Design of a flexibility hub within a Net-Zero Energy Factory. The MESH4U demonstrator

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Abstract

Industrial facilities might offer a high contribution to the integration into the grid of the volatile power generated by renewable energy sources (RES). In order to do that, flexibility must be identified, quantified and exploited. The flexibility might be exploited through the control of the manufacturing processes and/or by designing other flexibility options, such as energy storage systems (electric, thermal and compressed air) or controlling the logistic sector if it is electrified. Within the ERA-NET Project "MESH4U," the flexibility of an industrial facility is used both for operating the facility as a Net-Zero Energy Factory and to react to signals sent from a central flexibility hub. The aim of the study is to present the MESH4U demonstrator by pointing out the solutions developed for identifying, quantifying and exploiting the flexibility and how such flexibility could be used to better integrate the power generated by volatile RES.

Keywords

Digitalization, Energy Storage, Flexibility Hub, Net-Zero Energy Factory, Renewable Energy Sources

I. INTRODUCTION

The decarbonization process requires that renewable energy sources (RES) supply power to be consumed in the electric, gas, thermal and mobility sectors. The electric grid will play an important role because most of the RES power generated will be supplied in an electric form and successively converted into other forms, such as gas (hydrogen, methane or compressed air), heat (hot water or steam) and mobility (by charging batteries of electric vehicles). In this view, the integration into the electric grid of the power generated by volatile RES is a huge challenge [1]. Industrial facilities might contribute to unloading the task of the system operators [2]-[3]. On the one hand, industrial facilities hide a set of flexibility options that need to be exploited, while, o the other hand, if the industrial facilities were operated as Net-Zero Energy Factories (NZEF), less volatile power would be fed into the grid. Consequently, system operators had to cover fewer costs to integrate the power generated by RES.

There are many definitions of NZEFs in scientific literature. The companies TESLA and Mitsubishi define NZEFs as facilities enabling locally generated electric power by RES to cover the annual electric demand of the factory [4]-[5]. In this study, the definition given in [6]-[8] will be considered. The NZEFs are defined as industrial facilities able to locally produce electricity using volatile RES, and to integrate it for covering the manufacturing loads by avoiding feeding the excess of electricity generated into the external grid. In such a view, the design of NZEF advantages both the factory operators by decreasing their energy costs and the system operators because less volatile power is fed into the grid.

Designing a flexibility hub enables the exploitation of the flexibility needed for operating an industrial facility as a NZEF, however, such flexibility could also be used by external actors during the time when it is not being used by the factory operator. For this purpose, the digitalization of the industrial infrastructure plays an important role. Indeed, the metering of the loads and generation within manufacturing systems allows one to identify and quantify the intrinsic flexibility that could be exploited by the industrial process.

The aim of the study is to point out the methodology developed to design a flexibility hub to operate a German carpentry as a NZEF included in one of the demonstrations of the ERA-NET Project "MESH4U"[9]. The particularity of such a flexibility hub consists of the possibility that it could be also used by an external actor (such as a system or an energy community operator)

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during the time when the factory operator is not using it (i.e. during the weekend or at night). The flexibility hub designed, therefore, might not only contribute to operating an industrial facility in a sustainable way, but it could also offer the possibility of generating extra cash flow if the flexibility designed is offered to external actors.

II. NET ZERO ENERGY FACTORY AND FLEXIBILITY OPTIONS

The electricity generated by RES within a NZEF must be balanced at every time step by avoiding surplus being fed into the external grid. Industrial facilities generally use electricity to drive thermal, gas (mostly compressed air) and logistic (mobility) processes. It implies that the exploitation of flexibility should have a holistic view to match the power generated by the volatile RES and the industrial loads better. Different flexibility options must be designed for operating an industrial facility as a NZEF. Figure 1 shows a concept of the flexibility options that could be exploited within industrial systems. Energy storage offers a large degree of flexibility. However, this option must be carefully designed due to the investment costs required and the energy losses related to the charging and discharging phases [11]-[12]. The electrification of the logistic sector [13][14] or the thermal processes [15] enlarges the options to be exploited for increasing flexibility. In the former case, logistic fleets must be optimally charged to fully exploit the flexibility potential, indeed, matching between high RES availability and the charging process is essential to contribute positively to balancing the energy fluxes within the industrial facility network. Moreover, if the charging infrastructure allows it, the logistic fleet could additionally increase the flexibility by feeding the power discharged from the batteries of the electric vehicles into the industrial facility grid. The control of the air temperature and the adoption of thermal storage systems also contribute significantly to increasing the flexibility options for optimally integrating the volatile RES into the industrial system. The variation of the manufacturing production rate is one of the options to increase the degree of flexibility of the industrial facility [16]-[18]. Discrete (customer-oriented, job shop and batch) processes are generally more suitable for exploiting flexibility if they are compared to the repetitive and continuous processes (see Figure 2). Material buffers allow one to anticipate or postpone industrial processes, exploiting not only the power but also the time flexibility [19].

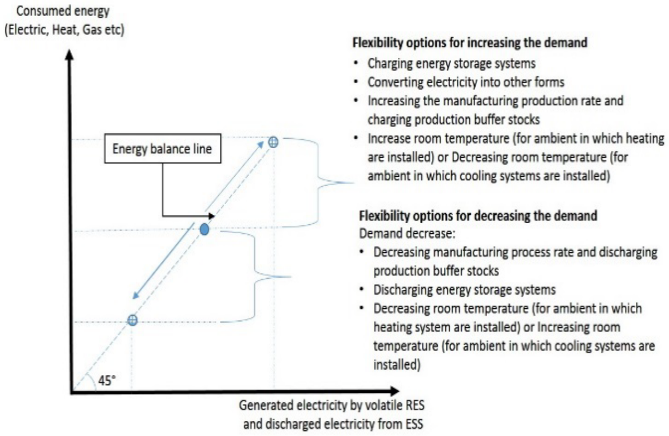

Figure 1 Flexibility options for operating an industrial facility as a NZEF

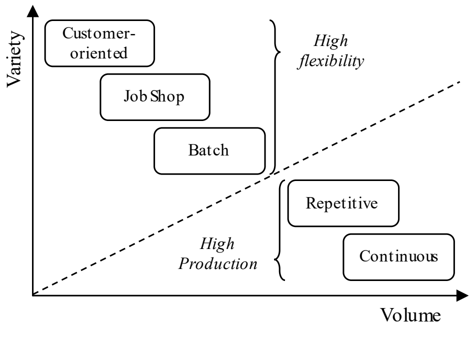

Figure 2 Correlation between industrial processes and the exploitation of flexibility

The energy balance can be defined as in Eq. (1), in which P_g and P_d depict the electric power generation from RES and the electric power demanded, respectively. The power generated and demanded has to be balanced during the generation times, t_i and t_f, which represent the initial and final electric power generation times, respectively.

$$NZEF_{balance} = \int_{t_i}^{t_f} P_g(t)dt - \int_{t_i}^{t_f} P_d(t)dt \leq 0 \tag{1}$$

Flexibility is required due to the volatile nature of the power generation. Considering T as the time frame of the electricity generation, such that $\mathbf{T} = \{t_i, t_j, \ldots t_f\}$, which is divided into t_j equal intervals (i.e. 15 min), the flexibility (φ) during the entire time frame **T** could be written as in equation (2), in which ΔP_{dj} is the change of demand in the time intervals t_j due to the change of the power generation ΔP_{gj} during the same time interval t_j.

$$\varphi = \frac{\Delta P_{dj}}{\Delta P_{gj}} \tag{2}$$

III. DESIGN OF A FLEXIBILITY HUB WITHIN A GERMAN CARPENTRY: THE MESH4U DEMONSTRATOR

The MESH4U demonstrator aims to develop a methodology for designing flexibility hubs. A German carpentry has been specifically considered. The carpentry generates electricity locally using a photovoltaic plant with an installed capacity of 126 kW. The electricity generated is fed into the external grid due to the contracts signed with the local system operator. The demand for electric power varies day by day. A maximum value of about 96 kW has been registered. Figure 4 shows an exemplary week during the springtime of 2022. The electric load demanded is day by day never identical because the carpentry adopts job-shop processes.

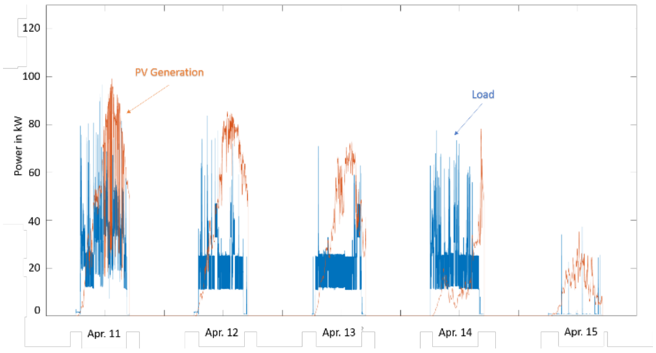

Figure 3 Load and generation profiles during a spring-summer week in 2022

The carpentry will be operated as a NZEF within the MESH4U project. Its main characteristic consists of integrating the power generated from the photovoltaic plant within the industrial facility. The aim is to avoid that part of the power generated being fed into the grid. This operating strategy will be conducted on weekdays (Monday to Friday) during the operative time 06:00–17:00.

Two main functionalities have been developed for operating the flexibility hub. On the one hand, it must supply the flexibility required for operating the carpentry as a NZEF (it is called internal flexibility), while, on the other hand, the flexibility hub must be able to receive signals from external actors (i.e. energy community operators, virtual power plant operators or system operators) and offer them the flexibility demanded (external flexibility) during the time of no or low operation of the factory. Figure 4 shows the concept design of a flexibility hub for the German demonstrator of the MESH4U project.

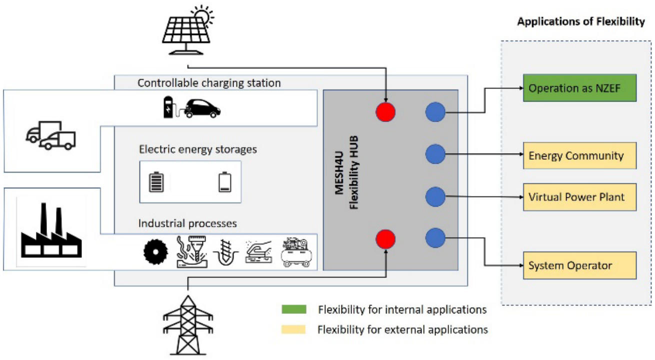

Figure 4 Flexibility hub within the MESH4U demonstrator in Germany

In order to design the flexibility hub, firstly, the hidden flexibility which could be exploited from the manufacturing processes has been identified and quantified. The methodology adopted for identifying and quantifying such a flexibility is based on the digitalization of the infrastructure and it is described in [20]. The exploitation of such flexibility consists of sending visual signals to the machine operators informing them that the process of the machine operated could be anticipated or postponed. A decision-tree (DT) based algorithm has been developed for elaborating the visual signals. The DT algorithm elaborates the historical data of all the machines and suggests which machines could be selected to increase or decrease the power. The objective function is to maximize the matching between the forecasted power generation and the forecasted power consumption.

The exploitation of such a flexibility is strongly constrained by the social aspects. The machine operators are not always able to follow the elaborate signals. For this reason, two batteries have been installed in order to increase the options which the flexibility hub might use. The batteries have an energy capacity of 40 kWh and a power capacity of 20 kW. In order to reduce the energy losses of using the batteries, the hierarchy of the flexibility exploitation considers as first option the flexibility that the machine operators could exploit by following the visual signals. In the case the exploited flexibility is not enough to match the power generation and the power consumption then the batteries are controlled. In addition to this, also a charging station has been installed. It can charge up to two electric vehicles with a total power of 44 kW. In the hierarchy of the flexibility exploitation, the charging station are selected as last (third) option.

Figure 5 shows the graphic user interface developed informing the machine operators how they could operate the machine in the next 15 minutes. If an energy shortage is forecast, then some processes should be anticipated. If an energy surplus is foreseen, then more processes should be performed within the next 15 minutes. If the energy generation forecasted equals the demand of electricity forecasted, then the scheduling of the processes should not be changed.

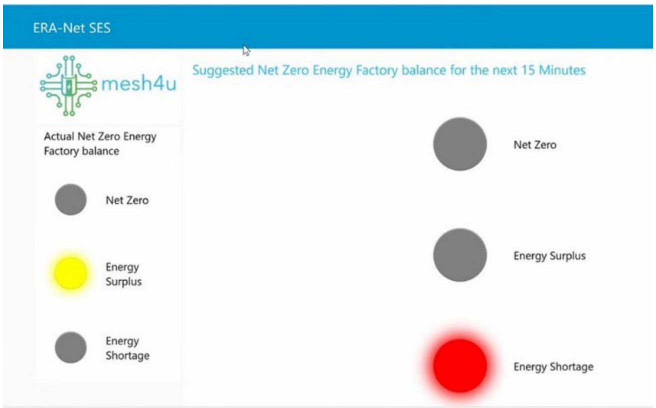

Figure 5 Visual signals to inform the machine operators to anticipate or postpone processes

IV. DESIGN OF THE COMMUNICATION PROTOCOL WITHIN THE FLEXIBILITY HUB

The flexibility hub could also be used to supply flexibility to external users, such as energy community, system or virtual power plant operators (see Figure 6). Such an option might be exploited mostly when the factory is not operating, namely, during the night and at weekends. All the users that wish to use the flexibility of the hub need to establish a WebSocket connection with it [21]. Unlike the client-server communication model, where only one party initiates the request and the other party only responds to the request messages, the WebSocket connection enables bidirectional communication through the internet where both parties can start a request message. In this protocol, when the flexibility hub receives a request from an external user, it must respond to the request stating whether it can be accepted or rejected. When the request is rejected, the response message contains a reason for the rejection.

The design of the flexibility hub with such a characteristic allows the NZEF operator to generate extra cash flows, which can speed up the cashback for that investment. Smart contracts based on blockchain technology could be developed to bill the utilization of the flexibility hub properly [22][23].

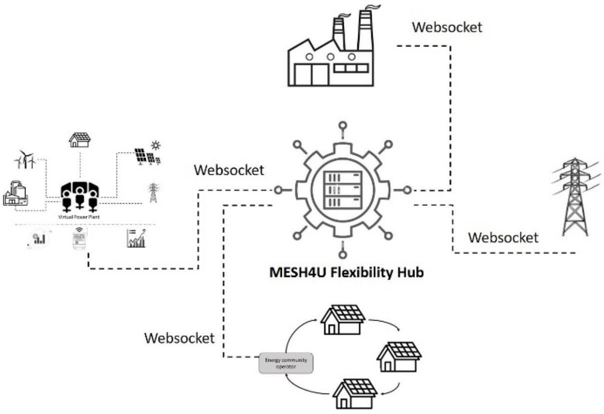

Figure 6 Websocket connection between the flexibility hub and the flexibility users

A. *Initial steps of connection*

All messages between an industrial unit and the central flexibility hub are on an encrypted communication channel (i.e. https:// or wss://). Initially, the industrial unit sends an HTTPS to WebSocket Upgrade request. This request also contains credentials to identify the industrial unit. After verifying the request credentials, the central flexibility hub and the industrial unit will connect using a WebSocket connection. Information about flexibility options provided by an industrial unit is sent as a request to the central flexibility hub. The request message contains the time range the central flexibility hub can control the industrial plant, current energy stored in the plant, maximum storable energy and power ranges that the plant can offer for different energy ranges. By sending information like this, the plant can send its degree of flexibility without exposing its internal electrical infrastructure. The central flexibility hub will process the request and send a response message containing a root/default load profile that the industrial unit has to maintain.

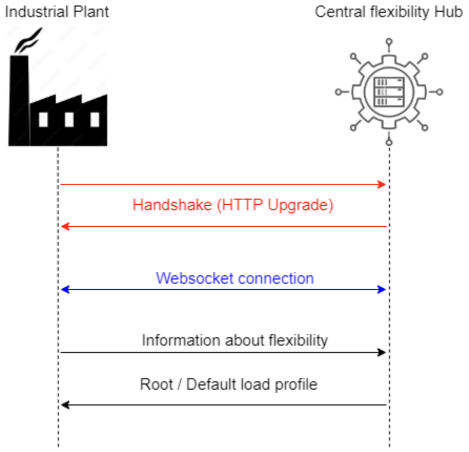

Figure 7 Flow of messages during the initial WebSocket connection

B. *During operation*

The central flexibility hub sends root/default profiles, whose ID value is 0, to all connected industrial plants; this profile is calculated based on historical load data. During controlling the industrial plant's flexibility by the central flexibility hub, it sends several load profiles based on real-time dynamic changes to the anticipated load. All load profiles contain an ID value, so, when there are multiple load profiles for the same time range, the industrial unit will follow the one with the highest number.

In the same way as the central flexibility hub sends load profiles due to dynamic changes, the industrial plant also responds to unanticipated internal changes. These changes can be due to a fault of the internal electrical infrastructure or sudden unplanned internal load demand. When such changes happen, the industrial unit sends a request message containing updated information about the flexibility options that it can provide. It is up to the central flexibility hub how it will respond. It can send a new profile with the highest priority to the industrial unit, or it can request the industrial unit to clear all the load profiles and send a new root/default profile based on new information provided by the industrial unit.

During operation, if the central flexibility hub loses connection with the industrial unit, then the central flexibility hub will wait for some threshold time until the industrial unit reconnects, and if the industrial unit fails to do so, the central flexibility hub assumes that the industrial unit will not participate in flexibility control and sends new calculated profiles to other connected industrial units. Similarly, if the central flexibility hub is unreachable, the industrial hub will try to connect several times with a delay. After several attempts, if the central flexibility hub is still unreachable, then the industrial hub will pause following the load profiles sent by the central flexibility hub.

C. *Exiting the connection*

Industrial hubs can remain connected even after the flexibility control session is completed. If the industrial unit wishes to close the connection, it will send a request message stating it will close it. The central flexibility hub will respond with an acknowledgement and an expected reconnection time. The industrial unit can disconnect and should attempt to reconnect when the actual time equals the reconnection time expected.

V. CONCLUSIONS

The design and exploitation of flexibility options are one of the main challenges for the decarbonization of the power system. Industrial facilities might be designed as NZEFs and contribute to integrating the electric power generated by volatile RES better. A flexibility hub has been designed within the ERA-NET MESH4U project. It is able to supply the flexibility required to a German carpentry for operating it as a NZEF. In addition, its flexibility could be offered to external actors, such as system, energy community or virtual power plant operators, during the time when the flexibility hub is not used by the industrial facility.

Different solutions have been developed for exploiting the needed flexibility to operate the industrial facility as a NZEF. The hierarchy of flexibility exploitation selects as the first option the machine operators and successively the stationary and mobile batteries which have been installed. Operating in such a way, the energy losses due to the charging and discharging of the batteries are minimized.

From the industrial facility point of vies, the design of a flexibility hub might be an added value which could generate extra cash flows. Indeed, it could minimize the power drawn from the grid, maximize the self-consumption of the power generated by the PV plant and share the flexibility to system or energy community operators.

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