

From Net-Zero Energy Factory to an Industrial Renewable Energy Community: A German case study

Pio Alessandro Lombardi
ESI

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

Finn Bennet Schröder
ESI

Fraunhofer Institute for Factory
Operation and Automation
Magdeburg, Germany
finn.schroeder@iff.fraunhofer.de

Stephan Balischewski
ESI

Fraunhofer Institute for Factory
Operation and Automation
Magdeburg, Germany
stephan.balischewski@iff.fraunhofer.de

Abstract— This study explores the design of an Industrial Renewable Energy Community (IREC) involving two small enterprises in Germany: a carpentry operating as a Net-Zero Energy Factory (NZE) and a funeral service company. Despite the delayed transposition of EU directives on energy communities in Germany, the proposed configuration illustrates a replicable model for integrating renewable generation, industrial flexibility, and digital trust mechanisms. Both companies operate photovoltaic systems, batteries, and electric vehicles, and are connected to the same substation. The carpentry controls production processes and an air compressor, while the funeral facility offers thermal flexibility through refrigeration units. By sharing surplus energy and coordinating flexible loads, the IREC aims to maximise self-consumption, reduce grid dependency, and create additional value through blockchain-based sustainability certification. The model aligns with the Clean Industrial Deal objectives and provides insights into economic, technical, and regulatory aspects of industrial community energy systems.

Keywords—Blockchain, Digital Trust, Industrial Renewable Energy Community, Net-Zero Energy Factory

I. INTRODUCTION

The transition to a fossil-free energy system is one of the main pillars of the European Union's climate strategy to be realized by 2050 [1]. Different instruments have been formulated to facilitate the reach of this target. Among them, the directive UE 2018/2001 (RED II) on Renewable Energy Communities (REC) [2]-[3] has emerged as key instruments to empower local actors to share energy generated by renewable energy sources (RES). This directive introduces legal frameworks for community-based models for renewable-only energy systems, enabling prosumers, small and medium enterprises, and public authorities to share, store, and consume electricity collectively. However, the transposition of this directive into national legislation has been uneven. Germany, in particular, has not yet a legislation enabling energy sharing over public grids.

Parallel to the regulatory progress on renewable energy communities (REC), increasing attention has been devoted to Net-Zero Energy Factories (NZE) as a mean to operate industrial sector in a more sustainable way. In [4]-[5] a structured methodology to design flexibility options for operating industrial systems as NZE have been proposed. Blockchain-based mechanism have been designed for enhance transparency, traceability and economic values through sustainability claims. Despite the increasing policy and academic interest in RECs and NZEs, limited research has explored their integration in an industrial context. The

concept of Industrial Renewable Energy Communities (IRECs)- where two or more industrial or tertiary actors collaborate to optimise local energy flows, manage collective flexibility, and increase renewable self-consumption- remain underdeveloped. While community energy models have traditionally focused on residential sectors, the industrial application is now gaining traction. This study contributes to this emerging field by presenting a designing case of an IREC in Germany, composed of a net-zero energy carpentry and a funeral service company, both connected to the same distribution station. The carpentry has been previously analysed in [5]-[8]. The funeral company adds further flexibility with the thermal inertia of the cold chambers. Together, they form an energy system capable of sharing surplus PV production, coordination demand, and maximising renewable self-consumption at the local level. The design of the technical solutions for planning IRECs is one of the aims of the CET Partnership project "FlexBIT" [9], which has the objective to develop a digital platform allowing to operate system typologies (residential, tertiary and industrial) allowing the energy sharing among all the involved actors and the digital trust.

II. NET-ZERO ENERGY FACTORY: WHAT IS IT?

There are different definitions of Net-Zero Energy Systems (NZES), encompassing residential, tertiary, and industrial sectors. Most commonly, NZES are defined as systems that, over a defined time horizon—typically one year—consume the same amount of energy as they generate from renewable energy sources [10]. In this general framework, the spatial distance between the point of energy generation and the point of consumption is not considered a critical factor. As a result, many companies claim to operate Net-Zero Energy systems by signing Power Purchase Agreements (PPAs) with operators of large-scale photovoltaic or wind farms [11]. These agreements allow them to match their annual energy consumption with an equivalent amount of renewable electricity fed into the grid, regardless of where the generation takes place or whether the energy is used at the same time it is produced. While this definition has the merit of being flexible and easily applicable in market-based frameworks, it overlooks several important systemic aspects. First, it ignores the temporal mismatch between generation and consumption, which can lead to significant imbalances in the grid. Second, and perhaps more critically, it disregards the spatial implications of off-site renewable production: electricity that is generated far from the point of use must be transmitted across the grid, involving physical infrastructure, energy losses, and increased pressure on transmission and distribution systems. In this study, NZEs are defined in a

more holistic and system-conscious perspective. Rather than relying on annual accounting via contractual agreements with distant generation sites, here the NZEFs are defined as systems that require that renewable energy be produced on-site or within the immediate energy environment of the industrial facility. Crucially, the factory is designed to maximize self-consumption of this renewable energy: the system avoids exporting surplus energy to the grid and instead integrates it through flexible industrial processes or local storage. Grid imports are allowed when necessary, but the goal is to avoid using the grid as a balancing tool or energy sink. This approach offers several systemic advantages as summarized in **Fehler! Verweisquelle konnte nicht gefunden werden..** The listed benefit levels are based on the authors ‘expertise on the field of integration of volatile renewable sources into the grid and on net-zero energy factory.

TABLE I. NET-ZERO ENERGY FACTORY: BENEFITS AND BENEFITS LEVEL

Category	Description of the Benefit	Benefit Level in %
Self-consumption of RES	Maximize local use of on-site generated RES electricity	100
Reduction of imbalance costs	Minimizes stress on the grid by reducing the need for balancing service	100
Grid efficiency	Decrease transmission losses thanks to localized generation and consumption	100
Energy independence	Increases autonomy from the electricity market and reduces exposures to price volatility	75
Reduction of local emission	Direct elimination of operational CO2 emissions on site	100
Industrial process flexibility	Encourages intelligent modulation of production processes	50
Energy resilience	Enhances continuity of operations in case of grid instability	50
Social acceptance/fairness	Does not externalize costs to other users (e.g. small consumers)	100
New business models	Opportunity to develop digital trust-based solutions to track the energetic sustainability of the industrial processes	100

III. NET-ZERO ENERGY FACTORY AND DIGITAL TRUST SOLUTIONS FOR NEW BUSINESS MODELS

The convergence between NZEFs and digital trust mechanisms enables a new generation of business models that integrate sustainability, transparency, and economic competitiveness. While the traditional view NZEF is centered on annual energy balance achieved through mechanisms such as PPAs, the NZEF concept, as considered in this study, shifts the focus to physical proximity and operational integration. In this view, renewable energy must be produced and consumed locally, and the factory must dynamically adapt its processes to the volatility of on-site renewable energy sources. This approach ensures that the benefits of decarbonization are not limited to accounting claims, but result in measurable reductions of grid dependency, transmission losses, and imbalance costs.

Within the project FlexBIT, the NZEF paradigm will be applied to a German carpentry. The carpentry, generates electricity using 125 kW of PV modules installed on the roof of the carpentry’s buildings. It integrates a 40 kWh, 20 kW of battery system, charging stations for electric vehicles, it adjusts its compressed air system and production processes in response to the power generated by the PV plant. These actions are managed by digital control algorithms based on decision trees and artificial intelligence, allowing the system to respond autonomously to changing energy availability. The result is a significant increase in self-consumption and a reduced need for energy import or export. However, the most innovative contribution of the NZEF concept lies in its potential to support new business models through digital trust frameworks. In the FlexBIT project, the integration of blockchain technology will enable the certification of sustainability claims associated with each production batch. Every product manufactured by the carpentry can be linked to a blockchain record that certifies its energy origin, and process timestamp. These data can be accessed by customers via QR codes, increasing transparency and potentially justifying a higher market value for sustainably produced goods.

The integration of NZEFs with digital trust solutions also contributes to policy goals at European and national levels. The Clean Industrial Deal [12], as outlined by the European Commission, calls for a deep transformation of industrial energy systems to align with climate neutrality targets. NZEFs respond directly to this call by combining renewable energy deployment, load optimization, and system decentralization. Meanwhile, digital trust solutions address the regulatory and consumer demand for transparency, accountability, and traceability in sustainability claims. Fig. 1 shows how the material flows are tracked and how the “parent” relation between the “mother” (piece of wood before the saw process) and “children” (pieces of wood after the saw process) is established. Fig. 2 shows the architecture for the material and energy flow tracks and for the exploitation of the flexibility.

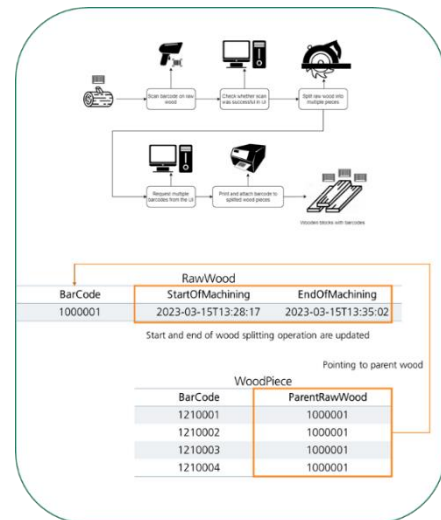


Fig. 1 Tracking of material flow

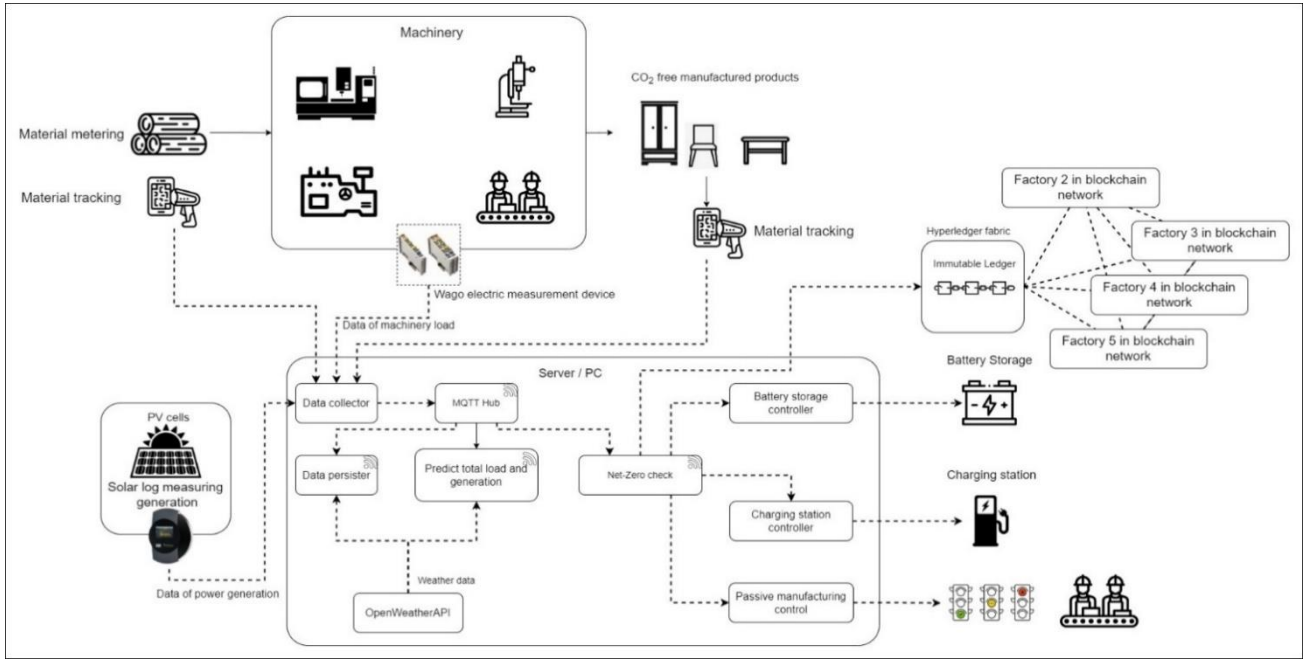


Fig. 2 Digital architecture for material and energy flows and exploitation of flexibility

IV. FROM NET-ZERO ENERGY FACTORY TO INDUSTRIAL RENEWABLE ENERGY COMMUNITY

Designing a NZEF requires significant investments in both infrastructure and operational transformation. These investments are primarily aimed at ensuring that the electricity generated from on-site renewable sources can be consumed directly within the facility. Such investments typically include storage systems (electric and mechanical), smart control platforms, smart meter for digitalisation and IoT sensors for collecting data. While a NZEF design offers clear benefits in terms of energy autonomy and sustainability, the economic justification may not always be straightforward—especially when the added value derived from digital trust mechanisms and sustainability certification is insufficient to fully compensate the capital expenditure. An alternative and potentially more scalable solution is the creation of an Industrial Renewable Energy Community (IREC). In this configuration, multiple enterprises—located behind the same transformer station or within the same segment of the low-voltage or medium-voltage distribution network—form a legally and technically integrated energy community. This structure enables the sharing of renewable energy among participants and allows them to coordinate flexible loads to improve collective self-consumption. Within an IREC, an NZEF can inject surplus renewable electricity into the grid, provided that the energy is consumed by another community member. This energy exchange does not count as a conventional grid export; rather, it is treated as internal sharing within the community, maintaining the net-zero balance for the generating facility. Conversely, if the NZEF requires additional renewable electricity to maintain its sustainability performance—for instance, during periods of low solar production—other members of the IREC who operate renewable generation assets can supply their surplus through the shared network.

Within the project FlexBIT the technical solution to operate an IREC will be developed. The German demonstrator integrates two small enterprises- a carpentry operating as a

NZEF and funeral building- through a digital infrastructure composed of MQTT brokers, local energy management systems (EMS), and a central data platform based on ASP.NET and Angular. The platform collects sensor data, enables control commands, and logs green energy exchanges, while blockchain-based smart contracts (Hyperledger Besu) are used to verify and record energy transactions (see Fig. 3.)

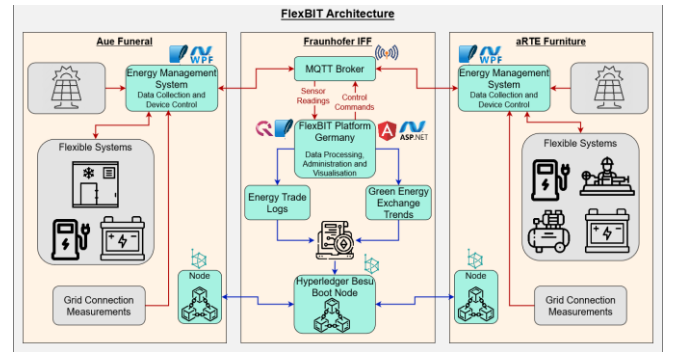


Fig. 3 Scheme of the FlexBIT's architecture

In the demonstrator, both buildings are equipped with photovoltaic systems, batteries, and flexible loads. The carpentry operates a 125 kW PV system and a 40 kWh battery, alongside industrial processes including a smart compressed air system. The funeral building has a 29 kW PV system, a 20 kWh battery, two hybrid plug-in vehicles, and a refrigeration system offering thermal inertia. One of the four cooling units in the funeral home can be controlled to act as a thermal storage buffer: it can be pre-cooled when excess electricity is received from the carpentry, or temporarily reduced in performance to free up energy for the carpentry during high demand. Table II summarizes the main technical parameters of the IREC.

TABLE II. THE TECHNICAL PARAMETERS OF THE TWO ENTERPRISES WITHIN THE IREC

	Carpentry	Funeral Building
RES installed capacity	125 kW (Photovoltaic)	29 kW (Photovoltaic)
Electrochemical battery	20 kW; 40 kWh	20 kW; 20 kWh
Electric vehicles	1x	2x (Hybrid Plug-in)
Additional Flexibility	1. Industrial processes 2. Smart Compressed Air	1x Cooling aggregate

This cooperative model creates a flexible, resilient, and economically efficient ecosystem where energy flows are optimized not just within individual facilities, but across an entire industrial cluster. It reduces the need for each enterprise to invest in oversized storage or generation systems by enabling complementarity—where the production and consumption profiles of different actors can balance each other out. Furthermore, the digital trust frameworks already described for individual NZEFs can be extended to the entire community, allowing the certification of sustainability at the product, company, and community level.

V. CONCLUSION

This study has demonstrated the technical and strategic value of transitioning from a Net-Zero Energy Factory (NZEF) model to an Industrial Renewable Energy Community (IREC) configuration. While the NZEF concept represents a significant leap forward in aligning industrial energy consumption with on-site renewable generation, it often requires high upfront investment in storage, control systems, and process flexibility. The additional economic value provided by sustainability certification and digital trust solutions may not always fully justify these investments, particularly for small and medium-sized enterprises.

The IREC model, as explored in the early stages of the German FlexBIT project, offers a potentially more scalable and economically balanced approach. By enabling energy sharing and demand coordination between multiple industrial actors located behind the same distribution transformer, IRECs allow for mutual balancing of renewable generation and consumption. This reduces individual infrastructure costs and increases the overall system efficiency. While the technical solutions for real-time coordination, digital tracking, and smart contract settlement are still under development, the architectural framework and use cases defined in FlexBIT establish a strong foundation for future deployment.

The cooperation between the carpentry and the funeral building illustrates a replicable concept in which diverse flexibility assets—ranging from smart compressed air

systems to controlled refrigeration and electric vehicles—can be orchestrated under a shared digital infrastructure. Though the platform is currently in development, its intended functionalities—including energy exchange tracking, flexibility optimization, and blockchain-based verification—point toward a new paradigm of industrial energy collaboration.

REFERENCES

- [1] European Commission, “The European Green Deal-Striving to be the first climate-neutral continent”, available on: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
- [2] Directive EU 2018/2001 on the promotion of the use of energy from renewable sources. Available on: [file:///C:/Users/lombardi/Downloads/DIRECTIVE%20\(EU\)%202018%2001%20of%2011%20December%202018%20on%20the%20promotion%20of%20the%20use%20of%20RES.pdf](file:///C:/Users/lombardi/Downloads/DIRECTIVE%20(EU)%202018%2001%20of%2011%20December%202018%20on%20the%20promotion%20of%20the%20use%20of%20RES.pdf)
- [3] European Commission, “Energy communities”, available on: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-communities_en
- [4] P. A. Lombardi, H. P. Wasser, A. M. Pantaleo, „Flexibility exploitation in Net-Zero Energy Factories. A Technical and economic study case for dairy systems located in Central and South Europe”, Renewable Energy, 234, 2024
- [5] P. A. Lombardi, S. Y. Mattepu, H. Wasser, B. Arendarski, M. Richter, A. Pantaleo, P. Komarnicki, „Net-Zero Energy Factories as Active Players in the Decarbonization Process. An application for Blockchain”, IEEE PowerTech Belgrade, 2023
- [6] P. A. Lombardi, S. Y. Mattepu, B. Arendarski, M. Richter, P. Komarnicki, „Blockchain application within Net-Zero Energy Factories. A cost-benefit analysis for a German carpentry”. Workshop on Blockchain for Renewables Integration, 2022, Palermo, Italy
- [7] P. A. Lombardi, M. Liserre, “Net-Zero Energy Factory: Exploitation of flexibility- A Technical-economic analysis for a German carpentry”, 21st IEEE Mediterranean Electrotechnical Conference (MELECON) 2022, Palermo, Italy
- [8] L. Bartolucci, S. Cordiner, V. Mulone, M. Santarelli, P.A. Lombardi, B. Arendarski, “Towards Net Zero Energy Factory: A multi-objective approach to optimally size and operate industrial flexibility solutions”, International Journal of Electrical Power & Energy Systems, vol. 137 2022
- [9] Flexibility Exploitation for Residential, Tertiary and Industrial Buildings (FlexBIT). Online: <https://www.cetp-flexbit.eu/>
- [10] H. Moghaddasi, C. Culp, J. Bagegaas, M. Ehsani, “Net Zero Energy Buildings: Variations, Clarifications, and Requirements in Response to the Paris Agreement”, Energies, 2021
- [11] R. Prendergast, “Tesla and Zelestra sign long-term solar PPA in Spain”, Power Technology, 17 February 2025. Available: <https://www.power-technology.com/news/tesla-and-zelestra-sign-long-term-solar-ppa-in-spain/?cf-view>
- [12] European Commission, “Clean Industrial Deal- A plan for EU competitiveness and decarbonisation”. Available on: https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en