

Extending the Automation Pyramid for Industrial Demand Response

by

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Abstract

Industrial demand response uses a multitude of energy flexibility measures. Their planning and control requires various production IT systems. A widely accepted approach to classify these inhouse IT systems are the levels of the automation pyramid in companies. This paper broadens the scope of this concept to overcome the limitation to companies' (virtual) borders by including required IT systems that refine and monetarize a company's energy flexibility, e.g. energy markets, aggregators, etc. Therefore, a holistic approach for the classification of functionalities for industrial demand response across companies and energy markets is developed and applied exemplarily.

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1. Introduction

The renewable energy law in Germany defines a share of up to 45 percent for electricity from renewable energy sources (RES) by 2025. By 2050, it will be increased up to a share of 80 percent [1]. Due to the increasing amount of renewable but volatile energy sources, the reduction of conventional power plants, and thus a higher volatility in energy supply, adequate reactions become more and more difficult [2, 3]. Therefore, the energy transition requires a re-design of today's energy supply that mainly follows demand.

Industrial processes consume most of total net electricity [4]. Researchers agree that flexible energy supply due to volatile feed-in of RES implies the necessity of energy flexibility measures within energy demand [5, 6]. Demand side management, or more precisely its component demand response (DR), may produce relief by providing significant potential for energy flexibility within energy demand [7, 8]

– not only in times of very high RES supply, i.e. “light breeze”, and in times of very low RES supply, i.e. “dark lull”. Energy flexibility measures such as storages or power-to-X technologies are not yet established in application comprehensively mainly due to the necessary financial invest. On the contrary, automated DR, i.e. load shedding, load growth and load shifting, offers great chances to cope with the challenges of the energy transition [8–10]. Companies react flexibly on fluctuating energy supply of RES so that variations and costs are minimized [11–13]. For example, the application of DR in companies may reduce energy demand, i.e. shut down manufacturing processes, in times of low feed-in from RES while the company gets a financial compensation for stabilizing the grid with this measure.

To use automated DR as part of a smart grid, companies must no longer focus on their internal, energy-related processes. They not only have to reflect and understand

energy markets, but must also integrate in it. Emerging concepts like a flexible IT-platform as proposed in [13] and [14] synchronizes energy demands with volatile energy markets, and therefore link companies with energy markets by information technologies (IT). Under the term energy markets, this paper sums up not only classic energy (only) markets but also markets where energy flexibility may be traded.

The current IT structure of production companies can be well described by the automation pyramid, which was originally developed in the 1980's defining the integration of strategic, tactical and operative IT systems [15]. Since its focus is on internal systems of the respective company only, there is a need to extend it by additional levels of the energy markets side. Therefore, this paper presents a holistic approach for structuring information flows and IT-systems for DR across companies and energy markets by extending the automation pyramid for automated industrial DR.

2. Current perception of the automation pyramid

The increasing industrial automation requires multiple IT-systems to cope with resulting challenges due to complex manufacturing systems. In order to structure the different applications in a functional and hierarchical manner and thus to reduce complexity, the automation pyramid is established as reference model [16]. However, "cyber physical systems", which merge the physical and virtual world by embedded hardware and software systems present a new, non-hierarchical approach in production [17]. Nevertheless, the hierarchical architecture of the automation pyramid is still present and very common in production systems. This is also indicated by the adoption of automation pyramid within the RAMI 4.0 reference model for industry 4.0 [18]. However, research applies many different versions of the automation pyramid since research removes or merges different levels together, occasionally [19]. In the given context, the commonly used specification IEC 62264 is referred: it consists of five different hierarchy levels (see Fig. 1) [20]. In the following, the different hierarchy levels are discussed from a bottom-up approach.

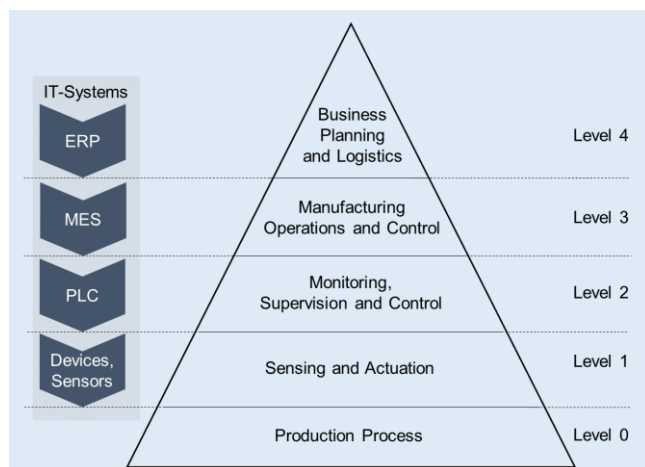


Fig. 1. Current perception of the automation pyramid, consisting of five (0 to 4) different hierarchy levels and corresponding IT systems.

The actual value-creating production or manufacturing process, e.g. a machining process, takes place at the lowest hierarchy level 0. Its physical sub-processes are executed and controlled by devices and sensors assigned to level 1. In case of a machining process, an electric spindle drive displays an actuator on this level. The sensing and actuation units on level one commonly operates within milliseconds or seconds in order to control the physical manufacturing processes and to reach the required quality demands. Considering energy aspects, the actuators on level one consume most of the energy demand of production systems [21].

Monitoring, supervision and control is the task of level 2 systems. Thus, level 2 controls the sensors and actuators on the lower level. Production environments mainly use programmable logic controllers (PLCs) [22]. Depending on the individual production system, PLCs operate within a period of hours down to less than periods of seconds. As level 2 directly controls the actuators, PLCs may implement short-term energy adaptations.

On the next level 3, there are located all activities of Manufacturing Operations and Control (MO&C) [20]. The scope of MO&C is to manage work sequences, part lists and production receipts that are essential for manufacturing the required products. This includes the dynamic scheduling of jobs, the optimization of production processes, as well as the aggregation and distribution of data. In most cases, a Manufacturing Execution System (MES) executes these activities. The MES operates within one day or shift and must be capable to react to unexpected events like machine breakdowns in a reasonable time [23]. Thereby, the detailed schedule of manufacturing operations is appointed, which directly specifies the temporal energy demand.

The top level 4 entails the Business Planning and Logistics (BPL). It consists of planning the material demand, logistics and inventory stock. In addition, the production program is defined, based on the given production capacity and resource availability. Compared to MO&C, BPL operates on a longer time horizon up to several weeks and several months. In practice, an Enterprise Resource Planning (ERP) tool executes the required tasks and manages inventory and resources. As the ERP defines the long-term production utilization, also the long-term energy demand is determined here [24].

In order to apply adequate measures for energy flexibility in a production system, the different operational levels also need to enforce the measures. As indicated, there are different possibilities for energy-oriented adaptations within each operation level. [22] presents an aggregation of measures with a focus on the given time for reaction.

3. Extension of the automation pyramid

Since research reflects DR as a key energy flexibility measure to overcome the challenges of the energy transition, questions arise on how to enable it [6, 8–10]. The application of DR mechanisms is particularly relevant in industry as the industrial sector is the largest consumer of electricity in many countries [4]. Although, DR is usually a by-product of a manufacturing process, companies that hold their utilities

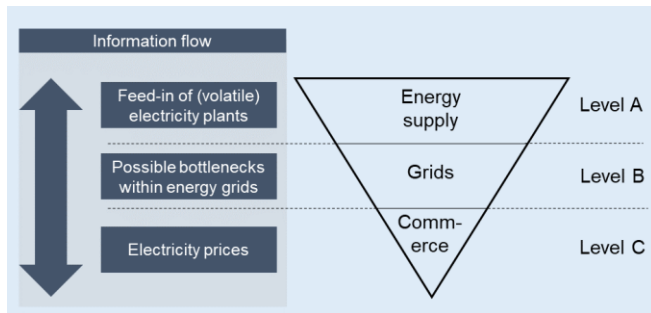


Fig. 2. Relevant levels providing information for DR on the energy markets side.

and production plants for DR available need to know when to activate which DR measure to what extent [9, 13].

To guide companies by providing an approach for the classification of functionalities for DR across companies and energy markets, this chapter develops a holistic approach for the classification of functionalities for DR as an extension of the automation pyramid. Consequently, the extended pyramid reflects both, the current perception of the automation pyramid including inhouse IT systems (see chapter 2) and corresponding levels of energy markets. The following briefly outlines these levels up to the interface of the market and company side that an integrated IT architecture may adopt (see Fig. 2).

The energy transition requires new mechanisms to keep the grid stable, and supply and demand in balance, which is a challenge due to the increasing feed-in of volatile RES [2]. Hence, the basis for the energy system's need for DR lies within the energy supply of volatile RES that will account for the majority of overall energy supply, prospectively [9]. While in times of nuclear and coal-fired power plants the supply of electricity was stable and well manageable, the volatile supply of electricity from wind or PV farms results in market situations where supply no longer follows demand only. Thus, information about the amount of energy supplied, generating plants, and consequently about the needed extent of DR measures may be an origin of an information flow for scheduling DR measures. Consequently, energy supply is the basis, i.e. level A (see Fig. 2), within the extension of the automation pyramid.

The volatile supply of RES results in an increasing number of bottlenecks within electricity grids and in increasing costs for redispatch, i.e. congestion management, already [25, 26]. While DR measures may help to decrease these costs, the current state of electricity grids influences the need for DR measures due to (possible) bottlenecks [27]. Bottlenecks that occur on a daily basis nowadays may be the result of an over- or under feed-in of level A [3]. Bottlenecks within the distribution grid usually arise due to a missing or misleading feed-in management while bottlenecks within the transmission grid usually arise due to market mechanisms. DR measures may contribute to overcome these bottlenecks, on the one hand by unloading the distribution grid within a region, and on the other hand, by unloading the transmission grid to overcome bottlenecks in another region. Hence, level B entails information from transmission and distribution grid

operators that are highly relevant for a comprehensive information flow in order to stabilize the grid by DR measures [5].

In addition, the energy markets side of DR includes a level containing the commerce of energy. While level C also reflects OTC trading, for example, the exchange that serves as dealer of supply and demand, and that publishes electricity prices [28], is located here. The states of the previous levels A and B thereby determine the prices, mainly [29]. Its information needs to be included in a comprehensive information flow. Today, companies only participate in the energy markets side through (own) traders and aggregators at the exchange or other market platforms [30]. Level C thereby serves as a natural interface between the company and the energy markets side, although it is clearly part of the energy markets side as it is company external.

Hence, this paper proposes to adopt the energy markets side by including the following three levels representing relevant stages of energy markets and determinants of a well-functioning DR:

- Level A: Energy supply (electricity plants)
- Level B: Grids (transmission and distribution grids)
- Level C: Commerce (exchange, traders and aggregators)

Today, energy markets assume a conceptual “copper plate”, i.e. markets do not directly consider physical restrictions or bottlenecks within a region. Hence, today's sequence of levels is as follows: first, there is the energy supply. After the energy consumers purchase their appropriate products on the exchange, the grid operators communicate in order to avoid bottlenecks. With an increasing volume, this happens by means of redispatch measures [26] – also due to the conceptual “copper plate”. This paper therefore proposes to consider the three levels as described above in an integrated way to avoid expensive redispatch measures. However, literature reflects that this may result in a nodal pricing system (see, for example [31] or [32]).

The inclusion of three proposed levels leads to a holistic interlinking with information that is permanently visible to all actors and with information that can flow back and forth in order to transmit respective states of the levels from companies and the market, simultaneously. For example, it may be possible to use weather data to forecast supply from RES at an early stage and to calculate any resulting grid bottlenecks. As a result, it will be possible to implement DR measures with a time lead efficiently and thus even to increase the DR potential.

4. Application and reference implementation

To lift overall efficiencies of DR by an end-to-end IT architecture, companies need to link their inhouse IT system to the information flow of the energy markets side. While the commerce level serves as natural interface between the energy markets and the company side, Fig. 3 illustrates the application of the extended automation pyramid for industrial DR. It entails both: the company-internal levels of

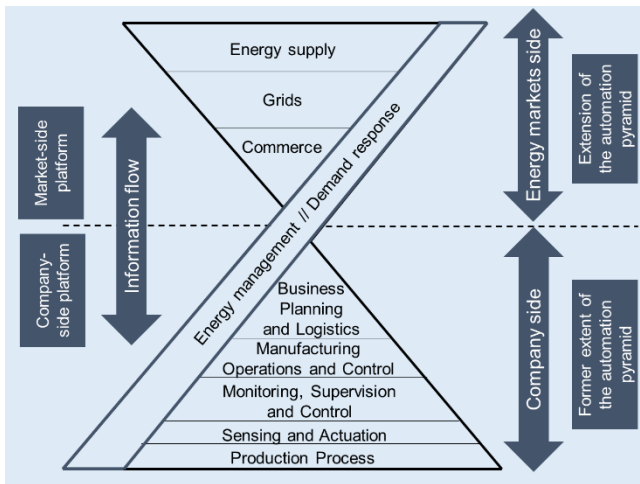


Fig. 3. Linking the company side (current perception of the automation pyramid) and the energy markets side (proposed extension of the automation pyramid) for a well-functioning energy management, i.e. DR.

the automation pyramid as well as the proposed levels of the energy markets. This illustrates again that a well-functioning energy management or DR measures ubiquitously penetrate all levels of the extended automation pyramid, i.e. both sides.

An information flow (see left side of Fig. 3) may serve as basis for a well-functioning energy management that includes DR measures. For example, weather data, i.e. information about future energy supply, may influence scheduling operations on the company-internal side by a linked ERP-system.

A reference implementation is given by the concept of an Energy Synchronization Platform (ESP) to automate and standardize information flows between manufacturing companies and various parties of the energy system in [13, 14]. Two logical platform types – the Market-side platform (MaP) and the Company-side platform (CoP) – structure the ESP [13]. While the CoP addresses the traditional company-internal automation pyramid, the MaP aims for the discussed extension regarding the energy markets side. The decomposition into two logical platforms is required to achieve a certain security level, ensuring the encapsulation of each domain's specific knowledge, technologies and methods.

To overcome domain boundaries a data model is required. A possible data model to describe energy flexibility which is used by the ESP is proposed by [33]. The data model supports energy flexibility measures such as the previously mentioned load shedding, load growth and load shifting. In order to ensure chronological sequences such as load recuperation, instances of the data model are strictly state dependent and include dependencies to other instances of the data model. Furthermore, the data model serves as foundation for aggregation and optimization of energy flexibility respective their digital representation by services of the ESP.

Among others, an industrial application example for the ESP is the monetarization of energy flexibility occurring due to a buffer. Applying the ESP for processes of this type, such as an oil bath [34] or molten metal [35], has been successfully realized in model factories as well as in industry. Energy

flexibility arises within defined limits by increasing the buffer's current content and, therefore, consuming more energy, i.e. load growth or decreasing the content of the buffer by supplying subsequent process steps and, therefore, consuming less energy, i.e. load shedding or load shifting. PLCs control this energy flexibility on levels 0 and 1 of the company side, i.e. of the automation pyramid. Level 2 integrates the ESP when using a smart connector to represent this process and its inherent energy flexibility in services on the ESP digitally. Levels 3 and 4 manage, assess and prepare the energy flexibility and its dependencies to other flexibilities for monetarization. While the CoP and its respective services process these steps, it operates on information received from the MaP or energy markets side, i.e. information on the current need for DR measures. Therefore, the functionality of the MaP integrating levels A to C of the extended automation pyramid entails the merging and the provision of data in order to monetarize energy flexibility, i.e. DR measures. A comprehensive optimization based on the data model serves as specific interface between the MaP and the CoP.

5. Discussion and further research

The automation pyramid structures the automation of processes and the decision-making in processes within companies [19]. While this paper introduces an extension of the automation pyramid, new questions arise. In particular, the question arises whether reliable automation can be guaranteed if parts of the decision making process are no longer carried out by companies alone but relating to the current state of the energy markets side.

While today's IT systems and implemented data models stop at a company's (virtual) border, future research may also consider the scope of a proposed data model [33]. Of course, this means and may result in a consistent linking to the energy markets side. However, companies may not desire influence on production control from outside its (virtual) border. Hence, (IT-) security protocols are necessary to encapsulate knowledge of separate domains without affecting the overall automation. Consequently, there is a need for interfaces and data models for a defined exchange of data between companies and energy markets.

Further research may reflect the role of new distributed technologies, such as blockchain [36, 37]. Additionally, the chronological (planning or sequential) horizon of the extended pyramid should also be reflected. As mentioned in chapter three, the current sequence (supply, commerce, grids) leads to increasing costs for redispatch [26]. The hierarchical structure of levels on the company side determines a clear top-down structure for the given time for reaction of a company's processes, with ERP systems having the longest planning horizon. While e.g. the MES needs to introduce short-term adaptations of the energy demand within one day, further research may analyze a temporal dimension or structure of the energy markets side. Moreover, practitioners may develop tools that implement the extended automation pyramid with the aim to represent the chronological sequence for the automation of industrial DR.

Furthermore, researchers can also analyze a fit of the introduced extension of the pyramid to the services of the MaP from [13].

Summarized, the communication, i.e. an information flow, between the company and the energy markets side is important and necessary for an efficient industrial DR. Hence, companies need a stronger linking to the energy markets side. However, companies must tackle IT-security challenges, first. Therefore, research may propose standards for links and interfaces based on the structure given by the extended automation pyramid.

6. Conclusion

To overcome the challenges of the energy transition, and particularly the integration of an increasing share of RES, the implementation of DR is a key factor. However, a well-functioning industrial DR requires various and comprehensive planning and control IT systems. Previously existing versions of the automation pyramid structured inhouse IT systems by different levels. This paper broadens the scope of the automation pyramid by including company-external, i.e. energy markets side, levels. Therefore, it proposes to consider three levels on the energy markets side: energy supply, grids, and commerce. The inclusion of these levels in an end-to-end IT architecture enables an integrated automation of processes and a comprehensive decision-making in DR measures. While merging the current perception of the automation pyramid and our extension, this paper applies the developed approach to an existing concept as a reference implementation.

This paper contributes to an enhancement of DR measures in research and practice by providing a first attempt for a holistic approach for the classification of functionalities for DR across companies and energy markets that further research may specify.

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