Net-zero energy factory: Exploitation of flexibility – A technical-economic analysis for a German carpentry

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Abstract— **Industrial facilities hide a high potential of flexibility, whose exploitation might contribute to accelerating the decarbonization process. This study deals with the identification, quantification and exploitation of flexibility within a German carpentry works. The exploitation of flexibility is considered from the point of view of the factory manager with the aim of operating the factory as a net-zero energy system. A methodology for the identification and quantification of the flexibility has been implemented. A technical and economic analysis has been performed to evaluate the benefits of operating the carpentry works studied as a net-zero energy factory. The simulations point out that about 79 % of the renewable energy source power generation can be integrated directly into the manufacturing system through the methodology suggested. The required investment might be paid back within nine years.**

Keywords— Flexibility Options, Job Shop Process, Net-zero Energy Factory, Renewable Energy Sources.

I. INTRODUCTION

Many European countries have accelerated their action plans to decarbonize the power system since the ratification of the Kyoto protocol. Among the action plans, the economic incentive to generate electric power by using renewable energy sources (RES) has received the highest success. Many operators of small and medium enterprises (SMEs) have taken the opportunity to install photovoltaic (PV) panels on the roof of their enterprise's buildings. In the majority of the cases, PV plants are operated according to the *feed it* and *forget it* approach, which establishes the feeding of the generated power into the external grid. The incentive to operate PV plants in such a way is guaranteed in almost all the European countries for 20 years. When this time expires, the PV can still feed the grid, but the PV plant operators no longer receive any incentive or are only paid a very low price. The price paid in Germany, for example, after the expiration of incentive time is about 20-25 €/MWh, which is 10-15 times lower than the electricity price paid by a small residential consumer [1]. It is expected that about 10.6 GW of solar panels installed on German SMEs' buildings will expire their incentive time by 2031 (see Fig. 1). In such a context, operating an industrial site as a net-zero energy factory (NZEF) might become an attractive business model for SME operators. However, the full integration into the industrial processes of power generated by volatile RES might require huge investments if it is realized by only using energy storage (electric and thermal) [3]-[4]. Indeed, energy storage systems, mostly the electric ones, are still very expensive [5]-[7]. Therefore, other solutions should be investigated in order that SME operators might plan and operate industrial sites as NZEFs. Accordingly, new flexibility options need to be identified, quantified and sized.

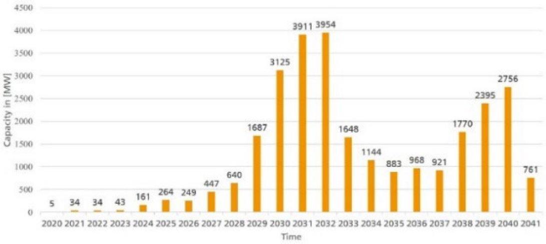

Fig. 1 Photovoltaic capacity expiration installed on German SME buildings [2]

The flexibility of the load consumed within industrial systems can be exploited in different ways. Demand side management programs offer different options to match the load with the power generated by volatile RES better (see Fig. 2 [8]-[9]. Valley filling aims to increase the power consumption at the time in which the load is generally low. Load shifting allows anticipation or/and postponement processes. It might entail the rescheduling of the industrial process [10]. Strategic load growth and conservation ensure that the consumption increases or decreases, respectively. Such a flexibility is generally associated with a material storage [11]-[12]. Peak clipping enables the decrease of the power consumption in particular situations. Flexible load shape enables the load to be changed continuously according to defined control signals.

Regarding particular industrial architecture, energy storage systems (i.e. batteries) and/or smart transformers might be used [13]-[14]. Flexibility can be also achieved through frequency converters, which control the speed of electric motors. However, the speed control of the electric motors in manufacturing processes might affect the quality of the manufactured items required [15].

It is mostly used in the processes in which mass is subtracted (i.e. grinding processes). Differently from the exploitation, the identification and quantification of the flexibility of loads might be achieved in different ways. Smart agents for identifying and exploiting flexibility within industrial systems have been developed in [16]. The analysis of metered data of active power consumption has been used in [17] for identifying and quantifying the flexibility exploitable by a tertiary system. Recurrent neural network models and model-based clustering layers have been developed for quantifying the flexibility of an industrial conveyor within manufacturing processes [18].

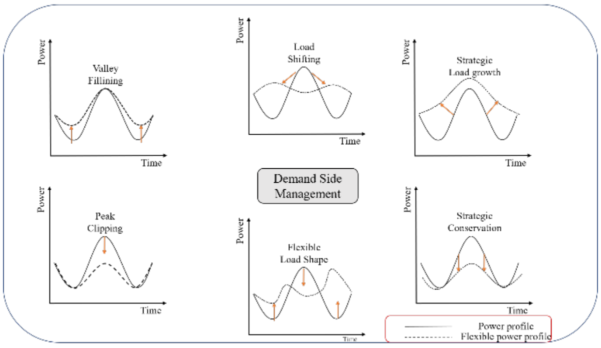

Fig. 2 Examples of demand side management programs

Operating manufacturing processes as a NZEF allows the volatility problems going into the grid to be reduced and, therefore, support system operators by compensating for it. Such a double effect also affects the social acceptance of the power generated by RES. The costs that the small consumers generally pay for the actions used by the system operators to compensate for such a volatility are decreased by reducing the volatility problems going into the grid.

This study contributes to formulating a definition of NZEFs and developing a technical-economic methodology for identifying, quantifying and exploiting flexibility within job shop processes has been developed. The methodology developed is applied to a small carpentry works located in Germany. The methodology allows one to better plan the flexibility options needed for designing and planning the carpentry works considered as a NZEF. The study is structured as follows: the formulation of NZEFs is given in section II. Section III deals with the methodology for identifying and quantifying the flexibility within job shop processes. A study case considering a small carpentry works located in Germany is explained in section IV in which the main results are described. The conclusions and outlooks are listed in section V.

II. NET-ZERO ENERGY FACTORY

"Net-zero energy" is generally understood as a system (residential, tertiary or industrial) in which the energy demand (electric, thermal, energy for transportation) is balanced through the generation of energy (electric and/or thermal) produced on-site [19]. The terminology "net-zero emission" system is sometimes used. In this case, the emphasis is given to the balance of the emissions of greenhouse gases within a determined system [20]. However, in many cases, not only RES-based technologies are considered but also carbon dioxide neutral ones, such as nuclear or natural gas plants coupled with carbon capture and sequestration plants [21]-[23]. The time horizon during which the energy generated balances the demand is usually extended to one year. Therefore, the solutions developed within the net-zero energy system (NZES) field generally focus on the optimal planning and sizing of the power generation and the energy storage systems enabling the supply of energy (electric and thermal) to the site considered [24]-[27]. Different NZES applications have been already realized in various industrial sites. The companies Tesla and Mitsubishi have already adapted their industrial sites as NZEFs [28]-[29]. However, in these cases, the planning actions chosen have also focused on improving the energy efficiency of the site, investigating energy harvesting solutions and integrating power generation technologies (i.e. PV) in the industrial building. A different definition of net-zero energy has been formulated in this study. As net-zero energy is understood as a system able to generate power (electric and/or thermal) using volatile RES located in the site considered, the NZES defined has to be able to fully integrate the power generated into its infrastructure as a unique selling point. Therefore, the power generated (if electric) should not be fed into the grid but consumed or stored within the NZES. Such a system allows the power generated by volatile RES to be exploited better, avoiding the transfer to the system operator's power balancing problems. However, system operators might supply the NZES if the weather conditions are not favorable to generate the energy (electric and thermal) demanded locally. Such a NZES might contribute, therefore, to extending the operating lifetime of the RES-based power plants after the expiration of the incentive time. The planning actions of a NZEF so defined requires not only choosing and sizing the best energy generation technologies but also identifying, quantifying and exploiting the intrinsic flexibility which is hidden in the industrial processes. In addition, the operation of such a system needs an intelligent energy management system, which optimally controls the loads and the flexibility options identified with the aim of fully integrating the power generated by RES into the industrial site. In order to do it, the control system should be able to monitor all the flows (electric, gas, thermal and material) of the NZEF. Standardized protocols, such us MODBUS TCP or OCP-UA, could be used for communication between metering devices and the data acquisition platform [30]-[32]. Differently from the classic definition of NZES, the energy is balanced only during the RES generation time. Therefore, the NZEF energetic 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. The exploitation of the flexibility should avoid that the value in Eq.(1) becomes higher than zero since in this case RES power will be fed into the grid.

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

The flexibility potential within the NZEF is defined as the capability of the industrial process to change its energy demand according to the power generation by RES. Considering T as the time frame of the electricity generation, such that **T** = $\{t_i, t_j, \ldots t_f\}$, which is divided into t_j equal intervals (i.e. 15 min), then 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. IDENTIFICATION AND QUANTIFICATION OF THE FLEXIBILITY IN JOB SHOP PROCESSES

The industrial processes of SMEs are generally discrete processes [33]. Customer-oriented and job shop are typical discrete processes, which generally offer a higher flexibility potential than continuous or batch processes [34]-[35]. The methodology for identifying and quantifying the flexibility potential within industrial processes has not yet been standardized and it depends on many factors. Different models and tools have been developed in the last few years enabling industrial processes to be represented through energy and material flows, human resources and external factors, such as ambient temperature, electricity price signals or weather conditions. A variety of models, including agent and multi-agent [36]-[37], algebraic logical [38], regression [39]-[40], state-space [41]-[42], data mining methods [43]-[44] and graphical models [45]-[46], are used for manufacturing system analysis and to perform indicators. A methodology has been developed in this study which is based on the metering of the active power consumption of the manufacturing machines. The methodology is a readjustment of the manufacturing processes of the methodology suggested in [17]. It is based on the axiom that by metering the same consumption profiles for a long time (i.e. different months), if the pattern of the loads metered is never identical, then these loads hide a flexibility potential. The application of this methodology to discrete manufacturing processes can be described in eight steps:

I. Description of the manufacturing process
II. Metering of the electricity consumption of all the devices and machines within the factory
III. Qualitative analysis of the data metered
IV. Classification of the electric load among controllable loads (P_{con}) and non-controllable loads (P_{ncon})
V. Evaluation of the difference between P_{con} and P_{ncon} of each t_j time interval
VI. Sorting the positive values calculated at the point V in decreasing order and the negative values in increasing order
VII. Evaluation of the flexibility duration curve
VIII. Statistical analyses

The value calculated at point V depicts the denominator of equation (2). If it is positive, then the load can be decreased. Contrarily, if the difference is negative, then the load can be increased. Such a flexibility consists of postponing (decrease of load) or anticipating (increase of load) processes which needs to be rescheduled at the time in which the consumption matches the power generated by RES. A way to evaluate the degree of flexibility of the manufacturing processes is to rate the difference which is estimated at point V to the maximal total power consumption of the processes (see equation (3)), in which t_{ip} and t_{fp} depict the initial and final time, respectively, during which the manufacturing processes are activated.

$$\phi = \frac{[P_{con}(t) - P_{ncon}(t)]}{\max\,[P_{con} + P_{ncon}]} \cdot 100; t \in [t_{ip}, t_{fp}] \tag{3}$$

Such a methodology, therefore, allows the manufacturing processes aiming to increase the matching effect (ME) to be scheduled between the power demanded and the power generated by RES (see equation (4)). The ME within the NZEF concept should be never higher than 1. It is calculated only when the RES plants generate power ($P_g(t) > 0$) and only when the factory is in operation ($P_d(t) > 0$)

$$ME_{NZEF} = \frac{\int_{t_i}^{t_f} P_g(t)dt}{\int_{t_i}^{t_f} P_d(t)dt},\; P_d(t) \cup\; P_g(t) > 0 \tag{4}$$

In addition to the scheduling of manufacturing processes, the speed control of the machines allows the quantity of the flexibility options to be used to operate the factory at net-zero energy to be increased. The flexibility offered by the speed control of machines can be evaluated as in equation (5), in which P_{nom} depicts the nominal power of the motor and $P_{op}(t)$ represents the power consumed by the machine at its operating point. P_{op} depends on the motor speed of the machine (n) and on the torque (M) required by manufacturing processes (see equation (6)).

$$\phi_{sc} = \frac{[P_{nom}(t) - P_{op}(t)]}{[P_{nom}]} \cdot 100; t \in [t_{ip}, t_{fp}] \tag{5}$$

$$P_{op} = \frac{n}{60} \cdot 2\pi \cdot M \tag{6}$$

The quantification of such a flexibility can be graphically explained through the representation of flexibility duration curves. Such curves depict the power and the time of the loads which could be consumed before or later than usually scheduled. Every line depicted in the flexibility duration curves represents the electric load of a particular machine during a working day for which the suggested methodology has been applied. The flexibility duration curves can also be realized for a group of loads.The concentration of lines in the range of particular values (for the power and time) indicates the probability that the load of the considered machine could be flexibilize by anticipating it (negative flexibility) or postponing is (positive flexibility) (see points V and VI of the suggested methodology).

IV. FLEXIBILITY EXPLOITATION WITHIN A GERMAN CARPENTRY WORKS: A CASE STUDY

A carpentry works located in Magdeburg (Germany) has been considered as a case study. A PV plant with an installed capacity of 126 kW supplies electricity to the carpentry works. In order to time the power generated, it is firstly fed into the grid and successively drawn from the grid to supply the industrial processes. TABLE I summarizes the main parameters of the energy generation and consumption within the carpentry works.

In order to identify and quantify the flexibility potential hidden in the manufacturing processes of the carpentry works, twenty meters have been installed for measuring the electricity consumption of all the manufacturing machines and other loads which do not take part directly in the manufacturing processes. The processes have been classified into two groups: controllable loads and non-controllable loads. Five processes belong to the first group: sawing, milling, drilling, air compression and air suctioning. Among these, the milling and drilling are considered to be supplied through machines provided with frequency converters. The main parameters of the controllable and non-controllable loads are listed in TABLE II, while the total load and the load of all controllable loads during a metered week are shown in Fig. 3 and Fig. 4, respectively.

TABLE I Yearly electricity demanded and generated within the carpentry works considered

	Electricity demanded	Electricity consumed during the generation	Electricity generated
Energy in MWh	62.4	31	120

TABLE II Rated power consumption

Production processes	Maximum operating power in kW	Minimum operating power in kW	Average operating power in kW
Sawing	11.5	3.9	5.8
Milling	13.3	4.6	6.2
Drilling	12.1	4	5.9
Air compression	38.4	0.6	6.1
Air suctioning	29.6	2.6	14.3
Office and other loads	53.5	2.8	21.6

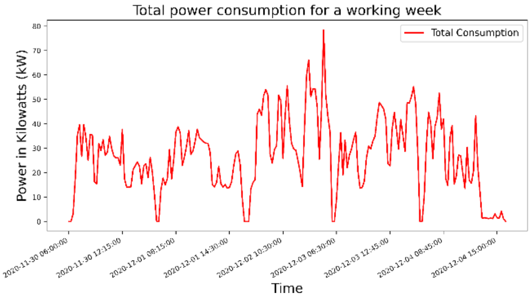

Fig. 3 Metered total power consumption

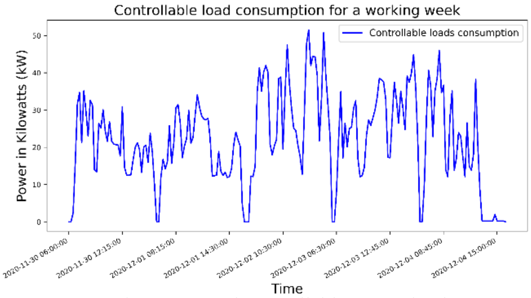

Fig. 4 Metered controllable power load

The methodology explained in section III has been applied for the identification and quantification of the hidden flexibility. Such a methodology might allow the factory operators to schedule their manufacturing processes better with the aim of increasing the matching effect between the power generated by the PV plant and that consumed within the NZEF approach. Decision tree (DT) algorithms have been developed for scheduling the processes. More and more applications based on DT algorithms have been developed for scheduling job shop processes in the last few years [47]. The main advantage of such algorithms lies in the need for few computational resources. The DT algorithms select the most appropriate combination of processes which should be scheduled [48]. As a main attribute, the DT algorithms consider the energy demanded by every single process whose value has been performed through the statistical analysis of the metered data. The DT algorithms anticipate or postpone manufacturing processes with the aim of minimizing the energy balance by checking the energy balance between the predicted energy generated by the PV plant and that required by the whole manufacturing system (see equation (7)).

$$\Delta = \int_{ti}^{tf} [P_g(t) - P_d(t)]dt \tag{7}$$

In addition, the drilling and milling processes might be controlled in real time to match the power generated by the PV plant better. It has been assumed in the case study considered that the electric motors driving these processes are controlled by frequency converters. Constraints have been considered for the maximum and minimum speed of the motors. Such constraints are mostly imposed by the relation between the motor speed and quality of the items manufactured. Low speed or very high speed effect the surface quality required. TABLE III shows the technical values considered for the speed control for the milling and drilling processes.

TABLE III Operational range for the optimal surface quality of the wood product [49]-[50]

Process	R-Double Drill	Table Milling Machine
Minimum speed in rpm	1000	12000
Maximum speed in rpm	3000	18000
Operation torque in Nm	38.5	7.0
Minimum operating power in kW	4.0	8.9
Maximum operating power in kW	12.0	13.3

In order to estimate the goodness of the solution developed, 15 min matching effects during six working weeks have been evaluated. Fig. 5 shows the heat map of the matching effect of the carpentry works as it is actually operated. Red spots depict the situation in which the electric power generated by the PV plant is higher than the electricity demand. In this case, power is fed into the grid. Blue spots (from dark to bright) depict the case in which the power generated by the PV plant is not enough to cover the manufacturing loads. In this case, power is withdrawn from the grid. White spots represent the case in which the power generated by the PV plant matches the power demanded exactly. In this situation, the facility is operated as a NZEF. Fig. 6 shows the matching effect during the same time period in which the flexibility identified is exploited. By considering one year analysis, the methodology developed allows the matching effect to be increased by about 30 %, switching the matching effect from 49.6 to 79 %. Fig. 7 represents the flexibility duration curve for the drilling and milling processes which could be exploited if these processes are reduced in speed. Each curve depicts a working day. The concentration of the curves near a particular value of the power indicates the flexibility potential in the power, that the combination of drilling and milling processes offers if they were postponed. How long that power could be postponed is indicated from the concentration of the lines towards the x-axis. For example, the potential to postpone 2 hours later processes with a total power consumption of 4,3 kW is very high. This flexibility could be exploited by decreasing the speed of the milling and drilling processes and therefore by reducing the rate at which wood items are manufactured. The maximal power which can be postponed through the speed control is about 12 kW. However, this power cannot be postponed longer than 5 h. Lower power (about 1 kW) could be postponed for a longer time (about 7 h).

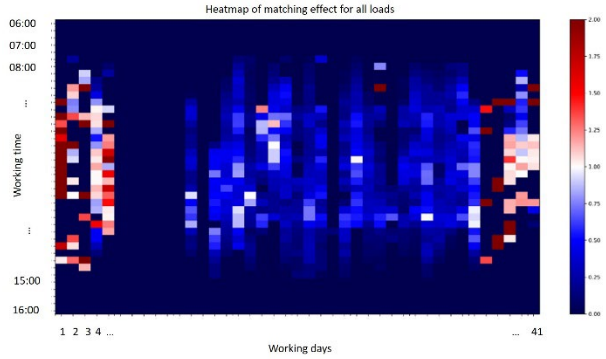

Fig. 5 Heatmap representation of the matching effect without exploiting the flexibility identified. Data recorded from 04.11.2020 to 31.12.2020

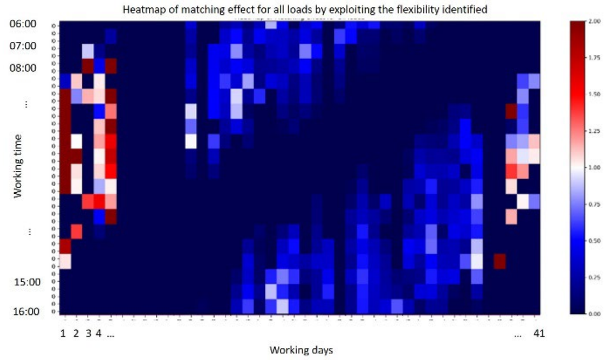

Fig. 6 Heatmap representation of the matching effect by exploiting the flexibility identified. Data recorded from 04.11.2020 to 31.12.2020

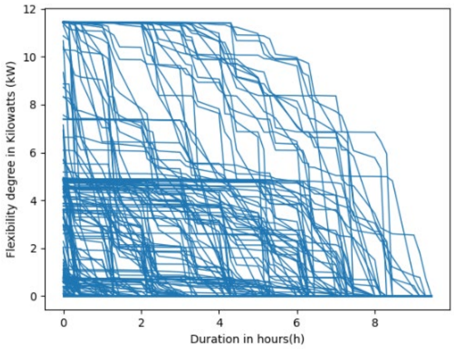

Fig. 7 Positive flexibility duration curve for drilling and milling processes

The exploitation of the flexibility identified allows the matching effect of the manufacturing process to be increased and, therefore, the integration of the power generated by the PV plant into the facility is also increased. By excluding the advantages that a green production might bring to the image of the facility and considering the case in which the incentive time of the PV plant is expired, the adoption of the methodology suggested might bring economic advantages to the carpentry works considered. Indeed, by simulating a year's manufacturing process, about 79 % of the electric power generated by the PV plant can be integrated directly in to the manufacturing processes. A payback time of nine years is expected considering an electricity price of 200 €/MWh and the investment costs listed in TABLE IV. However, it is important to point out that the results obtained do not take into consideration that the flexibilities identified must be operated by human resources, which can limit the flexibility potential. It is mostly true for job shop processes.

TABLE IV Economic and technical values

	Meters	Frequency converter [51][52]	Electricity	Matching Effect
Investment in €	20,000	3,068		
Price in €/MWh			200	
RES integration in processes %				79

V. CONCLUSIONS

The operation of facilities as NZEFs might contribute to speeding up the decarbonization process and could be an attractive business model for the factory operators. In this study, a German carpentry works which is operated as a job shop process has been analyzed. The carpentry works also generates electricity through a PV plant. At this time, about 49 % of the electricity generated is integrated directly into the manufacturing processes. A methodology has been suggested for identifying, quantifying and exploiting the flexibility within the carpentry works considered. The methodology foresees the use of meters and the adoption of variable speed drivers. Utilizing the methodology suggested, the integration of the PV generation into the manufacturing process reaches 79 %. The investment required to operate the carpentry works as a NZEF could be paid back within nine years.

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