Implementing Energy Flexibility Measures in an Industrial Smart Grid: A Systematic Approach

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Abstract: Industrial energy flexibility (DSEF) is the capacity of industrial systems to adapt (increase, reduce or shift) their energy consumption over a specific period based on changes in the energy context. These capabilities acquire an exploitable form as Energy Flexibility Measures (EFMs), meaning conscious and quantifiable actions that carry out a defined change in the operative state in an industrial system. Modern factories usually present a wide variety of available EFMs, that to be implemented and managed effectively demand the transformation of industrial energy grids into DSEF capable smart micro-grids. For this purpose, this paper presents a methodological approach that employs a variation of the Use Case Methodology and the Smart Grid Architecture Model (SGAM) to design comprehensive energy flexible Industrial Smart Grid (ISG). The developed ISG-design outlines the necessary physical and virtual elements to incorporate multiple EFMs into Brown- and Greenfield industrial sites. The paper concludes with a summary of the lessons learned during the application of the developed approach in a brownfield automobile manufacturing plant.

1 INTRODUCTION

Demand-side energy flexibility (DSEF) has a considerable capability for providing the power grid with the added necessary flexibility to help guarantee secure and resilient operation. (Alemany et al. 2018). DSEF from industrial processes, or industrial energy flexibility (IEF), is strongly relevant due to the high share that the industrial sector represents in the overall electrical consumption. Moreover, energy-intensive Factories can also cause a high level of stress and instability on the power grid, which could also be mitigated via IEF (Dulău et al. 2016). Various analyses have already quantified the energy flexibility potentials of the German manufacturing sector with promising results (Eisenhauer et al. 2017) (Ausfelder et al. 2018).

Currently, one of the main challenges to exploit IEF is the implementation of the previously identified energy flexibility measures (EFMs) in the industrial systems across a production site, i.e. a factory. EFMs are usually highly complex as they influence the material, information and energy flows in the factory. This paper presents a systematic approach to overcome this challenge via the development of a multidimensional design (physical, functional, technological and economic) of energy flexible ISG. The approach, as an abstract concept, was proposed in previous work (Tristan et al. 2019). In this publication, the concept has been, revised, concretized and complemented with the experiences from its application in brownfield sites. The article concludes with a summary of the insights gained through the application of the developed approach and an outlook of its prospective applications.

2 KEY CONCEPTS OF IEF AND INDUSTRIAL SMART GRIDS (ISG)

In this section, the key concepts of IEF and ISGs necessary for the development of the proposed approach are presented, starting by defining the concept of energy flexibility measures in industrial systems.

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2.1 Energy Flexibility Measures in Industrial Systems

Energy flexibility measures (EFMs) are conscious, and quantifiable actions to carry out a defined change of an operative state in industrial systems (Reinhart et al.). The identification of prospective EFMs is a three-part process that involves: (1) identifying those systems suitable for energy flexible operation, (2) recognizing the nature of the flexibility they could offer and, (3) characterizing the EFM, which consists in the quantification of the characterization parameters of an EFM. An EFM is fully characterized when its functional, performance, temporal and economic dimensions are established. For this purpose, the characterization framework presented in (Tristán et al. 2020). The most relevant characterization parameters in this framework, necessary for the implementation are (VDI 5207):

- **Flexibility Type**: the direction on which the operative state will be changed by the activation of the EFM. (Load increase, decrease, temporal shift)
- **Flexible Power**, ΔP_{flex}: the maximum difference of rate of energy demand between the reference operative state and the EFM-induced operative state. The unit for this parameter is usually kW_{flex}.
- **Active Duration**, Δt_{active}: comprises the minimum and maximum period on which the EFM is active, meaning the duration on which the industrial system operates under the EFM-induced operative state(s).
- **Activation Frequency**, $N_{activation,T}$: the activation frequency parameter quantifies the maximum number of times an EFM can be executed over a specific period, T, usually a calendar year.
- **Flexible Energy**, $E_{flex,T}$: the average amount of energy that could be flexibilized as a result of activating an EFM over a specific period, T, typically a year.
- **EFM specific cost**, $c_{flex,T}$: cost summary indicator of the EFM, it represents the cost of the EFM by a unit of flexible energy over a specific period (T).

Once the identification of prospective EFMs has concluded, they need to be evaluated regarding their viability. This evaluation consists of balancing the costs, benefits and risks of implementing each prospective EFMs. The evaluation analysis has then as output, a catalogue of viable and ready-to-be-implemented EFMs.

2.2 Micro Grids and Industrial Smart Grids

A smart grid is defined as an electricity network that uses information exchange, control technologies, distributed computing and associated sensors to integrate the behaviour and actions of the network users and other stakeholders (DIN Spec 42913-1; Wilker et al. 2017). Meanwhile, microgrids are electricity distribution networks containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) with the ability to be operated in a controlled, coordinated manner either while connected to the main power network or in isolation. The electrical grid in a production site is, under this definition, a microgrid that is delimited by the physical boundaries of the site.

Therefore, in the research context, the concept Industrial Smart Grid (ISG) was introduced to conceptually describe smart micrograds aimed towards the smart integration of the industrial systems in a production site. (Sauer and Weckmann 2017). The development of an ISG, nevertheless, differentiates itself from the classic understanding of a microgrid, due to the multidisciplinary nature of its requirements. The conception, planning and implementation of an ISG entail the balance of the expectations and necessities of a broad range of stakeholders (DIN Spec 42913-1; Sauer and Weckmann 2017). A general overview of the relevant stakeholders for the development of an ISG is presented in Figure 1.

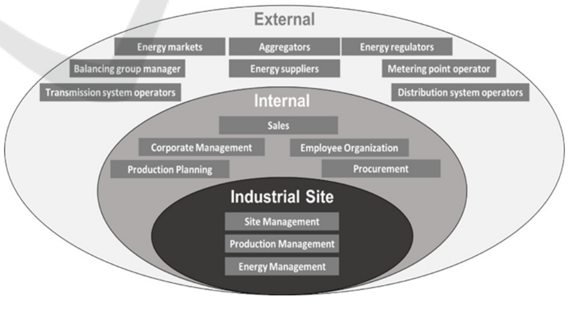

Figure 1. Relevant stakeholders within the development of an ISG (VDI 5207).

As can be seen in Figure 1, the ISG stakeholders can be divided between external, which are actors that are not directly affiliated to the site's managing organization and internal, i.e. actors under the purview of the organization managing the site. Internal stakeholders might or not be present in the site's physical location. Depending on the size and complexity of the industrial processes, some additional actors might also be relevant for the ISG.

2.3 The Need for an ISG in Production Sites

From a general standpoint, the need to develop ISGs is comparable to that for the Smart Grid as a whole. The ISG allows the energy consumption of the different industrial systems in a production site to be coordinated dynamically based on the changing conditions within the site and in the electrical grid. The ISG, therefore, transforms previously energy consuming-only loads into reactive, intelligent, loads.

Furthermore, as mentioned, there is a decarbonisation effort in the electrical grid that hinges considerably on the electrification of the demand sectors. The effort is particularly strong on industrial systems that were previously supplied on energy vectors with high carbon footprints. The shift towards electricity, adds additional stress on the power grid, and increments the need for grid resilience but also presents an opportunity (Smart Grid Coordination Group 2012).

The implementation of Smart Grids in general and of ISGs in particular, enables better autonomous control actions, operator assistance, integration of renewable sources, better market efficiency through innovative solutions for different types of products, better service quality, situational awareness, efficiency enhancement, and overall resilience (Dulău et al. 2016). And, in the particular case of IEF allows companies to optimize their energy consumption while collaborating with the energy transition.

2.4 The Required Capabilities of an Energy Flexible ISG

The functions of an ISG will not be limited to the support of the energy flexible operation of industrial systems. Nonetheless to support IEF the ISG must a-) swiftly detect a change in behaviours in the internal and external energy grids, e.g. considerable price variations), b-) calculate the magnitude and expected duration of these variations and, c-) deliver an optimal response. These responses can be divided between proactive and reactive. A proactive flexibility response asks production sites to offer ahead of their flexibility potential so that other external stakeholders can retrieve it at short notice. In this case, communication is bidirectional, i.e. the company and the respective stakeholders exchange information, in real-time, regarding the specific characteristics of the flexibility response. The ISG should then maintain a considerable level of readiness to energy flexible operation. In reactive flexibility, production sites, adapt their consumption as a response to fluctuations in the peripheral energy context. The communication for reactive flexibility is, in principle, unidirectional, as the site does not provide any information to external stakeholders (VDI 5207). In this case, the ISG should be capable of projecting the optimal magnitude and duration of the response. The optimal energy flexible ISG should be capable to provide both proactive and reactive flexibility responses.

Moreover, the nature of flexibility responses should prioritize the organization's motivation to deliver IEF and balance them with potential risks that the retrieval of EFMs might entail. The overarching motivation for IEF from a macro-perspective should be to serve the demand-side balance of the volatility of renewable energy supply sources. While at a micro-scale, IEF should create a direct or indirect benefit, usually economic, for the industrial site as an energy consumer. Potential risks from retrieving EFMs can be summarized as the deterioration of the optimal operation of the site's material and energy flows and/or, potential impacts on the industrial systems lifetime (Simon et al. 2018).

The heterogeneous nature of these requirements demands a more specific analysis than the one performed during the architecture design of the entire smart grid nonetheless, due to their similar end-goal the smart grid design tools can be adapted for the ISG development.

2.5 Smart Grid Architecture Model and the Use Case Methodology

The Smart Grid Architecture Model (SGAM) and the Use Case Methodology have been selected by the Smart Grid coordination group behind the EU Mandate M/490 as the basis to standardize the development of the European Smart Grid. Currently, both tools, in combination, are used by TSOs[1] and DSOs[2] to develop their respective electrical smart grids (DIN Spec 42913-1).

The SGAM is based on interoperability and allows the creation and formalization of solutions that can then be implemented as Smart Grid Functionalities. It is subdivided into five so-called interoperability layers. The component layer is the foundational layer. It serves to map and describe

[1] TSO: Transmission System Operator

[2] DSO: Distribution System Operator

every physical component from information, communication and control equipment to the power network itself. The function layer describes functions and services, and, hence the relationships, between the components in the component layer. The information layer describes information objects within these described components, which are transferred with specified tools inside protocols described in the communication layer (Wilker et al. 2017).

The SGAM can be understood as a 3-D model where the layers stack vertically and cover two dimensions the Domains (Generation, Transmission, Distribution, Distributed Energy Resources and Customer Premises) and Zones (Process, Field, Station, Operation, Enterprise and Market).

The Use Case Methodology is a software-based method that allows describing, statically and dynamically, a to-be-developed system and its functionalities. It is usually then used, to establish specific applications that are desired in the smart grid. The different use cases are then aggregated to develop the different layers of the SGAM (Gottschalk et al. 2017).

3 DEVELOPING THE ENERGY FLEXIBLE ISG THROUGH PREVIOUSLY IDENTIFIED EFMS

The proposed systematic approach employs the Use Case Methodology to translate EFMs into fully described use cases of the energy flexible ISG. The individual interoperability layers are built then, by aggregating the different elements describing each use case and merge them into an Industrial Smart Grid Model (ISGM). The resulting ISGM can thereafter be used to map the gaps between the current and desired topology in the production site and facilitate the implementation of the energy flexible ISG. An overview of the individual steps of the developed approach is presented in Figure 2. The individual steps in Figure 3 are described in the following subsections.

Figure 2. ISGM development steps.

3.1 Input Definition

The first step is to define the EFMs, which, are intended to be implemented on the production site. The EFMs should be fully characterized, meaning that their different features should be enumerated to the point that a use case could be built for each EFM. As a part of the characterization a brief comprehensive understanding of the industrial system on which the EFM acts should also be available. In addition, the current relationships between the system and the relevant stakeholders should be known.

3.2 Scope and Objectives

Step 2 is to define the implementation objectives of the intended energy flexible ISG and its scope. These implementation objectives can be internal, involving only stakeholders and activities under the company's purview, or external, involving stakeholders and activities in the site's periphery. Internal objectives include, for example, the postponement of infrastructure expansions, the improvement of voltage quality, increased system resilience, the maximization of the self-consumption of local renewable sources and peak-shaving. These objectives are usually limited to reactive flexibility responses. Examples of external objectives may be, maximising the usage of their renewable energy portfolio, offering energy flexibility in the energy markets and/or optimising energy consumption as a function of energy costs (VDI 5207). External objectives usually combine proactive and reactive flexibility responses.

The second part of Step 2 is to delimit the scope of the intended ISG. The delimitation consists of identifying, out of the current topology of the industrial site, which components will need to be retrofitted to implement the ISG on site. The scope should be wide enough to encompass the relevant components to implement the EFMs and achieve the intended objectives but should be specific enough to limit potential risks in the implementation of the ISG.

3.3 Define Zones and Domains

Similar to the SGAM, the definition of zones and domains for the ISGM forms the frame of reference within the ISG. As is the case for Industry 4.0 concepts, the ISGM merges the physical and cyber systems of the production sites. (VDI 2015). Therefore, the domains of the ISGM represent the different physical elements that define an industrial site. These units can be visualized hierarchically e.g. Site/Building, Energy Infrastructure (Technical Building Services), Hall, Manufacturing/Auxiliary Systems and Machine/Tool (Weeber et al. 2017; Posselt 2016). The specific domains that will be present in the ISGM depend on the elements of the analysed manufacturing site. The zones are, in turn, based on the classical automation pyramid, which consists of Field, Control, Supervision, Operation and Organization.(Sauer and Weckmann 2017) Due to their hierarchical nature, both, the zones and domains for ISGM can be represented as pyramids, as shown in Figure 3. Depending on the complexity of the industrial site and the selected scope, the ISG description may require adding or remove zones and domains.

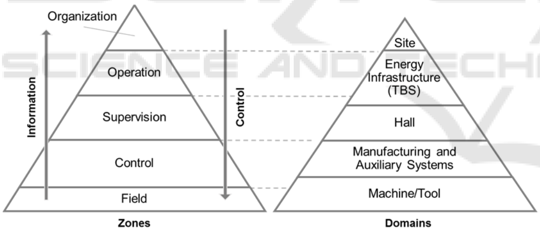

Figure 3. Visualization of ISGM zones and domains.

3.4 Building up Use Cases from EFMs

The Use Case methodology is an ideal tool for converting fully characterized EFMs into the functionalities that will constitute the building blocks on the energy flexible ISG. This methodology is described in the IEC 62559-2 standard. The procedure is divided into the following basic stages (Gottschalk et al. 2017):1-) *Use Case description*, 2-) *Use Case diagrams*, 3-) *Technical Details* 4-) *Step-by-step analysis*, 5-) *Information exchange*, 6-) *Requirements*.

The *Use Case description* is already completed during the EFM identification and characterization analysis and constitutes an input, as explained in section 3.1. The *Use Case diagrams,* are based on Use Case, Activity and Sequence diagrams from the Unified Modelling Language (UML) and enable a dynamic and static representation of the sequential activities that constitute the retrieval of each EFM. The *Technical Details* stage should describe the actors and roles. Actors are physical or virtual entities that communicate or interact during the activation of an EFM. A role describes the actor's responsibilities and hence, their decision-making authority. The *Step-by-step analysis* describes, in detail, the activation procedure of an EFM. Based on the desired result, this procedure can follow different paths or modes of operation. The modes of operation are divided into individual actions that constitute the functionalities necessary to achieve the intended goal of the EFM. The *information exchange* creates a description of the necessary information that has to be traded between actors to achieve each mode of operation. The *Requirements* stage describes the necessary internal and external contexts, on which each mode of operation takes place. It consists of a description of the triggering event that demands the activation of the described EFM.

3.5 ISGM Component Layer

The content of the *Component Layer* is derived from the *Use Case descriptions* of the respective actors. Each actor îs represented either directly or indirectly by a component in the *Component Layer*. Since the actors are not necessarily physical units, several actors can be replaced by one component. The various components must be assigned to their specific domains and zones. Once all the Use Cases have been aggregated into the *Component Layer*, the components here constitute the necessary common infrastructure necessary to achieve the different EFMs from the energy, information and control flows perspectives. Figure 4 shows a generic *Component Layer* with the previously defined zones, domains and potential components located across them.

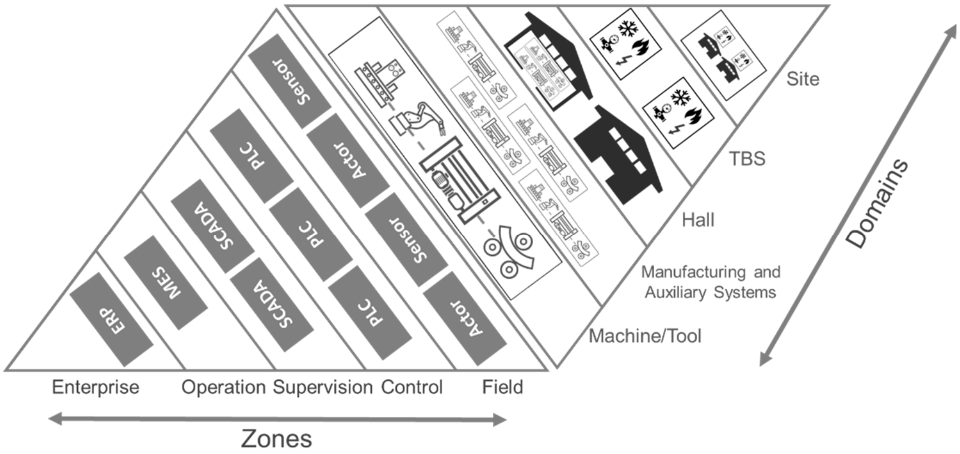

Figure 4. Conceptual Component Layer.

3.6 ISGM Function Layer

The Function Layer shall represent the functionalities and relationships between components across the domains and zones. Functionalities are derived from the use cases by transforming each, mode of operation from the characterized EFM (As described in Section 3.4) into the specific set of commands to be performed by the relevant components. Functionalities within the Function Layer are usually decided and triggered at the supervision, operation and/or enterprise zones. On the other hand, depending on the scope of the EFM, these functionalities represent, their scope extends across different domains.

3.7 ISGM Business Layer

The *Business Layer* integrates the intended objective*s*, as defined in section 3.2, with the *Requirements*, from the Use Case methodology of section 3.4, and serves as the main input to build a business case for the energy flexible ISG. The *Business Layer* is intended to harmonize intentions, in the form of the intended objectives of the ISG, with the current and future context on which the production site finds itself, in the form of the *Requirements*. As mentioned, the end output is a business model or models that make the case to implement the designed energy flexible ISG. The creation of these business models is crucial as they are the cornerstone on which the energy management strategies for the energy flexible ISG are built.

3.8 ISGM Information and Communications Layers

The development of the Information and Communications Layers are based on the aggregation of the information exchange stage of each Use Case, as described in section 3.4., and their correlation with the Component and Function Layer. The Information Layer will assign to each component, all the information packages that it should be able to swap with the other components, thus defining the necessary capabilities of those components in charge of information and control (The components located in the ISG Zones, see section 3.3). If a component in the Component Layer is unable to gather and exchange any of the assigned information packages, it needs to be retrofitted.

The creation of the *Communications Layer* is based on the actor-information assignment performed in the *Information Layer*, and consists of synthesizing, the necessary protocols and mechanisms for interoperable exchange of the information packages between components. The *Information* and *Communications Layer* should be homologated with platforms developed for the marketing of energy flexibility (Körner et al. 2019).

3.9 Implementation Plan

Once the ISGM has been developed, it serves as the blueprint to implement the energy flexible ISG. The Component Layer will describe the physical topology of the ISG. For greenfield sites, it will provide the necessary IT-component topology. In the case of a brownfield site, it will serve to identify the shortcoming of the current IT infrastructure. The

Function Layer will provide the basic input to develop the energy management system (EMS) that will control the ISG. The Business Layer provides the necessary logic that the EMS needs to follow to techno-economically optimize the energy performance of the site. The information and communications layer allow for the homologation of the new infrastructure with the existing one in the case of brownfield sites, or the selection of the most optimal configuration in the case of greenfield sites. In a nutshell, the ISGM is a multi-disciplinary tool allowing production sites to transform their existing electrical, and also other energy, grids into ISGs.

4 INSIGHTS AND OUTLOOK

The systematic approach presented in this article was applied to develop an energy flexible ISGM based on 3 previously identified EFMs in an existing automotive manufacturing plant. Two primary objective*s* were defined for the implementation of these EFMs: a-) Internal "Peak Shaving" and b-) the intelligent response to the volatility of energy prices. The scope was determined by the selected EFMs, which were two energy storage measures at a hall and TBS level respectively and one measure dealing with the adaptation of process parameters also at the TBS level. The involved domains, as can be inferred from the scope, were until the auxiliary processes level, as explained in section 3.3 and, due to the current automation strategy of the site, all of the identified zones were involved in this specific ISG. The application of the approach provided the following insights:

- The implementation of the use case methodology, in particular of the *Use Case diagrams*, *Technical Details* and *Step-by-step analysis* stages, is crucial to fully understand the effect the implementation EFMs might have on the production site. The subdivision of the EFM in individual activities, as performed during the development of the *Use Case diagrams*, allowed to fully identifying the sequence in which events should take place to achieve the different modes of operation, identify which are their triggering events, and the actor-activity relationships. Based on the developed diagrams, the building up of the *Technical Details*, which consists of the creation of the actors' list of each EFM and the assignment of roles to some of these actors, was considerably straightforward. The diagrams allowed the identification of actors that initially were not considered relevant for the activation of the specific EFMs. Likewise, the *step by step analysis* allowed for potential previously unidentified influences and risks of the retrieval of EFMs on the material, energy, information flows to also become clear.
- The build-up of the *Component Layer* serves as a comparison between the current and should IT infrastructure of the site. It served to also identify components, that are currently available on-site but for which relevant capabilities are not yet being used.
- The construction of the *Business, Function and Information Layers* outlined in detail the necessary specifications that are required in hardware and software to connect the industrial systems with the external stakeholders. They also served as a crucial input for innovative plant management strategies to optimize the energy flows within the plant.

Overall, the implementation of the proposed approach allowed to identify gaps in the current energy and information flows, which can substantially improve the transparency, resilience and, of course, flexibility, of the analysed production site. Furthermore, once the design was concluded it was clear that although its main goal was the inclusion of IEF, other energy management goal, i.e. efficiency, resilience, can also be easily achieved by the designed ISG. The presented approach, therefore, allows for industrial sites, of any nature, to develop smarter energy grids that increase the productivity and competitiveness of the site.

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