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Energy-Cost-Optimized Strategies for Discrete Mechanical Manufacturing

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Abstract

Ongoing electrification on the demand side, a growing share of mostly weather-dependent renewable energy, and the further liberalization of trading lead to increased price volatility of electrical energy. Thus, industrial companies dependent on electrical energy to run production processes need to mitigate the resulting increase in energy costs. Based on Austrian energy pricing and the current market for electrical energy within the synchronous grid of Continental Europe, this paper proposes three basic strategies: (1) reducing the energy demand through efficiency, (2) optimizing energy purchasing through anticipation or determination of the load profile and (3) avoiding load peaks caused by simultaneities.

Keywords: Industry; Energy flexibility; Demand side management; Demand response; Energy price volatility; Day-ahead; Intraday; Energy-cost-optimization

1. Introduction

In late 2021 the price of electrical energy for delivery on the following day reached an all-time high of € 620 per MWh on the Austrian wholesale market for electrical energy. A development said to be caused by rising prices for natural gas which is coupled with electric energy because of the 17.9% share taken by gas-fired power plants in the European electricity generation mix and by partially setting prices through merit order [1], [2]. The effect of this dependency was further aggravated just lately by the conflict in Ukraine. While the current highly volatile prices can be seen as a singularity, long-term changes such as those described hereafter may lead to the same outcome.

In contrast to wholesale market prices, the levelized cost of energy (LCOE) considering variable renewable energy (VRE) already are the lowest compared to fossil and nuclear energy sources, see table Table 1 [1]. Thus, we will witness an ongoing expansion of production capacity for VRE [4].

Table 1: The three cheapest forms of utility-scale electricity generation in 2021 [1]

		$/MWh
1.	photovoltaics (crystalline)	36
2.	wind	38
3.	natural gas	60

Traditionally the demand side governed the production of energy, and utilities focused on predicting demand and optimizing response to demand [5]. This is due to conventional electricity generation capacities, i.e., such from fossil fuels (coal, oil, gas) being flexible, with nuclear power plants to cover the base load [6]–[8]. The more VRE will replace conventional or fossil sources, the less the supply side can be controlled, because of weather-dependent delivery behavior [9], [10]. Storage technology is a possible alternative for future grid flexibility, but it is not yet economical and will take years to gain acceptance [6], [11]. This leads to the **first**

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premise: *Volatility will increase on the supply side of electrical energy*.

In parallel, electrification is advancing on the demand side where all sectors are affected, be it the industry [12]–[14], individual transport [15], or heating [15], [16]. These disparate developments will lead to an aggravation of stochastic end-use customer behavior and to (for now) unknown load profile patterns whereby power utilities will have to adapt [15]. Therefore, we derive the **second premise:** *Volatility will increase on the demand side of electrical energy*.

Another aspect lies in the inner workings of how the supply and demand sides are interconnected. The synchronous grid of continental Europe has expanded steadily over the last years [17], and market liberalization is ongoing. Electrical energy can be traded over increasing distances [18], increasingly short-term [17], [19], and by ever more participants where the latter must not be suppliers or consumers or even regulators but can be mere traders [20]. This leads to the **third premise:** *Volatile prices incentivize speculative trading, which will lead to further volatility*.

2. Delimitation of discrete mechanical manufacturing

Industry in the European Union caused 26% of the final energy consumption in 2020, excluding large amounts consumed by the energy-intensive sector (EIS), which are attributed to primary energy transformation, e.g., the energy uptake of blast furnaces and petrochemical plants [21]. The EIS largely coincides with the production of primary commodities (steel, non-ferrous metals, pulp & paper, plastics, petrochemical products, non-metallic minerals), where energy-related costs account for a substantial amount of production costs [14], [22]. The corresponding subset of companies causes a large share of the demand for energy and thus is also very much dependent on its availability [21], [23]. In 2019, the steel producer Voestalpine alone consumed 31.8 TWh at its Austrian sites in Linz and Donawitz, or around 10% of Austria's total final energy consumption [23], [24]. In corresponding facilities, single plants or processes are causal for the better part of energy consumption. The shutdown of a single blast furnace in 2018 caused a drop of 2.5 TWh in the company's yearly energy uptake in Austria [24]. These energy-intensive production environments are typically rather inflexible. Value-adding steps are chain-linked linearly and thus must always be executed in sequence [22]. Such production systems are typically (quasi-)continuous or semi-continuous, i.e. mass flow entering the process chain would be steady or raw material is processed in batches respectively. A qualitative representation of the load curve caused by multiple processes in such environments can be seen in Figure 1. Another characteristic of the EIS is that plants will seldom be shut down, e.g., a blast furnace will run for over ten years until an infeed takes place. Hence, through high and steady utilization of plants, optimization measures are very much focused on process technology [22]. These companies shaped the overall trend in energy-related research within the industry to this day.

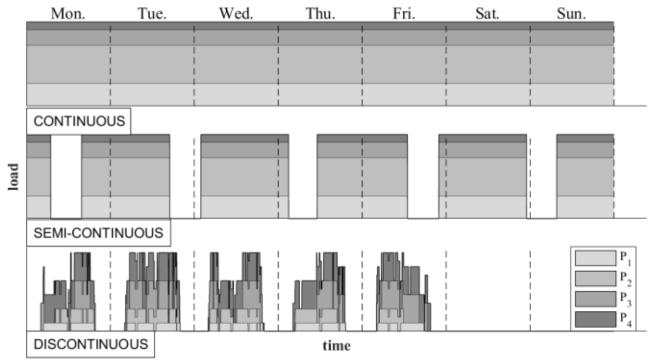

Fig. 1. Qualitative representation of a continuous, semi-continuous and discontinuous production environment with different loads P_1, P_2, P_3, P_4.

Industrial companies outside the EIS, which still must rely on the availability of energy at reasonable prices, are increasingly affected by additional costs caused by climate change, energy price volatility, and policy initiatives. We will refer to these intermediate energy consumers as the energy-dependent sector (EDS). The systematic differences in energy consumption between the two sub-sectors are substantial. Directly transferring energy(-cost) optimization strategies derived within the EIS setting to EDS implementations may render these ineffective.

The EDS mostly coincides with discrete mechanical manufacturing (DMM), a production environment represented by a variety of technologically diverse manufacturing processes whose energy uptake ranges in a narrow bandwidth and which per se are not particularly energy-intensive in relation to prevalent technologies in the EIS [25]. Such production systems are discontinuous, which leads to a composite load curve with high variance, see Figure 1. Single value-adding steps are at least partially automated and may consume variable amounts of energy if they are enabled for varieties of products or processes. E.g., a machine tool could be used for roughing or finishing, resulting in different energy inputs [26]. Plants may also be interlinked linearly, e.g., with transfer lines, bundled to flexible cells, or operated as single units. In addition to metal cutting, heat or surface treatment, cleaning of parts, welding, etc. may also be used. Unlike in the EIS, the overall energy spent per part is added incrementally, and the increments may vary significantly with what kind of part currently is in production. Furthermore, whilst in the EIS value-creation always happens along a fixed route, in the EDS these routes may vary significantly, and so may the energy consumed per the production of a single part. A few outstanding characteristics typical for the EDS energy-wise can be derived:

- Optimizing the energy efficiency of single value-adding steps yields comparatively small gains while still being technologically challenging.
- Simultaneities lead to peaks in power demand which stresses the grid and results in additional costs.
- Downtime and times of operational readiness are much more common. Therefore, in theory, shifting loads in time is possible and base load or energy uptake outside of times when value is added must be addressed.

- Aggregating and anticipating energy uptake could be fully deterministic. The usage of a manufacturing execution system (MES) is state of the art and provides information on what parts will be produced at what time in advance. However, in practice, information about the energy to be added will be lacking.
- Even a highly deterministic production system is partly stochastic.

Regarding energy carriers in the EDS, Austria's final industrial energy consumption can be assessed. Here electricity took a share of 61 % in the demand of companies producing machinery and 54 % of those producing transport equipment, typically representing DMM. In the EIS however, gas is the dominant source of energy, ranging from 40 to 56 %, with the single exception of pulp & paper, where gas is behind renewable energies, whose usage is benefited by the employed production processes [23].

Hence, energy-cost optimization within DMM should preferentially focus on measures overarching or orchestrating a multitude of intermittent energy consumers within a production system. Furthermore, based on the composition of final energy consumption and the initially made premises, the focus is on electrical energy.

3. The incurrence of costs through the procurement of electrical energy using the example of Austria

Electricity procurement costs arise from fees or taxes due to grid usage and from the energy price itself. For cost optimization, it is practicable to describe the overall energy procurement costs over a billing period EPC with the following cost function:

$$EPC = C_f + c_p P_p + W\left(c_{W,f} + \bar{c}_W\right) \tag{1}$$

Herein C_f are fixed costs and c_p is the cost factor for peak power demand P_p, i.e., the maximum power uptake within the billing period. The cost factor $c_{W,f}$ represents all fixed rates as determined by law and can be applied to the cumulated electric work W . $\bar{c}_W$ is the average price achieved by procuring electrical energy on the wholesale market.

Electrical energy is traded on different trading floors which vary considering the time horizon of delivery. End-use customers may procure electrical energy by

1. concluding long-term delivery contracts with maturities up to several years,
2. procuring energy on the day ahead of delivery and
3. during the same day.

Long-term delivery contracts are concluded when prices are perceived as low and are based on load curve projections for up to several years. Such instruments are mainly used to hedge the portfolio and cover base load. Deviations from the prognosis must be covered by trading on short-term markets. With focus on short-term trading, the amount of energy secured by long-term contracts will be considered as a constant power supply $P_{lt} = const.$ over time. Thus, the relevant short-term electrical load $P_{st} = P - P_{lt}$ can be stated by subtracting the long-term power supply P_{lt} from the actual load curve P .

Table 2: Denotations and indices

denotations (left superscript)	**meaning**
d	the day of delivery
$d-1$	the day before delivery
$\bar{d}$	reference workday
indices (right subscript)	**meaning**
$i = 1,\dots,24$	hourly index
$j = 1,\dots,4$	quarter hourly index

One aspect of short-term trading takes place on the day before delivery (*day-ahead*), starting at noon, where prices are determined hourly by merit order [2]. On the intraday floor, energy can be traded on the same day. We will use denominations summarized in Table 2 to distinguish different action phases. $\bar{d}$ indicates a reference load-curve used as prediction for the next day. Billing is based on measurements averaged in 15-minute intervals. Also, the shortest interval for electrical energy to be traded is 15 minutes. Other maturities are of multiple lengths. Because until now, only 15- and 60-minutes products can be traded on the Austrian market, we use i and j for indexing, as stated in Table 2. A measurement of a daily load curve can be stated as $P_{i,j} = P_{1,1}, P_{1,2}, P_{1,3}, P_{1,4}, P_{2,1}, P_{2,2}, \dots, P_{24,4}$ which gives us the definition of peak power $P_p = max(P) = max\left(\{P_{i=1,j=1}, \dots, P_{24,4}\}\right)$. The quarter-hourly and hourly electric load, $W_{i,j}$ and W_i can be defined as followed:

$$W_{i,j} = 0.25 P_{i,j} \tag{2}$$

$$W_i = 0.25 \sum_{j=1}^{4} P_{i,j} \tag{3}$$

On the day-ahead trading floor the end-use consumer will order any amount of electrical energy that has not yet been covered by long-term contracts by procuring ${}^{\bar{d}}W_i$.

$${}^{\bar{d}}W_i = 0.25 \sum_{j=1}^{4} {}^{\bar{d}}P_{st,i,j} \tag{4}$$

The resulting costs on the day-ahead market ${}^{d-1}C$ are the product of the hourly prognosis of energy uptake ${}^{\bar{d}}W_i$ based on the reference data and the hourly price as defined by merit order ${}^{d-1}c_i$.

$${}^{d-1}C = \sum_{i=1}^{24} {}^{\bar{d}}W_i \; {}^{d-1}c_i \tag{5}$$

The cost component ${}^{d-1}C$ thus is fixed by the end of the day before delivery, but the actual electrical work consumed on the day of delivery ${}^{d}W_{i,j}$ deviates from the pre-ordered quantity ${}^{\bar{d}}W_i$.

$${}^{d}W_{i,j} = 0.25 \; {}^{d}P_{st,i,j} \tag{6}$$

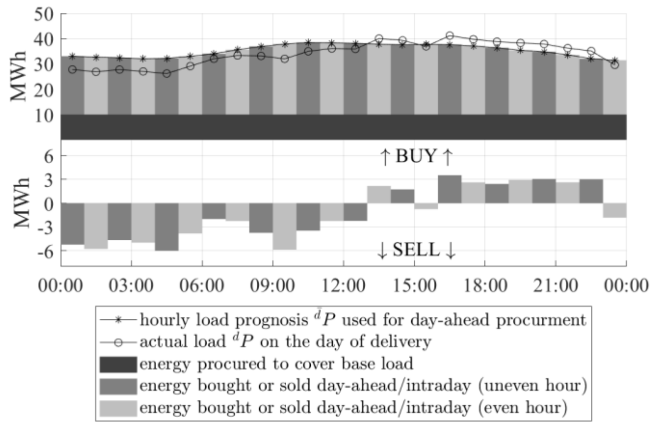

Fig. 2. Day-ahead procurement and necessary adaption intraday.

An actual production environment will not be entirely determined. Thus, any prognosis will somewhat differ from reality, and it is necessary to act on the resulting imbalance on short notice. A qualitative example of the situation in the course of the day of delivery is shown in Figure 2. The expected energy uptake is covered on the day-ahead floor as shown in the upper graph, but the real load curve deviates from the prediction. The electrical grid must be in balance at all times, where the participants have to make sure of that as far as their influence reaches. Thus, to avoid unnecessary costs, even end-users will have to sell surplus amounts of energy during the day or buy if they are lacking, which is shown in the lower graph of Figure 2 for hourly intervals. If they do not do it themselves, the power utility does, and costs will be handed down.

Increasing market liberation makes it possible to buy electric energy up to five minutes in advance to delivery and buy energy products with maturity as short as 15 minutes on the *intraday* floor. Procurement costs for same-day delivery are rather volatile and may differ significantly from *day-ahead* prices, see Figure 3.

The quarter-hourly outstanding amount of electrical energy on the day of delivery can be defined as $\Delta^d W_{i,j} = {}^d W_{i,j} - {}^{\bar{d}} W_i$ and must be covered by procuring on the *intraday* floor to converge equilibrium. The resulting costs for the two available maturities are displayed in the following equations.

$$ {}^d C_{i,j} = {}^d W_{i,j} \; {}^d c_{i,j} \tag{7} $$

$$ {}^d C_i = {}^d W_i \; {}^d c_i \tag{8} $$

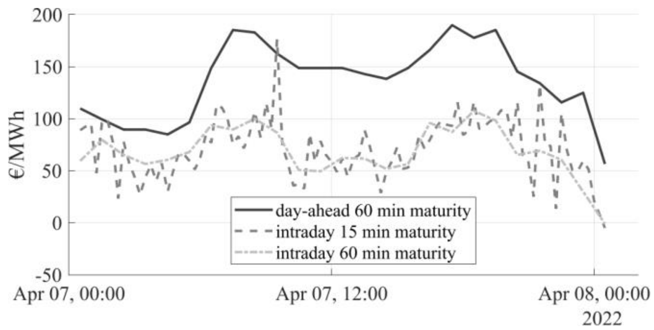

Fig. 3. Comparison of day-ahead and intraday wholesale prices.

Minimizing said costs, i.e., how to best mix different maturities, can be seen as a problem to be solved.

4. Energy-cost-optimization strategies within DMM

From equation 1, three basic strategies for energy-cost optimization can be deduced, being (1) efficiency through reducing the overall amount of energy W consumed, (2) balancing to avoid peaks in demand, i.e., lowering P_p, and (3) flexibilization, i.e., to be able to react to wholesale price volatility and thus, influencing $\bar{c}_W$.

4.1. Efficiency

In principle, energy efficiency, i.e., maintaining the same product output while lowering energy input to the process, has the most significant effect on costs. If costs that scale with the amount of electric energy needed can be avoided, the influence of market prices through the fixed factor $\bar{c}_W$ as of taxes and fees represented by the factor $c_{W,f}$ can be mitigated. Furthermore, energy efficiency measures can result in lowered base and peak load. However, many hindrances to energy efficiency measures exist specifically within the EDS:

- Economic gains in comparison to effort may be low, especially when energy prices are low.
- Process power uptake of individual processes is intermediate. Thus, specific optimizations yield minor benefits.
- As a variety of processes comes into use, companies primarily act as operators and maintainers and lack intricate technical knowledge about production processes.
- Equipment manufacturers on the other hand have little to no interest in prolonging the useful life of existing plants through improvement and will rather invest in the development of new equipment.
- The technological diversity of employed processes or even minor differences regarding similar processes greatly hinder the up-scaling of benefits.
- Lowering energy input may yield unwanted consequences in adversely influencing process quality while the results of such interventions are not well known.

Thus, justifiable strategies in the environment of DMM may be found in optimizing structures overarching the production systems. Such may be centralized facilities that are directly related to production, like the provision of pressurized air or coolant lubricant [27]. Similarly, the optimization of building technology like space heating and cooling, which is closely related to events happening in the production environment (e.g., the generation of waste heat), is viable [27].

Plant-specific efficiency measures with a relatively low barrier are control-related. E.g., implementing a demand-oriented operation of electric motors through the use of frequency converters and retrofitting components, e.g., fitting energy-efficient drives, is a proven strategy.

Energy efficiency measures are essential in any sector to lower costs and pollution and cannot be omitted in the long run. Still, as all these measures have to be individually tailored, we expect a transition phase until the better part of production processes will be as efficient as the state of the art allows them to be. Intermediate energy consumers need to adapt to a volatile supply-side dominated by VREs especially until then, but also afterwards because even the most efficient processes will still consume energy.

4.2. Balancing

As peak load P_p merely is defined as the maximum in power uptake over a given period $max(P)$ (typically a monthly billing period), to pinpoint a potential improvement the load curve must be assessed. In Figure 4, two load curves are displayed over a month, corresponding to two factories where injection molding machines are manufactured. The main differences between these are that plant B provides for the manufacturing of the larger machines and is solely equipped with heat treatment plants and space cooling. An evaluation of this data carried out by a person will yield insights like the higher base and peak load of plant B and the load curve of Plant A being relatively steady compared to the one of plant B showing a higher variance. Intuitively, infrequent spikes in demand may be identified.

If demand peaks shall be mitigated in the first step, this can be done manually. Hereafter, constant monitoring of the factory's load profile must be done as spikes will occur infrequently. Each change in production strategy, each new plant and each extension of production capacity may influence its characteristics and may lead to spikes anew. For an automated peak power assessment, spikes must be detected and evaluated in the same quality a human would, which is no trivial problem [28].

As far as energy costs are concerned, balancing peak demand is not necessarily a priority. Usually, costs caused by energy procurement on the wholesale market outstrip peak power costs which are fixed over long periods by law. Thus, it may even be preferential to induce phases of high energy uptake in the load profile through controlled simultaneities. To implement the flexibilization of load as pictured in the following section, peak load costs must be weighted in.

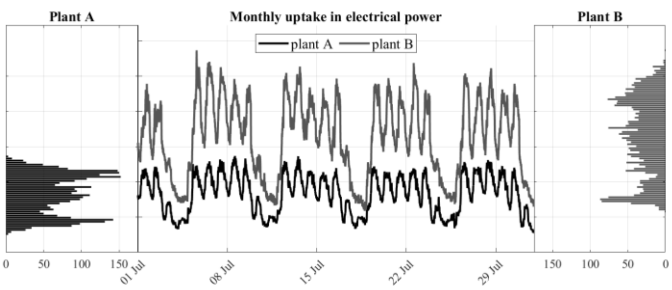

Fig. 4. Load curves for two different plants of the same company in Austria, where the same type of product is produced.

4.3. Flexibilization

While only grid operators, power utilities, and large end-use consumers directly participate in the wholesale market for electrical energy, intermediate energy consumers can make use of most of the market instruments indirectly via services provided by power utilities. Even when end-use consumers only act passively, the specific energy procurement costs $\bar{c}_W$ can be influenced by steering demand. Thus, our premise is that through enhanced price volatility in the years to come, intermediate consumers will emphasize demand response either by

1. *proactive flexibilization*, i.e., the customization of the load profile according to forecasts, or
2. *reactive flexibilization*, i.e., the nearly instantaneous adaption of the load profile based on prices on the intraday floor.

5. Proactive Flexibilization

Because the weather-dependent behavior of VRE generation can be predicted to a certain extent, weather prognosis will be the more reliable the less far into the future it reaches. Thus, wind and solar power generation prognosis works reliably for a day ahead [10]. Furthermore, through setting the price by merit order, when an abundance of VRE is prevalent, market prices are low, see Figure 5.

Based on the influence of the abundance of VRE on day-ahead prices, end-use customers can plan accordingly if enough flexibility is given regarding the energy demand of the production system. In DMM, such flexibilities could be provided by rearranging the sequence of processes on machine tools, e.g., by rough milling during price lows and end milling during highs or by ramping up or down process irrelevant heating cycles. Another example would be shifting fixed process cycles over time [29]. In the latter case, the best solution for the two immutable time series of the day-ahead prices ${}^{d-1}c(t)$ and the plant's power uptake $P_{plant}(t)$ must be found, a problem that can be described by the convolution of the two functions:

$$\left({}^{d-1}c * P_{plant}\right)(t_{start}) = C_{cycle,min} \tag{9}$$

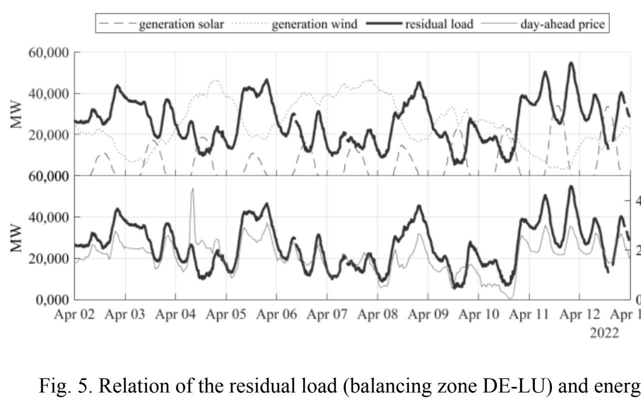

Fig. 5. Relation of the residual load (balancing zone DE-LU) and energy pricing on the day-ahead floor (AT) [30], [31].

By influencing the power uptake on very short notice, end-use customers are enabled to avoid high costs induced through momentarily price spikes (cf. Figure 3) and capitalize on lows by ramping up demand. The trading of electrical energy on the day of delivery (*intraday*) happens near real-time by procuring energy up to 5 minutes in advance to delivery and for maturities as short as 15 minutes. Furthermore, decisions have to be made on which maturity to buy or which combination of maturities is optimal regarding costs, i.e., to find the minimum hourly costs ${}^{d}C_i$.

$$ {}^{d}C_i = \sum_{j=1}^{4} {}^{d}W_{i,j} c_{d,i,j} + {}^{d}W_i c_{d,i} \tag{10} $$

6. Summary, Conclusion and Outlook

We premise a general increase in price volatility for electric energy and increasing cost uncertainty for intermediate industrial end-use consumers, which we delimit as the energy-dependent sector (EDS). To improve resilience and compatibility with an energy system that is in transition due to renewables, production systems must be adaptable in terms of energy consumption. From an energy procurement cost function, we deduce three potential approaches to energy-cost-optimization being energy efficiency, balancing the load curve and flexibilization. However, the scalability of energy efficiency is limited in the context of the EDS. Thus, we concentrate on flexibilization with consideration for spikes in demand and identify several issues to be tackled:

- Composite load profiles of multiple plants must be made as deterministic as possible through production planning. Therefore, knowledge about process-specific load profiles must be built.
- Load curve spikes must be detected automatically to detect irregular peak power phenomena.
- For proactive flexibilization a numerical and fast to compute solution has to be found.
- A solution for cost-optimal combination of different maturities, mainly on the *intraday* floor, must be found.
- Very short-term prognosis for power demand will be necessary for reactive flexibilization.
- The tradeoff between peak power costs and controlled simultaneities at price lows must be evaluated constantly.

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