Blockchain application within Net-Zero Energy Factories. A cost-benefit analysis for a German carpentry

Pio Lombardi
Fraunhofer Institute for Factory Operation and Automation IFF
Magdeburg, Germany
pio.lombardi@iff.fraunhofer.de

Sandeep Yadav Mattepu
Fraunhofer Institute for Factory Operation and Automation IFF
Magdeburg, Germany
sandeep.yadav.mattepu@iff.fraunhofer.de

Bartlomiej Arendarski
Fraunhofer Institute for Factory Operation and Automation IFF
Magdeburg, Germany
bartlomiej.arendarski@iff.fraunhofer.de

Marc Richter
Fraunhofer Institute for Factory Operation and Automation IFF
Magdeburg, Germany
marc.richter@iff.fraunhofer.de

Przemyslaw Komarnicki
Fraunhofer Institute for Factory Operation and Automation IFF/ Magdeburg-Stendal University for Applied sciences
Magdeburg, Germany
przemyslaw.komarnicki@h2.de

***Abstract*—The planning of Net-Zero Energy Factories might contribute to the better integration of power generated by volatile renewable energy sources into manufacturing systems. However, the investments needed for operating a Net-Zero Energy Factory might dissuade facility operators. The application of a blockchain might represent the missing element to make Net-Zero Energy Factories an attractive solution. The aim of this study is to present a cost-benefit analysis to plan a German carpentry as a Net-Zero Energy Factory. Businesses can increase the transparency of their energy usage by storing the Net-Zero Energy Factory's information, such as energy production, consumption and manufactured goods, in a blockchain. The increase in transparency can help to satisfy the regulatory compliance of green energy set by their respective governments. It is also helpful for businesses to demand higher prices while selling their products to customers, retailers and government projects.**

Keywords—Blockchain, Industry 4.0, Flexibility Options, Net-Zero Energy Factory, Renewable Energy

I. Introduction

The European Union (EU) has set a challenging aim to decarbonize the power system by 2050 [1]. Action plans have been drawn up through the European Green Deal to support power generated by renewable energy sources (RES). However, the decarbonization process requires the development of new flexibility options, which could facilitate the integration of the power generated by volatile RES into the grid [2]. Among these options, the planning of Net-Zero Energy Systems (NZESs), might be an attractive solution for speeding up the European Green Deal's action plans [3] [4]. Different NZES concepts have been formulated in the last few years. They consider both residential applications, such as houses or buildings, and industrial facilities. Even if there is not a unique definition of NZES, a common characteristic is that such systems are able to generate electric and/or thermal power using volatile RES, which is locally consumed. Most NZES concepts are designed to generate the annual power that they consume completely locally [5]. This is the case in the factories of Tesla [6] and Mitsubishi [7]. A definition of a Net-Zero Energy Factory (NZEF) is properly given in [8]. A NZEF is defined as an industrial facility enabled to generate electric and thermal power by volatile RES and consume it within the industrial system considered. The main characteristic is that the power generated (mostly electric) must never be fed into the external grid. The operation of an industrial facility in such a way allows one to manufacture in a reliable, sustainable and economic way. In addition, operating a NZEF also contributes to feeding lesser volatility into the grid and, thus, it indirectly supports the system operators, which will use fewer re-dispatch actions to balance the volatility in their grid.

The identification, quantification and exploitation of the flexibility is the first procedure for designing the flexibility needed to operate an industrial facility such as a NZEF. Energy storage systems (electric and/or thermal) generally offer a high degree of flexibility [9][10]; the electrification of the thermal processes (i.e. through heat pumps) also contributes to increasing the degree of flexibility which can be exploited [11]. The electrification of the logistics sector and control of the battery located in the logistic fleet have similar effects [12]. All these aspects must be considered and properly sized.

Regarding the facility managers, being able to manufacture CO_2-free products might open up new market opportunities. An increasing number of studies have pointed out how the supply chain must move forward to a net-zero concept in the near future [13]-[15]. Concerning a NZEF, blockchain technology can be used to track both the material and the energy flows. It will be a crucial element to certify CO_2-free production.

A German carpentry has been analyzed within this study. One of the demonstrators in the EU ERA-NET project MESH4U [16] aims to design a flexibility hub for operating a carpentry as a NZEF. This study aims to perform a cost-benefit analysis for the case in which sensors for the material flow track were installed in the carpentry considered and the data were saved within a blockchain system.

II. NET-ZERO ENERGY FACTORY: PLANNING AND DESIGN OF THE FLEXIBILITY OPTIONS IN A GERMAN CARPENTRY

The planning of NZEFs might be an attractive solution both for the facility operators and the grid operator. Indeed, within the given definition of NZEF, the power generated by RES should not be fed into the grid but must be consumed locally. The external grid will still play an important role in the cases in which the weather conditions are not favorable to generate enough electricity to cover all the loads located in the facility.

From the point of view of the grid operator, if industrial facilities were designed as NZESs, they must balance a lesser amount of volatile RES power in the grid. This will benefit not only the grid operator but also the small consumers, which generally cover the costs that the system operators face for integrating the volatile RES power into the grid.

Facility operators might have different benefits to design their industrial facility as a NZEF. It could be an attractive business model for all the facilities which want to operate a RES-based plant after the expiration of the incentive time (generally 20 years). Consequently, the facility's operative energy costs could be lower. In addition, the NZEF concept might also offer the manufacture of CO_2-free products to the facility operator. These could be sold labeling them as "green products." All these aspects should be considered during the decision-making process.

A carpentry located in Magdeburg (Germany) has been analyzed within the EU ERANET MESH4U project. It processes raw materials (wood) mostly through four industrial processes: sawing, milling, drilling and sanding (see Figure 1). Auxiliary processes, such as compressed air and air suction, are also activated when one of the four main processes is being implemented.

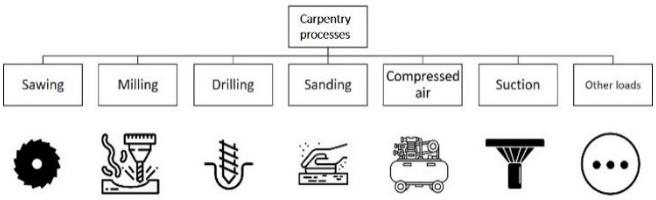

Figure 1 Main processes within the carpentry considered

A photovoltaic plant with a total power capacity of 126 kW is installed on the roof of the carpentry building.

Smart meters have been installed within the industrial site. They monitor all the loads and the power generation. Three kinds of flexibility options have been designed. Firstly, a passive demand-side management (DSM) has been developed. The methodology adopted for identifying and quantifying the degree of flexibility is described in [17]. The exploitation of flexibility is based on the use of artificial intelligence algorithms. They suggest that the machine operator anticipates or postpones processes according to an objective function that maximizes the matching between the power generation and the power consumption. Such a passive DSM has been realized using a traffic-light system (see Figure 2). A large monitoring device has been installed at the working station of the carpentry. When the green light is depicted, the machine operators continue their work as scheduled. When the red light is depicted, the machine operators are advised to adjust the scheduled working plant for the next 15 minutes by speeding down the process. In this case, some working processes will be postponed and the total electric load decreases. When the yellow light is depicted, the machine operators are invited to speed up the processes by anticipating some processes. Consequently, the total load increases.

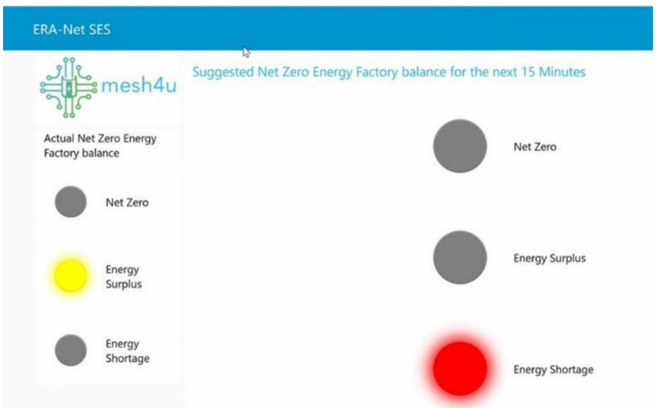

Figure 2 Passive DSM realized as a traffic light

Two battery systems have also been installed. They allow the storage of up to 40 kWh of electricity with a maximum power of 20 kW. Furthermore, a charging station allowing the charging of two electric vehicles up to 44 kW (22 kW per vehicle) has been integrated into the facility. Due to the energy losses during the charging and discharging of the batteries (stationary and mobile), these two flexibility options are activated only when the passive DSM is not enough to match the power generated by the photovoltaic plant.

III. Blockchain Application within Net-zero Energy Factories

The operation of the carpentry as a NZEF allows the facility operator to introduce new products, which could be labeled as "green products," into the market. A blockchain application has been designed to track the CO_2-free production of such items. Figure 3 shows the suggested architectures for operating the carpentry as a NZEF and tracking the energy and material flows.

Two approaches could be used for tracking the material flow: Firstly, when the material undergoes any machine operation that involves surface removal (such as a milling operation), machine operators enter the information about the start and stop of machining for each material on a dashboard. Secondly, a removable QR (quick response) code to the material is attached when it does not undergo further surface removal operations. The QR code is scanned to track the flow of materials. The information provided by both approaches is matched with the load profiles of machines, which gives the amount of energy consumed by a material at each production process. Each part of the product is scanned during the product assembly and, subsequently, the QR codes are removed. This gives detailed breakdown information of the amount of energy consumed by each part of the production process and the total energy consumed to manufacture the entire product.

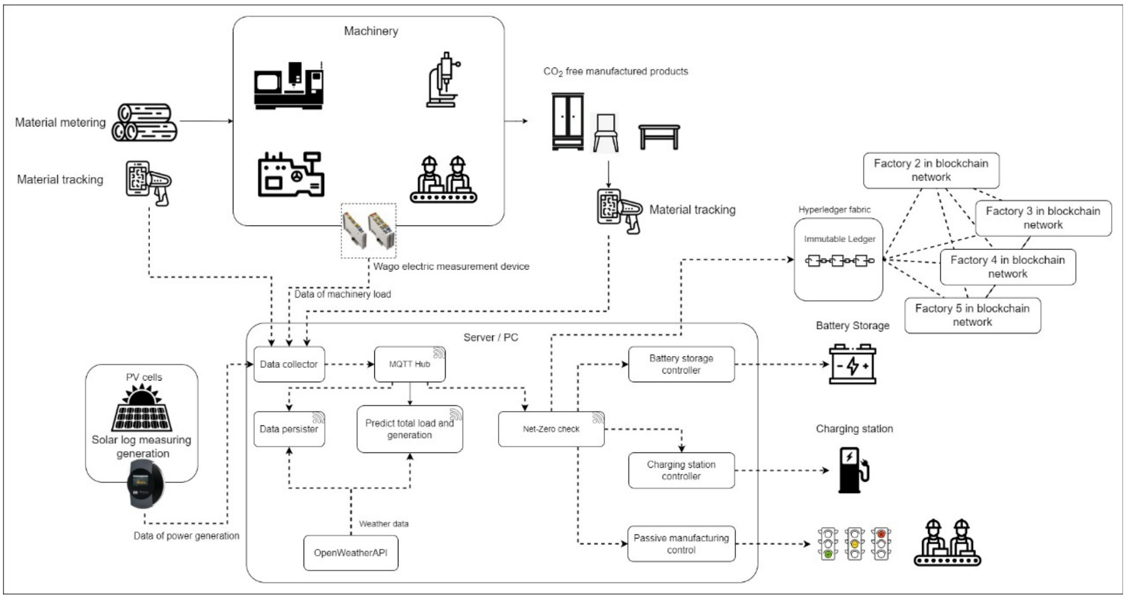

Figure 3 Energy, material and information architectures for operating a NZEF and tracking the energy and material flows

A data collector records data related to the material (raw material and final products) and energy flows (generation, load, storage and charging station). A MQTT broker receives all the data from the data collector and podcasts them to the data persister, the predictor of load and generation profiles, and the net-zero checker. The latter sends a signal to the flexibility option systems (passive DSM, charging station and the batteries). If the net-zero condition has been satisfied, the data are stored within a blockchain-based network.

Unlike blockchain networks used in cryptocurrencies, which allow anyone to join the network, a permissioned blockchain network has been chosen that allows only known participants into the network. The participant's identity can be verified thanks to the asymmetric cryptography [19] used in blockchain networks. Different companies must participate in the blockchain network to store their product's green energy usage to make the NZEF blockchain reliable. The participants need a consensus algorithm to enter new data into the blockchain. The Proof of Authority consensus protocol has been used, where a small set of validators have the authority to enter the information into the blockchain. Companies participating in the blockchain network can also be competitors. To prevent companies from reading other company's private sensitive data, companies are not allowed to store their information privately and can only share them with organizations they trust. A Hyperledger fabric framework [20] to create a blockchain network has been used to implement the requirements above.

IV. Cost-benefit Analysis for Operating a Net-Zero Energy Factory with Blockchain Application: Case Study

The development of a tracking system based on the blockchain might be an attractive solution for facility operators aiming to operate their factory as a NZES. An indicator, CoD_{NZEF} (cost of designing a NZEF) has been proposed which can support the facility operators in making the decision whether to design their facility as a NZEF (see Eq. 1). The CoD_{NZEF} meters the economic value of manufacturing items according the NZEF concept and tracking it using blockchain systems. It considers:

- the investment costs (ΔC) needed for the digitalization and for design of the flexibility options necessary, as well as the blockchain tracking system. Such costs are annualized over the lifetime using an appropriate discount rate;
- the yearly operation and maintenance costs (ΔOM) including variable and fix costs;
- the yearly saved energy costs thanks to the NZEF approach (ΔE_{saving}); and
- the yearly tracked items (ΔI_{NZEF}) which have been manufactured according to the NZEF concept.

$$CoD_{NZEF} = \frac{\frac{\Delta €}{year}}{\frac{\Delta I_{NZEF}}{year}} = \frac{\frac{\Delta C + \Delta OM - \Delta E_{saving}}{year}}{\frac{\Delta I_{NZEF}}{year}} \tag{1}$$

In order to estimate the CoD_{NZEF}, a mathematical model has been developed using the software Anylogic® [21]. Meter data have been considered for depicting the load of the manufacturing processes of the carpentry and the power generation by the PV plant (see Figure 4). The mathematical model implemented is able to track both the energy and the material flows. This flexibility option has been not considered in the model developed because, in practice, the passive DMS depends on the social flexibility of the machine operators, whose behaviors are too complex to be mathematically modeled.

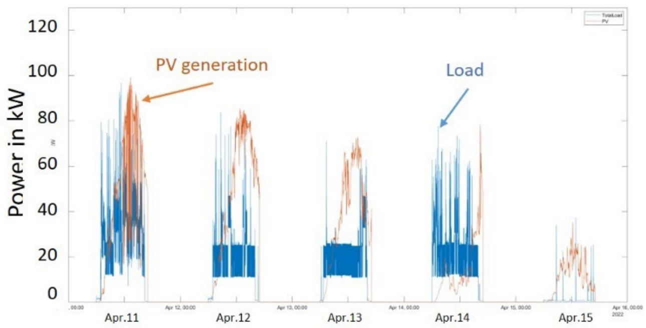

Figure 4 Meter data for the load and generation profiles during a week of April 2022

The model allows a comparison of the annual energy costs (for electricity and transportation) for the scenario in which no flexibility options are designed with the scenario in which stationary and mobile batteries are considered for supplying the flexibility required to operate the carpentry as a NZEF. The model also allows one to track the material, therefore, the number of CO_2-free items has also been compared among the scenario considered. Table 1 depicts the investment costs to design the flexibility hub and the blockchain system within the carpentry considered. Regarding the blockchain implementation and the electric vehicles, the project MESH4U does not foresee the implementation of these two actions, therefore, they are assumed costs. Regarding the stationary battery design, its size has been limited by the grant available for such an investment. Therefore, it does not depict the necessary capacity (in terms of power and energy) to operate the carpentry as a NZEF. The costs for sensors enabling the tracking of materials and for the data collector have been estimated as "blockchain implementation" costs. Finally, the analysis considers a discount factor of 5 % and a lifetime of 10 years for all the components listed in Table 1.

Table 1 Investment cost to design the flexibility hub and the blockchain system within the carpentry

Flexibility measurements	**Costs €**
Lithium-Ion Battery Storage System (20 kW, 40 kWh)	60,000
Measuring Instruments	20,000
Charging Station (2x22 kW)	8,000
Blockchain Implementation	24,000
Electric Vehicle A (van)	35,000
Electric Vehicle B (van)	50,000
Total costs	197,000

In order to calculate the impact of the electrification of the fleet and the effect on the total costs when the carpentry is supplied from the external grid, the values listed in Table 2 have been considered.

Table 2 Technical and economic parameters for the electrification of the fleet and for the electricity supply from the external grid

Parameter	**Value**
Route	38,800 km
Diesel price	1.8 €/l
Electricity price	202 €/MWh

The results of the simulations show that 558 items could be manufactured as CO_2-free products by operating the carpentry as a NZEF using the flexibility options designed, while 434 items were not fully manufactured using CO_2-free electricity. Table 3 summarizes the main results of the manufacturing in the two scenarios considered, while Figure 5 shows the comparison of the CO_2-free products manufactured in the case in which no flexibility options are used with the case in which the carpentry is operated as a NZEF.

Table 3 Comparison of the yearly manufactured green and gray items in the scenarios considered

Products	Operation without flexibility measurements	Operation with flexibility measurements
Number of “grey” products	642	434
Number of “green” products	350	558
Total number of products	992	992

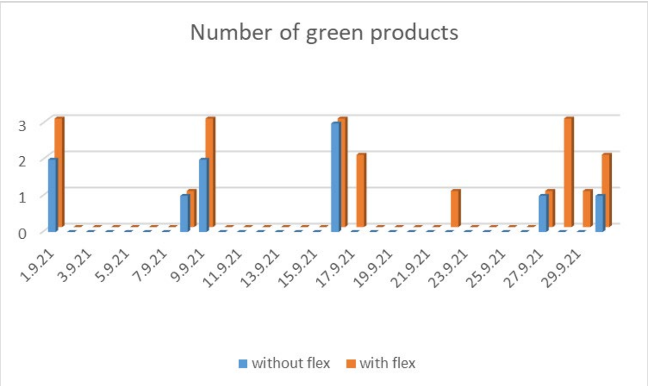

Figure 5 Comparison of the CO_2-free manufactured products in the case in which the flexibility options were used and in which no flexibility is used.

Table 4 shows the costs of designing the carpentry as a NZEF and for tracking the material flows. An extra cost of about 52 € should be allocated for each green product manufactured. These costs depend mostly on the costs of energy storage systems. A sensitivity analysis has been performed (see Figure 6) to evaluate how the investment cost for the electric vehicles impacts the cost of designing a NZEF. By decreasing the costs for electric vehicles by 35 %, the costs of designing a NZEF also decrease by about 15 %.

Table 4 Cost of designing NEZF

Costs	Value in €
ΔC	25,512.40
ΔOM	1,970.00
ΔE_{saving}	-1,294.50
ΔE_{saving}	558.00
$\boldsymbol{CoD_{NZEF}}$	**51.57**

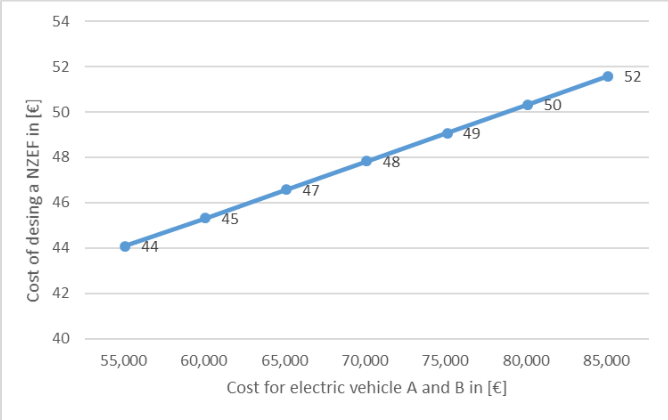

Figure 6 Sensitivity analysis between the costs of designing a NZEF and the investment costs for the electric vehicles

V. CONCLUSIONS

The design of the industrial facilities as NZEFs might contribute to a better exploitation of the volatile power generation by RES. A NZEF might be an attractive solution for manufacturing enterprises since they could bring green products into the supply chain. However, in order to do it, tracking systems are necessary. This study examines the case of designing a German carpentry as a NZEF which uses blockchain systems to track the sustainable production of the facility. The study points out that the design of the flexibility options impacts mostly on the extra costs which should be allocated to the green items manufactured. However, for the carpentry analyzed, these resultant costs are not excessive and could be easily allocated to the items manufactured.

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