storage as a flexibility option is not regarded.

To solve a flexible job-shop scheduling problem (FJSP), [51] utilize a non-linear mixed-integer optimization. The sum of energy costs under variable prices is minimized plus the sum of the individual orders' completion time weighted with penalty costs. Controllable generators, PV systems and a stationary energy storage are added in a model extension. The accuracy of the model is limited to an hourly observation; a peak load limitation is not depicted.

In summary, in the area of grids, DSM is discussed in almost all cases, including a time-of-use concept. The interactions between variable electricity prices and the load-shifting potential of consumers are examined with the goal of cost and peak demand minimization. Battery storage is mainly used in households, mostly in combination with a PV system to increase self-consumption. The adequate dimensioning of energy storage systems is rarely determined methodically.

In the area of factories, a main focus is on flexible loads due to the high energy consumption of industrial production processes. Battery storage, however, is rarely considered. The greatest research potential is the combination of both flexible loads as well as energy storage.

4. Approach

4.1. Overview and assumptions

The market prices for the energy supply of manufacturing companies are usually known one day in advance in 15-minute periods (day-ahead market). Likewise, the consumption quantity of the considered company is transmitted to the respective energy producer every 15 minutes. From this, it can be derived that there is a partially discrete problem in determining the energy costs for the optimal use of battery storage in a production system. In order to solve this problem, a "Mixed-Integer Linear Programming"-approach (MILP) is chosen in this contribution that was solved with the Branch-and-Bound function in Matlab. This method is a flexible technique that provides an accurate solution to many problems in the field of production engineering.

The simulation shall be used as an evaluation of the optimization as shown in [52]. For this purpose, the simulation model from [26] is modified in such a way that instead of the stochastic storage capacity by electric vehicles, a stationary battery is depicted. This should validate the limitations of modeling the battery within the optimization model and other assumptions made.

According to [53], three types of battery models exist: multidimensional physical-chemical, electrical spare circuit and mathematical black box models. Accuracy and complexity decrease in the order given. For operational planning, technical details can be neglected, and a black box model is sufficient. Thus, in the optimization, charging and discharging are supposed to be linear processes. Furthermore, the amount of stored energy at the start and at the end shall be the same. Inspired by the categorization in [35], a power-shiftable and a time-shiftable production process are considered.

With regard to the power-shiftable process, it is assumed that there is a sufficiently large stock so that its daily energy consumption can be planned freely within 24 hours. In the time-shiftable process, there are several jobs to be scheduled on a machine. These jobs have to be processed in the planning horizon: a 24-hour day.

4.2. Optimization model

The nomenclature used in the optimization model is shown in Table 1. For the sake of clarity, parameters begin with capital letters whereas decision variables start with lowercase letters.

Table 1. Overview of sets, parameters and variables used in the model.

Sets	Description	
$Periods$	Quarter hours of the planning horizon defined as $\{1,2,\dots,P\}$	
$Jobs$	Jobs to be processed on a machine defined as $\{1,2,\dots,J\}$	
Parameters	**Description**	**Unit**
$Cap^{battery}$	Total usable capacity of li-ion battery	kWh
Max^{charge}	Maximum amount of energy to charge per period (pp.)	kWh
$Max^{discharge}$	Maximum amount of energy to discharge pp.	kWh
η^{charge}	Charge efficiency of li-ion battery	
$\eta^{discharge}$	Discharge efficiency of li-ion battery	
Soc^{start}	State of charge of the battery in the first period	kWh
$DmdPS$	Daily energy demand of power-shiftable process	kWh
$MaxPS$	Consumable energy by power-shiftable process pp.	kWh
$Time_j$	Processing time of job j in periods	
$Dmd_{j,q}$	Energy demand of job j in period q since started	kWh
$Price_p$	Electricity price (day-ahead market) in period p	€/kWh
$FeedInTar$	Feed-in tariff for feed-in electricity into the grid	€/kWh
$PeakLoad$	Limit for the annual peak load	kW
$GenPV_p$	PV generated electricity in period p	kWh
$LoadFix_p$	Unalterable load in period p	kWh
$PerLength$	Duration of one period (quarter of an hour)	h
C^{max}/C^{soc}	Coefficients for less amount of energy to charge pp. depending on the current state of charge (SOC)	
Variables	**Description**	**Unit**
$charge_p$	Amount of energy to charge the battery in period p	kWh
$discharge_p$	Discharged energy from the battery in period p	kWh
$charging_p$	1, if charging battery in period p; 0, otherwise	
soc_p	State of charge (SOC) of the battery in period p	kWh
$loadPS_p$	Load of the power-shiftable process in period p	kWh
$loadTS_p$	Load of the time-shiftable process in period p	kWh
$start_{j,p}$	1, if processing job j starts in period p; 0, otherwise	
buy_p	Electricity bought from day-ahead market in period p	kWh
$sell_p$	Grid feed-in in period	kWh

The objective function is to minimize the costs for purchasing energy from the grid minus remuneration for fed energy:

$$Minimize \sum_{p \in Periods} \left(Price_p \cdot buy_p - FeedInTar \cdot sell_p\right)$$

Constraints (1) to (6) describe the lithium-ion battery module. (1) and (2) set a maximum for the charged or discharged amount of energy per period based on the charging or discharging power. The variable $charging_p$ implicitly ensures that each period the battery can be either charged or discharged:

$$charge_p \leq Max^{charge} \cdot charging_p \quad p=1,...,P \quad (1)$$

$$discharge_p \leq Max^{discharge} \cdot (1 - charging_p) \quad p=1,...,P \quad (2)$$

In (3), the SOC of the battery is determined based on the previous period depending on the energy quantity charged or discharged. (4) gives the SOC a defined initial value, while (5) guarantees that at least the initial SOC is reached after the last period. (6) sets the battery capacity as the SOC's maximum:

$$soc_p = soc_{p-1} - discharge_{p-1} + \eta^{charge} \cdot charge_{p-1} \quad p=2,...,P \quad (3)$$

$$soc_1 = Soc^{start} \quad (4)$$

$$soc_P - discharge_P \geq Soc^{start} \quad (5)$$

$$soc_p \leq Cap^{battery} \quad p=1,...,P \quad (6)$$

The following constraints define the degrees of freedom of movable production loads. The sum of the consumed energy of the power-shiftable process must reach the daily demand in (7), with the amount of intake per period being limited in (8):

$$\sum_{p \in Periods} loadPS_p \geq DmdPS \quad (7)$$

$$loadPS_p \leq MaxPS \quad p=1,...,P \quad (8)$$

The time-shiftable load per period equals the energy demand of the job currently being processed depending on when the job started. For this, in (9) the previous periods are considered within the processing time of each job. If the job has been started during these periods, its energy consumption is counted:

$$loadTS_p = \sum_{j \in Jobs} \sum_{q=1}^{\min(p, Time_j)} Dmd_{j,q} \cdot start_{j,p+1-q} \quad p=1,...,P \quad (9)$$

(10) ensures that each job is started exactly once by the latest time from which it can be fully processed:

$$\sum_{p=1}^{P+1-Time_j} start_{j,p} = 1 \quad j=1,...,J \quad (10)$$

Only one job can be processed in the same period on the machine. So, in the sum in (11), all previous periods are taken into account in which a job could have been started and still would be processed in the current period:

$$\sum_{j \in Jobs} \sum_{q=1}^{\min(p, Time_j)} start_{j,p+1-q} \leq 1 \quad p=1,...,P \quad (11)$$

Electricity supply via the grid must not exceed the peak load limit in any period. The limitation of the peak load is usually specified in kW. This is why it has to be multiplied by the period length for comparison with the variable buy_p in (12):

$$buy_p \leq PeakLoad \cdot PerLength \quad p=1,...,P \quad (12)$$

(13) establishes an energy balance: input must equal the output of energy in each period:

$$GenPV_p + \eta^{discharge} \cdot discharge_p + buy_p = charge_p + loadPS_p + loadTS_p + LoadFix_p + sell_p \quad p=1,...,P \quad (13)$$

Finally, non-negativity conditions (14) and value ranges for binary variables (15) are listed below:

$$charge_p, \; discharge_p, \; soc_p, \; loadPS_p, \; loadTS_p, \; buy_p, \; sell_p \geq 0 \quad p=1,...,P \quad (14)$$

$$charging_p, \; start_{j,p} \in \{0,1\} \quad j=1,...,J \quad p=1,...,P \quad (15)$$

To model the battery closer to reality charging in the area of a high state of charge can be limited more by an additional constraint (16). Through the used simulation the coefficients could be determined suitably as $C^{max} = 2$ and $C^{soc} = 0.25$:

$$charge_p \leq C^{max} \cdot Max^{charge} - C^{soc} \cdot soc_p \quad p=1,...,P \quad (16)$$

4.3. Application

The model is exemplary applied with data from a medium-sized company that uses a plant for nitrogen production. Since nitrogen can be stored well, this system meets the specifications of the power-shiftable process. Furthermore, a laser cutting machine is in use. This represents a time-shiftable process with a load profile subdivided into different jobs of various lengths. The company has self-generation through photovoltaics of around 290 MWh per year. The use case data is based on power measurements of various consumers and order data to illustrate the production restrictions.

A li-ion battery with a capacity of 75 kWh and a maximum charging power of 49 kW is in use, which means the amount of energy to be charged in one period is limited to 12.25 kWh. This scale seems adequate due to the energy consumption of the company. To reduce deviations from reality by assuming linear charging in the model, usable capacity is lowered to 70 kWh and the limit for charged energy is set to 10 kWh. Charge and discharge efficiency are set to 0.95, as in [27]. For the energy purchase, the day-ahead prices of a Wednesday in October 2018 were used. In each case, taxes according to [54] and the network charge from [55] are added. Without battery use and flexible loads, the energy costs amount to 125 €.

The optimization of load and battery storage scheduling results in energy costs of 105 €. This represents a cost reduction of around 15 percent compared to the original electricity procurement costs of the company on the exemplary day. Furthermore, the limit for peak load could be cut in half from the initial 140 kW to 70 kW in the specific use case. With a permanent lowering of the annual peak load, additional cost savings through lowered network charges could be achieved.

5. Conclusion and outlook

The presented approach is suitable for the operative production planning of manufacturing companies that have identified flexibility measures and want to use them cost-effectively in combination with an energy storage system. By adding further functionalities, it can be extended to feasible methods for different applications.

An example of this are additional constraints regarding the dependencies and restrictions of different orders. This enables the modeling of even complex production processes. In addition to the described order-related measures, flexible loads can be supplemented at the machine level. The inclusion of potential production risks makes it possible to schedule battery capacity as a buffer for unexpected deviations in ongoing operation. The planning of controllable generation, for example, by a combined heat and power plant, can also be added in the form of generation-side flexibility. The further development of electromobility can prove to be interesting if the aforementioned vehicle-to-factory approach finds practical application. The available storage potential can then be differentiated between stationary and mobile storage and, for example, coordinated by a supplementary simulation.

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