JOURNAL OF ENERGY SYSTEMS

2025, *9*(1)

2602-2052

DOI: 10.30521/jes.1524221

Research Article

Qualitative and quantitative analysis of ultra-efficiency projects: Commonalities, differences, and lessons learned

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Submitted: *29.07.2024*
Accepted: *06.02.2024*
Published: *31.03.2025*

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Abstract: Industrial companies must become more sustainable and environmentally friendly to cope with rising energy and resource costs and regulatory requirements. One approach achieving these goals is the concept of ultra-efficiency, which has been developed and promoted by Fraunhofer in recent years. In many cases, measures to increase sustainability are more effective when neighboring companies work together than when they act individually. This is why the concept of ultra-efficiency has been extended from a single factory to multiple factories in industrial zones and, more recently, to agriculture in mixed-use urban districts. Understanding the benefits and identifying barriers and best practices for fostering such collaboration is important for translating scientific concepts into practice. Therefore, three completed projects are selected and qualitatively and quantitatively analyzed in terms of their similarities and differences. Based on the analyses, a list of eight lessons is highlighted to assist in its quest for greater sustainability: Project complexity increases with diverse stakeholders. Public engagement and demonstrators are key to communication. A strong lead entity is essential early on. Decision maker engagement, clear benefits, data sharing, and independent operator models are key to achieving viable synergies. Long-term planning and infrastructure investment are essential to achieving sustainability goals.

Keywords: *Industrial symbiosis, Industrial park, Sustainability, Ultra-efficiency*

Cite this paper as: Koch, D, Balve P, Gerdes JN, Hertwig M, Kröll M, & Lentes J., Qualitative and quantitative analysis of ultra-efficiency projects: Commonalities, differences, and lessons learned. *Journal of Energy Systems 2025; 9*(1): 68-84, DOI: 10.30521/jes.1524221

2025 Published by peer-reviewed open access scientific journal, JES at DergiPark (https://dergipark.org.tr/jes)

1. INTRODUCTION AND CONCEPTUAL BACKGROUND

The world's population is projected to increase dramatically by 2.3 billion people between 2012 and 2050 [1]. As a result, the demand for resources will increase significantly, for example, the demand for goods has more than doubled since the 1970s and more than tripled since the 1950s [2]. Similarly, the demand for resources has increased many times over [3]. As a result, the Earth Overshoot Day is coming earlier and earlier - and it is estimated that by 2050, resource consumption will be almost three times the availability of resources on our planet [4]. To summarize the resulting trajectory, the increase in the global Ecological Footprint from 1961 to 2022 is visualized in Figure 1.

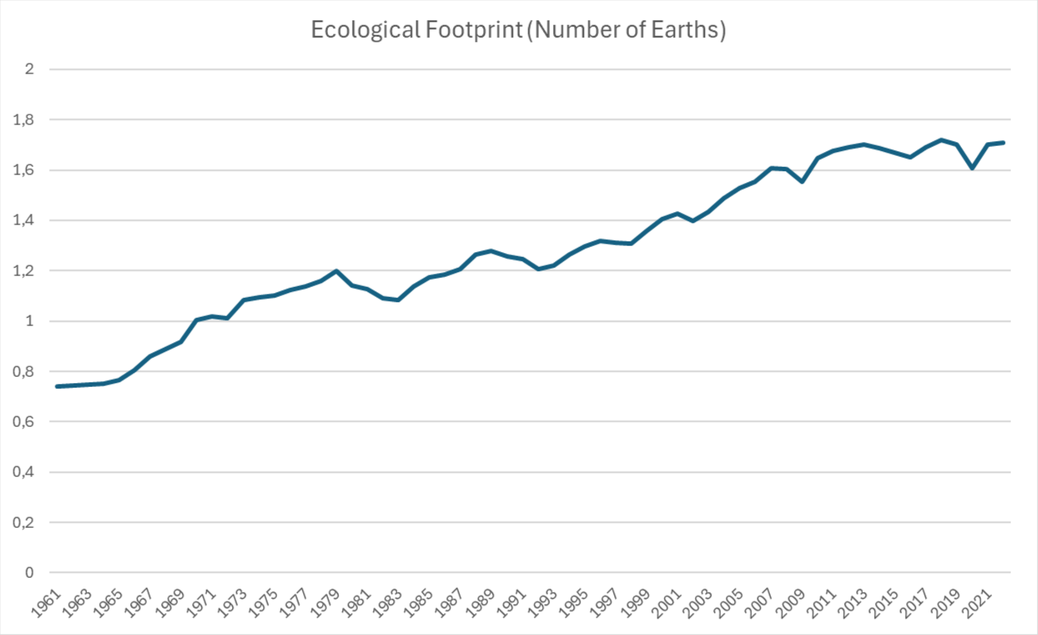

Figure 1. Development of the ecological footprint from 1961 to 2022 [5].

However, recent increases in energy and material productivity have only reduced raw material consumption in Germany by about 10% over the past 30 years [6], which is still unsustainable. As a result, we need to rethink the way we live and do business - and companies and societies are facing ever greater challenges.

This situation requires us to use existing resources much more effectively and efficiently, especially under the conditions of further targeted economic growth in industry. This has led to the concept of ultra-efficiency. Its goal is to decouple economic growth from resource consumption [9] by addressing five fields of action: (1) Maximizing resource efficiency, (2) reducing energy consumption, (3) avoiding any kind of harmful emissions, while at the same time (4) providing a work environment that fosters high performance and employee satisfaction and health [8]. Furthermore, (5) an optimal business organization is required to act as an enabler for these goals (Fig. 2, based on Refs. [7,8], shows the ultra-efficiency concept with its five fields of action and varying spatial focus, extended by including stakeholders and business models). In recent years, research has focused on applying the concept by involving more and more stakeholders and shifting the focus from within the company to entire industrial zones and mixed-use districts.

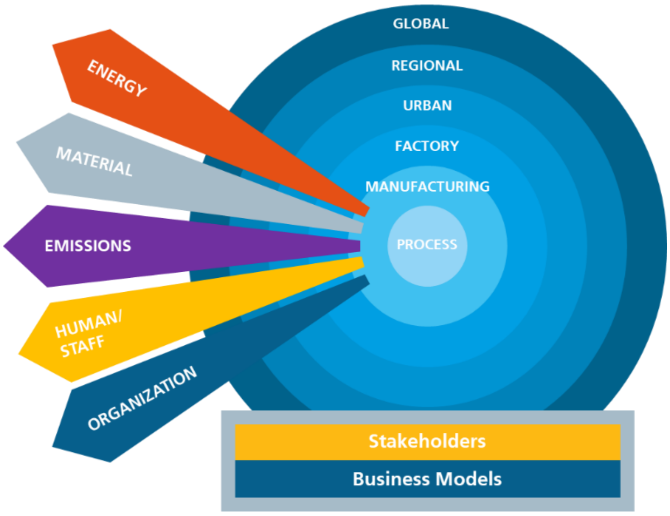

Figure 2. The ultra-efficiency concept.

The ultra-efficiency approach was developed and introduced by Lentes, et al., [10] and by Kuhlmann et al., [9]. The universal approach for industrial companies was specified by Sheeran, et al., [11] to improve material efficiency for factories in closed-loop value networks. In addition, Miehe and co-workers [12] improved manufacturing systems toward ultra-efficiency. Waltersmann and co-workers identified industry-specific guidelines for initiating sustainability in companies [13]. Waltersmann, et al., presented a concept for deriving specific sustainability recommendations for companies based on benchmarking of holistic optimization potentials in the manufacturing industry [14]. Schutzbach, et al., presented principles and design strategies for ultra-efficient production systems in the process industry [15]. Schutzbach, et al., presented principles of management systems for positive impact factories [16]. Sielaff and co-workers developed a classification model that considers ultra-efficiency criteria for the consequences of machine failures [17].

Progress has also been made in leveraging ultra-efficiency from a higher level perspective, looking at firms and their environments as well as multiple firms. Singh, et al., studied the economic impact of ultra-efficient urban manufacturing [18]. With respect to industrial zones, ultra-efficiency effects were studied by Lentes and Hertwig [19]. Work on symbiotic loss-free industrial production in ultra-efficient urban industrial parks was presented by Hertwig, et al., [20].

This paper draws on the results of these contributions and, for the first time, analyzes and compares successfully completed projects and derives a systematic perception of different types of projects based on their respective characteristics. To this end, we first discuss the ultra-efficiency framework in more detail. Based on this framework, an appropriate methodology for comparing ultra-efficiency initiatives is developed and then used to describe three ultra-efficiency projects. This allows us to highlight findings and lessons learned from the three projects. In Sec. 2, a brief methodology and literature information on the comparison are given. Sec. 3 presents ultra-efficiency projects in detail. The main results and discussion are given in Sec. 4. The paper concludes with a summary and an outlook for future work.

2. METHODOLOGY FOR COMPARISON

In this section, we elaborate on the five fields of action mentioned above (see Figure 2, left hand side) by combining them with additional elements of the ultra-efficiency model. This results in a set of evaluation categories that serve as the basis for the structured comparison of the three selected projects.

First, ultra-efficiency initiatives differ significantly in their geographic expansion (Figure 2, circles). The nucleus is always a specific manufacturing, transformation, or value-adding process of some kind.

For example, a factory consists of at least one of these processes. In many cases, however, it will consist of several manufacturing processes, all belonging to the same legal entity. Although these core processes should already be designed with sustainability goals in mind, it may not always be technically or economically feasible to achieve these goals at this level. Following the concept of industrial symbiosis [21], it makes more sense to consider the "collaboration and the synergistic possibilities offered by geographical proximity" [22] of two or more independent entities, i.e., companies. With increasing spatial expansion and by adding an institutionalized approach to the exploration and exploitation of synergies between different entities, we end up with industrial parks that can easily cover an area of several square kilometers. For our purposes, it is not necessary to go beyond the level of industrial districts or parks; however, we anticipate that the ongoing pursuit of zero emissions and circular economy will lead to larger symbiotic networks across regions. In addition to the geographical aspect, the second characteristic of the collaborating units is their specific value-adding process, i.e., their type of business. The projects described in this paper cover a wide range of businesses and business models, which always influence the interest and need for collaboration. To name a few examples: manufacturing, logistics and warehousing, agriculture, office space, lodging, shopping, and recreation of all kinds.

Third, when comparing ultra-efficiency projects, we need to consider the role and position of the stakeholders involved. Questions about the initiator and the strongest beneficiaries come to mind: How strong is the drive of the company owners to collaborate, what is the role of public authorities, are there subsidies involved, do we need or do we already have an operator to orchestrate the intended exchange of materials and energy, etc.?

As argued in the previous section, to achieve the goal of sustainable operations in a holistic way, it is necessary to develop activities in five areas. In order to examine the similarities, differences, and challenges in all three projects below, we need to be very specific about each field of action:

"Energy" includes all forms of energy (e.g., electrical, chemical, thermal) required or consumed in the operations. "Materials" includes raw materials for the core process, as well as operating and auxiliary materials (e.g., fuel, lubricants). It also includes material wastes such as metal shavings or plastic from injection molding machines. 'Emissions' are all pollutants or other material and non-material discharges from industrial and other activities that are considered pollution (cf. Ref. [23]). Because of this broad understanding, we pay attention to a wide variety of manifestations of emissions, ranging from liquids, gaseous substances, vibration and sound, and even light. According to the ultra-efficiency ideal, emissions must be avoided in the first place or, if that is not possible, they must be reduced, contained, cleansed, converted or consumed.

When it comes to "humans/staff", we need to look at compliance with ergonomic standards [24] and policies that ensure the well-being of employees in the workplace. In addition, the various aspects of job satisfaction and corporate culture must be taken into account. The latter in particular can make the difference between a strong or weak contribution of individuals to sustainable behavior in the workplace. Finally, we will characterize each ultra-efficiency case on the basis of "organizational" aspects. The project environments differ in their political and legal frameworks. With regard to the other four fields of action mentioned above, "organization" also covers the degree to which the structures and processes of the parties involved enable the sustainability goals as a whole. At a higher level, the existence and characteristics of an operating entity responsible for the synergetic exchange of waste energy and materials, or shared resources such as childcare or a central canteen, must also be considered.

3. DESCRIPTION OF THREE ULTRA-EFFICIENCY PROJECTS

To put the ultra-efficiency framework into practice, several projects have been carried out in order to explore the potential for sustainability improvement based on the five fields of action of the ultra-efficient factory. The first project under consideration focuses on the application of the ultra-efficiency framework within the boundaries of a single company. The second project extends beyond the boundaries of a single company to investigate the synergy potential in the five fields of action within an industrial park and the third project changes the view from the typical industrial park to a mixed-use district to be transformed into a sustainable urban space. Table 1 provides a general overview of the projects' characteristics that will be examined in the following sections.

Table 1. Overview of ultra-efficiency projects.

	Ultra-Efficiency Projects		
	Factory Level – Schaeffler	**Industrial Estate Level – Rheinfelden**	**Mixed-Use District – IBA'27 Project Fellbach**
Fields of Action	Energy	Energy	Energy
	Materials	Materials	Materials
	Emissions	Emissions	-
	Humans/Staff	Humans/Staff	Humans/Staff
	Organization	Organization	Organization
Spatial Expansion	Process	-	-
	Manufacturing	-	-
	Factory	Factory	Factory, Farm
	-	Urban	Urban
	-	Regional	Regional
Type of Business	Manufacturing	Manufacturing	Manufacturing
	-	-	Logistics
	-	-	Warehousing
	-	-	Agriculture
	-	-	Office Buildings
	-	-	Lodging
	-	-	Recreational
Stakeholders	-	Initiating Party	Initiating Party
	-	Main Beneficiary	Main Beneficiary
	-	Authorities	Authorities
	-	Business Owners	Business Owners
	Managers	Managers	Managers
	-	-	Residents
	-	Operators	Operators

3.1 Ultra-Efficiency on Factory Level – Schaeffler

In a joint project with Schaeffler, a tier-one automotive supplier (second column in Table 1), a real ultra-efficient factory was established as an example on a single site and for a single production line. The 490,000 m^2 facility is located in an industrial area adjacent to a residential and mixed-use neighborhood in Bühl, Germany. The facility houses both engineering and manufacturing, with a production focus on e-mobility parts for the automotive sector. It was expected that the lessons learned from this project could later be transferred to other production lines and sites of the company, and eventually to as many other companies as possible [25]. The overarching goal was to transform production to become more sustainable and climate-neutral. To this end, we investigated the following three design areas of factory planning:

-The factory processes,
-The infrastructure,
-The factory building.

A total of 12 factory processes with varying degrees of inherent optimization potential were analyzed and quantified. Two processes were identified with a high degree of improvement potential in multiple areas: the handling and transportation of magnets and the bonding of electric motor components. The handling and transportation of magnets was particularly problematic because of the effort required to unpack the magnets, which impacted the fields of action "organization" and "humans/staff", and the waste generated by damaged magnets and packaging, which impacted the field of action "materials".

Therefore, packaging concepts from suppliers were examined and evaluated based on an evaluation framework developed with company experts, taking into account the sustainability of the packaging, setup costs and time, magnet supply costs, risk of damage, risk of contamination, and the required investment in handling equipment. This evaluation showed a significant advantage for the blister packaging process over shrink-wrapped and vacuum-packed concepts, as it had the lowest risk of contamination and damage, despite scoring lower in the sustainability criteria.

Another process step studied is the bonding and curing of the magnets in the electric motor, which requires high quality adhesives to ensure reliability in subsequent operation. While this method offers many advantages over mechanical coupling, it is significantly more energy intensive, with only about 5% of the energy used going to the adhesive bond, and the rest being used to maintain temperature levels in the curing oven (62%) and to heat instruments (33%). This was determined by making measurements on the production equipment and calculating the respective fractions based on the thermal capacities of the individual components. [25] On the other hand, there are significant improvements in the recyclability of the magnets, which can be recovered and reused for future electric motors, reducing the carbon footprint of the magnets by about 56%, which in turn accounts for 23% of the carbon footprint of the electric motors. Thus, while this method poses challenges in the field of action “energy”, there are improvements in “emissions” and “materials”.

The plant infrastructure primarily includes its energy conversion and generation facilities, its energy grid, and its IT infrastructure. While significant investments are required to modify or improve the existing infrastructure, significant financial and environmental savings can be achieved. One measure that has been studied in detail is the use of available roofs and parking lots for photovoltaic power generation of approximately 3.5 MWp, which will significantly reduce the company’s carbon footprint by generating clean energy. This can be further enhanced by the potential of a direct current (DC) grid in the company’s infrastructure, which will improve financial viability through increased energy efficiency. Further decarbonization can be achieved by converting excess electricity into hydrogen for energy storage or as a substitute for natural gas in the plant’s thermal energy supply. Investments in the energy system and distribution network can result in improvements in the fields of action “energy” and “emissions” and reduce the carbon footprint of the company’s products, making them more competitive. In addition, these investments demonstrate the company’s commitment to sustainability and attract more employees in a competitive labor market.

With regard to the factory building and its surroundings, the employees’ commute to and from work is a crucial aspect that affects the “energy” and “emissions” fields of action due to the use of fossil fuels in cars and company vehicles. Survey results show that most employees commute by private car (56%) or company car (5%), with only 19% using public transportation and a small minority biking (9%) or walking (3%). The company aims to support the shift from fossil fuels to renewable energy by expanding electric vehicle (EV) charging stations, as 54% of employees surveyed are potential EV drivers. In addition, to promote cycling, including e-bike leasing, the company has worked with vendors to facilitate this option for its employees. The need to improve public transport connections and increase the use of electric shuttles for inter-factory travel has also been identified, as current services are inadequate and run on fossil fuels. These measures are expected to be implemented in the coming years and will result in significant improvements in the fields of action “emissions” and “energy”.

To better understand and leverage synergies, similar or interdependent activities were grouped into overarching innovation labs. These considerations initially led to eight innovation labs for further elaboration and implementation:

- *Production process*
- *Efficient supply chain*
- *Ultra-efficient energy system*
- *Digital twin and ultra-efficient functions*
- *Circular economy strategy*
- *Energy optimized and automated solutions*

- *People centeredness in and around production*
- *Ultra-efficient management system*

By implementing and evaluating various ultra-efficiency measures over an extended period of time ("ultra-efficiency labs"), it was possible to identify which combinations of measures produce long-term sustainability and climate protection effects. In this way, building blocks were created for the successful planning and transformation of ultra-efficient factories under real-life conditions.

3.2 Ultra-Efficiency on Industrial Estate Level – Rheinfelden

Ultra-efficiency is a scalable concept that can be applied at multiple levels. Its application is not limited to factories to enable holistic improvements in the five fields of action. Potential measures to improve ultra-efficiency in certain areas may not be economically viable. In these cases, and in order to exploit synergy potentials that go beyond the boundaries of a single factory, it is necessary to consider a wider scope, i.e., the cooperation of neighboring companies and organizations. This can result in greater overall benefits than any single entity can create [26].

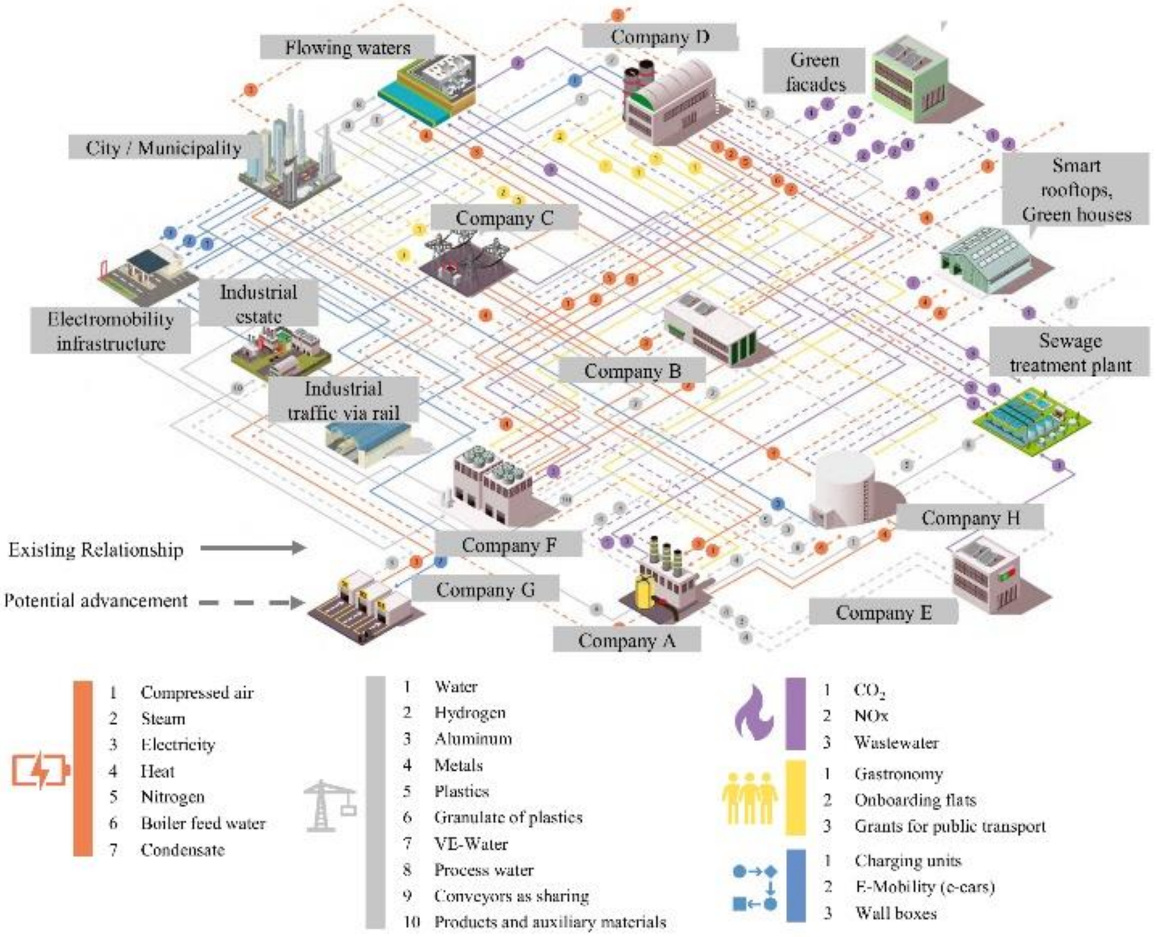

Figure 3. Interdependencies of existing and potential measures at Rheinfelden

In order to explore the potential of extending the implementation of measures beyond the boundaries of a single company, a competition was held to select an industrial zone best suited to carry out an ultra-efficiency project. This competition included a self-analysis and Rheinfelden (Baden) was identified as a very promising model zone in 2017. The site has a number of peculiarities that have a positive impact on possible ultra-efficiency measures for an industrial zone. There are two separate industrial zones, which have been studied together because the distance between them is not great and the conditions in both zones are very different. In the industrial zone called Herten West, the companies are small and diverse. Each company is individually owned and therefore highly independent of the surrounding companies. The other industrial zone was formerly a large company that downsized and now acts as a landlord for the other companies on the site. Due to this legacy, the connection and interaction of the stakeholders within this zone is much more established than in Herten West. However, both areas are located close to the residential areas of the city of Rheinfelden, which creates challenges that are being addressed by urban manufacturing initiatives.

An initial analysis of the current situation in Rheinfelden was carried out using various means and formats. As a first step, roundtable discussions with all potential stakeholders were organized by the local economic development organization. Individual interviews were then conducted with all interested parties. The interviews were processed to collect relevant data and information in detail [17]. With all this information, the research team conducted input-output analyses and developed an interdependency model [27]. Based on this detailed analysis, the results were documented in a study to present potential measures for improvement in terms of ultra-efficiency [28]. Figure 3 shows the results of the study. The different actors in the Rheinfelden industrial estate are depicted together with the existing and potential energy and material flows between them. Based on the potential interactions, the potential ultra-efficiency benefits of collaboration can be assessed.

3.2.1 Tool for cross-organizational discussions and decision making

The detailed description of appropriate actions did not immediately lead to implementation activities. Potential actions would have required financial investment and their potential return was unclear to most participants. In order to promote transparency regarding the potential benefits, a tool was developed based on the developed interaction map (Fig. 3), which quantifies the value added for each partner based on the available information [29]. For this purpose, relevant key performance indicators (KPIs) representing the fields of action were calculated and estimated before and after the implementation of potential measures [30]. In this way, the benefits for each potential participant could be clearly and transparently demonstrated, and the basis for a return-on-investment assessment could be provided.

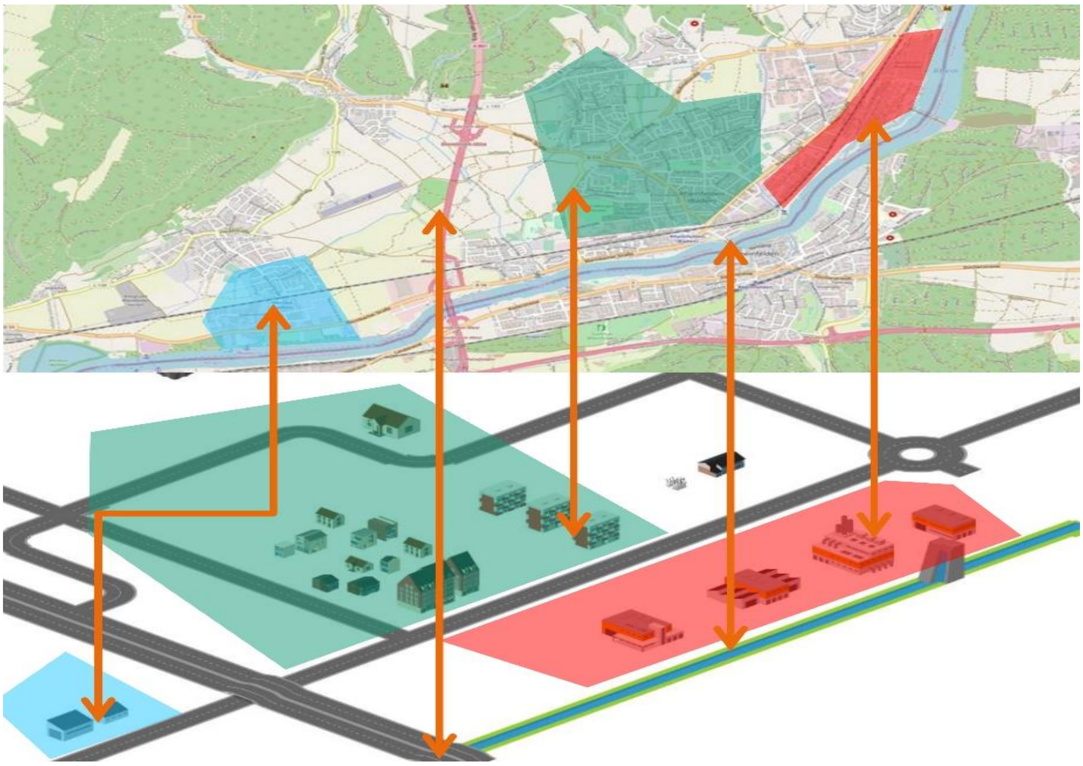

Figure 4. Visual representation of the Rheinfelden industrial estate as part of the software tool to foster multi-lateral exchange between the different stakeholders.

The tool to facilitate the exchange between the participants consists of two main elements, namely a visual interface and a backend. For the discussion, the visual interface provides relevant information in an easy-to-understand format. The visualization is a simplified representation of the local situation. All relevant elements are shown, but the dimensions and distances are not to scale. The focus is on comprehensiveness as well as straightforward and easy interaction with the visual representation. Therefore, landmarks such as rivers, major roads and highways, as well as industrial and residential areas are shown (see Fig. 4). Each partner involved is represented by an individual icon, which is also used as an indicator to show the individual KPIs after changes have been introduced. The visualization needs to be designed only once for each location and all relevant data can be imported via an interface. To make the visualization compatible with any user interface, the tool is based on web technologies and can be used both online and offline.

The data needed for the visualization is generated in the backend, which consists of a mathematical model and a database. The role of the discussion tool in the optimization process is shown in Figure 5. Some steps can be performed multiple times to support the iterative evolution of the industrial zone toward ultra-efficiency.

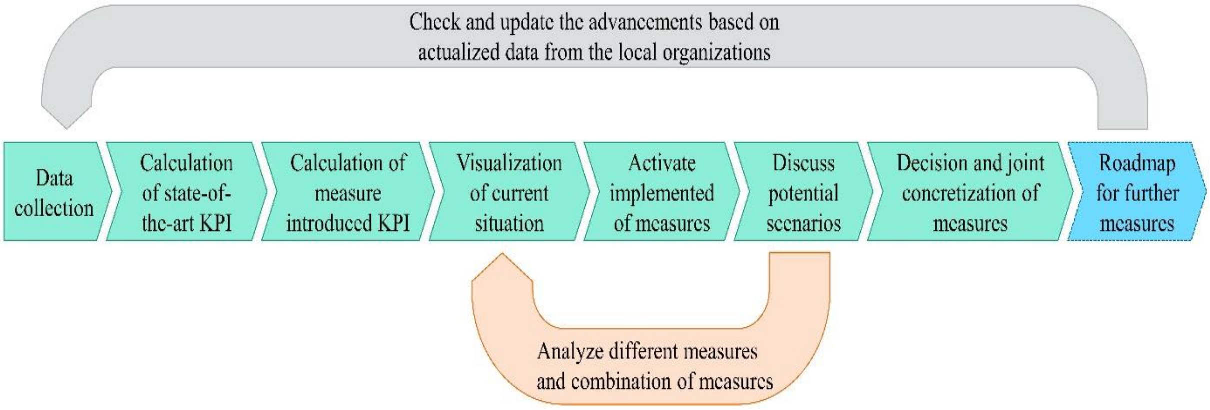

Figure 5. Steps of the tool to support advancement procedures for a cross-organizational collaboration.

An important input is the data collected from the companies using Excel spreadsheets. This method was chosen to ensure a similar data structure and level of detail in the responses from all stakeholders. The data collected was used to calculate KPIs of the current situation to establish a baseline. Based on the actions specified for the analyzed site, the changes in the KPIs introduced by the impact of the actions are calculated. The calculation code is created using MATLAB (version R2023b), which provides a wide range of functions [31]. The impact of each intervention is calculated by subfunctions within the MATLAB code in the development environment. The core of the m-code was used to import data from Excel files, structure the data, and call subfunctions. Additional subfunctions can be easily added as needed. Each subfunction uses a subset of the participant-specific data provided as input and, if necessary, values from external sources to calculate the output values that are returned to the core script. The current calculation time was about 1 min 50 seconds, depending on the number of partners involved (13 input datasets) and measures evaluated (12 measures considered). After calculating the impact of the individual measures, the interdependencies between the measures are highlighted and the combined impact is derived and discussed [32].

An important aspect is the anonymity of the results. Companies were concerned that their competitors might draw conclusions about their current business situation from potentially disclosed data. To address this concern, only data that pertains to the company can be exported. The exported data sets are used for the visualization. This visualization of the benefits of synergistic cooperation between companies can serve as a basis for discussion. For this reason, the baseline visualization shows only current measures and functions. During the discussion, the potential actions can be activated, resulting in the appearance of additional infrastructure elements and the calculation of individual changes in KPI values for each participant. This allows stakeholders to discuss different scenarios (a subset of the actions selected by the company delegates) with the goal of finding a scenario that is suitable for all organizations involved. The selected actions can be detailed and implemented in collaboration with internal and external experts, and if more than one action is selected, a roadmap can be defined regarding the implementation schedule.

The situation in Rheinfelden is representative of many industrial areas in Germany and Europe, where cross-company cooperation is required to identify and implement major improvement measures. Therefore, another goal was the transferability of the tool to other locations. Thus, the two main elements of the tool, the visualization and the computational model, are connected by documented and standardized interfaces. Each element can be used and adapted individually.

3.2.2 Example: Implementation of a waste heat recovery network

Together with the stakeholders, the list of potential measures for the industrial sites identified during the project was further prioritized according to the strategic interests of the companies involved. Several measures were analyzed in all fields of action. Two measures in the field of action ‘energy’ were selected for further analysis.

Initially, the implementation of shared combined heat and power (CHP) plants was evaluated. Second, the implementation of a waste heat distribution network, where waste heat from one company is distributed to others, was considered [33]. The first option was rejected because of the large number of heat pumps (HP) already in operation. In order to evaluate the potential of a waste heat recovery network, the companies had to provide an estimate of the waste heat production and the potential for waste heat use. This is shown in Fig. 6 along with the required temperature levels. In addition, the comparison was based on the amount and type of energy required (e.g., electricity, thermal energy, steam). In the MATLAB model, the comparison of the potential energy supply and the current demand was calculated. An analysis of potential matches was calculated and the maximum potential benefit was quantified. The following issues were considered:

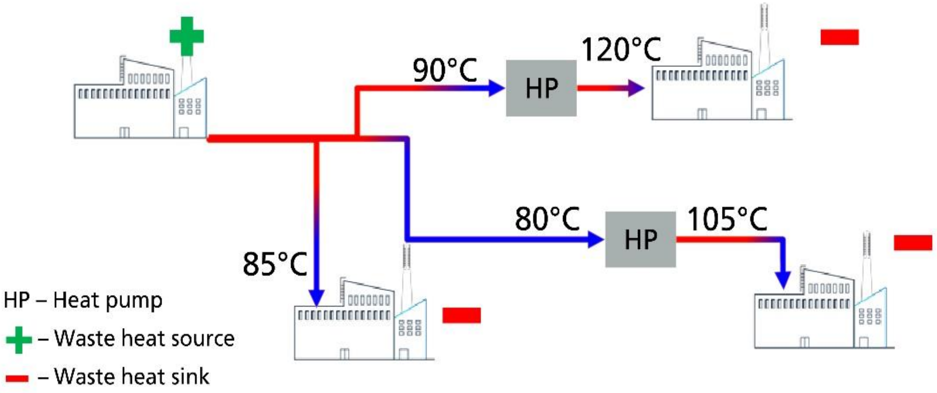

Figure 6. Illustration of the potential of a waste heat recovery network.

- *Frequency of supply and demand – Buffering thermal energy is costly and difficult to implement. A high similarity between demand and potential supply leads to a higher utilization efficiency. The frequency of use can be viewed in different temporal resolutions: e.g., yearly, weekly, daily. The better the match in all temporal resolutions, the higher the potential use. An example of a suboptimal match is industrial waste heat (available year-round) to residential demand (primarily in the fall, winter, and spring months).*
- *Temperature level – The processes on the user side require a certain temperature to perform the required function. Therefore, the heat flow should be as similar as possible in both temperature level and power. If the temperature levels do not match, the lower temperature level must be adjusted by technical means (e.g., heat pump).*
- *Spatial distances – Thermal energy is often transported by steam or hot water through pipes. Depending on the distance between the energy source and the energy sink, heat loss becomes a relevant factor. Despite insulation, thermal energy is released into the environment and reduces the*

amount of usable energy. The distance in combination with the type of transmission system allows a calculation of the heat loss, which is taken into account in the analysis.

Based on this information, the tool performs an initial analysis to derive an appropriate match. Based on the data collected from the companies, the primary energy consumption at the partners' sites could be reduced by 26% by matching the type of energy and its primary energy factor with the waste heat recovery potential provided by the companies. As the tool does not take into account economic aspects such as investment costs, market price of energy, operating model, billing and fulfillment, further negotiations between stakeholders are required.

In Rheinfelden, the companies defined an operating model in which the local energy supplier acts as an intermediary between the waste heat supplier and the waste heat users and is responsible for handling payments and billing. Investment costs are taken into account in the pricing model, as the investment costs are shared among the parties involved. Once the framework was defined, the mandatory building permit was obtained to begin implementation.

3.3 Ultra-Efficiency in Mixed-Use District – IBA'27 Project Fellbach

The third project in focus is a mixed-use district in Fellbach, a city northeast of Stuttgart, the capital of the German state of Baden-Württemberg. The district covers an area of 1.1 km² and includes a variety of businesses as well as agriculture and a residential area consisting of multiple housing units. The district was entered as a participant in the International Building Exhibition IBA'27 in the Stuttgart region. The goal of the IBA'27 is to "the Stuttgart urban region a liveable, sustainable place" [34]. 100 years after Weissenhof, the famous exhibition of modern architecture in 1927, the focus is now on sustainable urban concepts. The mixed-use district in Fellbach is unique in that it is the first time the concept of ultra-efficiency has been applied to areas that include agriculture. However, there are many similar districts in Germany and Europe that need to change to be part of the sustainable transformation of the future. Key stakeholders in the project include the Baden-Württemberg Ministry for the Environment, Climate and Energy Sector, which funded the research, the city of Fellbach, participating research and consulting institutes, the IBA'27 organization, and the owners and management of businesses, farmers, residents, and public utilities in the city of Fellbach [35].

In order to analyze the current situation and the synergy potential for a sustainable urban area, Fellbach's stakeholders were contacted in various ways. Workshops with residents, business representatives, representatives of the city of Fellbach, farmers, representatives of the IBA'27 organization, research and consulting institutes, and farmers were held in person to present the goal and scope of the project and to initiate discussions with interested parties about possible collaboration [36]. In addition, questionnaires were sent to businesses, residents, and farmers to establish a baseline of existing energy flows, material inputs and outputs, emissions, working conditions, and availability of social spaces in the district. In a final step, detailed structured interviews were conducted with interested parties to elaborate on the information previously gathered through the questionnaires. The approach of providing different communication platforms and opportunities led to intense cross-pollination and exchange of ideas. Ultimately, we were able to raise awareness of sustainability goals among a large segment of the local population and business community.

As a result of the data collection and synergy analysis, the following potential ultra-efficiency measures were identified. They are discussed in more detail below:

- *In the field of 'energy', the rooftop surface area can be used for the installation of solar panels for consumption in the district. The potential has been estimated to be at least one third of the annual electricity consumption.*
- *In the field of 'material' synergies, it was discovered that precipitation on the business side of the district is currently a cost factor. Since it is drained through the local sewer system, it is considered waste water by the municipality. Farmers, on the other hand, need large amounts of water for*

irrigation. However, realizing this potential has proven to be challenging from both a technical and commercial standpoint.

- *With regard to the heating requirements of the buildings, the potential lies in extending the heating network of an existing CHP plant. This step, which is logical from an energy point of view, should be considered in the long term and has been discussed in detail with the Fellbach municipal utility. In order for this measure to be fully effective and efficient, efficiency measures for the buildings supplied with this type of environmentally friendly heat should be considered. [37]*

In order to optimize the energy efficiency of the entire district, an estimation of the residential rooftop photovoltaic (PV) potential was performed using data provided by the Landesanstalt für Umwelt Baden-Württemberg (LUBW) [38]. The analysis was carried out using the following settings: rooftop areas with "very high irradiation intensity", taking into account factors such as building orientation and shading effects, most recent data from 2016 to 2021. The selection of "very high irradiance" locations avoids the need to account for shading effects, which can significantly limit the effectiveness of solar panels [39]. This assessment did not include a technical evaluation of factors such as the load-bearing capacity of the rooftops or the capacity of the existing electrical grid. The analysis of the 23 largest rooftops in the district (Fig. 7) showed that the theoretical electricity yield potential was approximately 8.4 GWh per year, which was adjusted to 6.2 GWh per year after taking into account buildings with already installed PV systems. The anonymized annual electricity demand of the 23 selected consumers was between 17-18 GWh, suggesting that approximately one-third of the demand could be met by self-generated solar electricity.

Extending the scope to all roofs in the district and based on area proportionality, the estimated theoretical power potential is about 10 GWh per year. Using typical PV yields for flat roofs in Fellbach of about 87 kWh/(m^2), an additional area of 340 m×340 m could be equipped with PV modules, equivalent to about 16 soccer fields. Economically, with a potential production of 10 GWh per year at an electricity price of 0.40 €/kWh, the district could save about € 4,000,000 per year, highlighting the economic and environmental benefits of investing in rooftop PV systems in areas of high irradiation intensity such as the Fellbach district. However, this does not take into account temporal differences in yield/consumption, seasonal variations, or the lack of electricity storage.

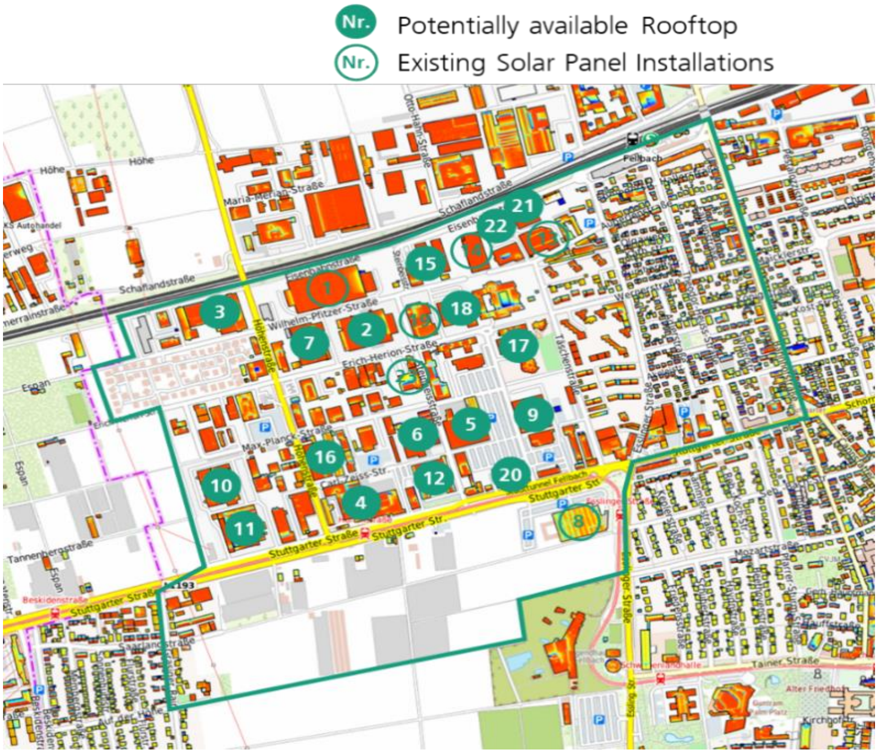

Figure 7. Rooftop areas to be potentially used for solar panel installation.

In a recent assessment of rainwater harvesting from industrial roofs, a significant potential for resource conservation and cost reduction was identified. The study examined a roof area of 3,600 m^2, which receives an annual rainfall of 720 lt/m^2 according to the Deutscher Wetterdienst (DWD) [40], resulting in a collection of approximately 2,600 m^3 of rainwater per year. If used, this amount of rainwater could reduce the need for freshwater purchases, especially for farmers who already have their own rainwater storage tanks. However, an additional 15,000 m^3 of freshwater is still needed annually for agricultural use, at a cost of about € 33,000 (at about 2.20 €/m^3 according to SWF 2023 rates [41]). The assessment also identified the potential based on the 23 largest roof areas, totaling approximately 100,000 m^2, which could theoretically yield rainwater equivalent to € 160,000 of fresh water per year, representing a cost saving potential of € 30,000 per year for the industry by avoiding rainwater costs.

Further detailed assessment for the farmers involved in the project showed that only about 21,000 m^2 of roof area would be needed to collect the 15,000 m^3 of rainwater, which is about one-fifth of the roof area considered in the study. However, the implementation of rainwater collection, storage and distribution systems requires careful technical and economic planning. This includes an assessment of potential additional requirements, such as flushing the sewer system. The total savings potential from the effective use of rainwater in this scenario is estimated at € 39,000 per year. In addition, the concept of integrating a stormwater pond with a local recreation area was proposed, which could increase community engagement and provide multiple benefits beyond economic savings.

Due to the lack of heavy industrial activity in the project area, other ideas for economically beneficial exchanges of energy and materials, such as excess heat or waste products, could not be identified at this time. Many of the businesses in the district are small businesses without much room for social spaces such as break rooms, cafeterias, etc. Since space currently used for these purposes could be used for business purposes, a business model where social spaces are provided by a service provider for a fee is conceivable.

As the mixed-use district has some difficulties in coping with the traffic generated by transport and commuting, it is necessary to reorganize the existing space. One possible approach is to define different lanes and one-way street regulations. In addition, logistic areas within the district could be used to concentrate the handling of goods, resulting in less dispersed truck traffic within the area. Increased utilization of parking facilities may provide an opportunity to reduce the amount of public space used for parking. Parking management allows for alternative uses of parking lots during periods of reduced vehicle occupancy.

4. FINDINGS AND LESSONS LEARNED

Before we look at the lessons learned from the three ultra-efficiency projects described above, we need to recognize how profound the differences between them are:

To begin with, the projects differ in terms of their duration and, consequently, the results that could realistically be expected from them. “Rheinfelden” was the longest project, lasting six years. Considering the large number of different manufacturing companies and the sophisticated model building, the duration of the project was well justified. The “Schaeffler” project comes in second place; it lasted about three years and involved only one company. In addition, a time horizon of three years corresponds to what the Schaeffler management considers to be medium-term strategic planning. These two fortunate circumstances – and, of course, the need to improve the level of sustainability – lead to strong management support, allowing us to develop eight innovation labs and implement numerous measures. The objective of the “Fellbach” project was more analytical in nature, and consisted of conducting a study of ultra-efficiency potentials for a highly diverse structured business environment, even including agriculture as its most distinctive feature. The project duration of nine months was sufficient to achieve this goal, although at this point in time the implementation experience of the identified potentials is still pending.

In light of the project characteristics just described, we could derive eight lessons learned (LL) as follows:

LL1: Project complexity is a function of the number of stakeholders and interests. It increases significantly the more stakeholders there are and the more diverse their goals (e.g., in terms of their individual and business motivations, the urgency to change, and the need to break new ground). This requires an exponentially increased effort for communication and coordination among the project partners. Therefore, the commitment and resources of all participants must increase as the complexity increases. For this reason, a 3-year project in a single-company environment is more likely to produce useful results than a 6-year project in a highly complex and diverse environment.

LL2: Whenever the wider public needs to be involved in identifying – and ultimately exploiting – ultra-efficiency potential, even more additional time must be allowed for the entire communication process. In addition, the use of a demonstrator was critical to effectively communicating the project's potential. By providing a visual representation, it facilitated communication and highlighted possible future developments. This is also beneficial when partners are independent and pursue individual goals. It is helpful to identify and communicate the benefits to each stakeholder (including the public) as early as possible to build and maintain interest.

LL3: At an early stage of the project, when potential benefits are not clear and stakeholders need to be informed about the project and motivated to participate, it is important to have a lead entity that takes ownership and drives the project. Its role is to reach out to potential participants and facilitate exchanges between the different stakeholders.

LL4: It is essential to actively involve decision makers from all entities, especially in a mixed-use district where different roles are possible. There are land and building owners, entrepreneurs (as owners or tenants), private individuals, and administrative bodies. The implementation of inter-organizational measures requires the support of all partners in terms of financial commitment, legal acceptance, development of operating models, and support for installations on private property.

LL5: Because sustainability measures require investment, they limit other business development opportunities. Therefore, they are usually not the first choice for business owners as they usually do not pay off quickly enough. Typically, investments need to pay off in a short period of time, which is difficult to achieve with ultra-efficiency measures. To encourage participation, a meaningful benefit for each party is required, sometimes based on environmental and social perspectives.

LL6: Identifying potential synergies requires open communication about each company's detailed energy and material inputs and outputs. This is a challenge for the researcher as companies are often very restrictive about sharing data. It is therefore essential to ensure anonymity and confidentiality. Involving a neutral party, such as a research institution, that has no financial interest in the project can help build trust and willingness to share data.

LL7: To take advantage of synergies, consider and promote the sharing of resources (e.g., energy, materials, space) or emissions (e.g., waste heat). In addition to protecting confidential data, stakeholders are often concerned about tying their processes and business models too closely to other parties and losing their ability to make independent decisions. These concerns can be addressed by using an independent operator model (e.g., through municipal utilities) that balances the corresponding energy and material flows and assumes responsibility for billing; contractual terms between the operator and the affected companies can be specified in a way that respects the specific interests of all parties involved.

LL8: Finding and achieving higher-value synergies in the exchange of energy, materials, and the like between different types of enterprises can be challenging if they are to be financially viable. The symbiotic use of resources often requires infrastructure measures (e.g., in the form of pipelines of all kinds) for their transport and provision to another actor, which, especially in urban areas, must be accompanied by medium- to long-term (urban) planning. In addition to involving and convincing the relevant decision-makers, important milestones of higher-level planning and implementation projects must be synchronized in good time and taken into account in one's own planning for such mostly strategic measures. The financing of early phases of ultra-efficiency projects must also be considered, especially if they do not offer immediate operational savings potential, but rather a strategic perspective. These facts make a strong case for increased public funding to achieve overarching sustainability goals.

5. CONCLUSIONS AND OUTLOOK

In this paper, we have examined three ultra-efficiency projects that differ in their spatial expansion, number of stakeholders, and urban setting. To this end, we first elaborated the goals and five fields of action of the ultra-efficiency concept. After combining the latter with a layer model specifying geographic expansion and adding the stakeholder and business model aspects, we derived a methodology for comparing the three projects.

By describing and contrasting the key features of each project, we were able to identify eight lessons that can help practitioners and fellow researchers alike in their quest for successful ultra-efficiency projects. It became clear during the research that for the majority of stakeholders, the ultra-efficiency measures identified during the projects usually don't pay off quickly enough from an individual financial perspective. This fact – together with the challenges of achieving participation in a diverse stakeholder environment – leads to the conclusion that only publicly supported initiatives can close the gap to more sustainable business activities, especially in an industrial and mixed-use zone environment with multiple companies.

Therefore, future research should focus on appropriate methods of public funding and on identifying synergies between the different fields of action. Other areas of research should focus on the geographical expansion of industrial zones, their interconnection, and the further application of the ultra-efficiency concept to mixed-use urban districts. Part of this research is an ongoing project funded by the Baden-Württemberg Ministry for the Environment, Climate and Energy Sector. The project focuses on synergies, interdependencies and conflicts of objectives between the fields of action of ultra-efficiency (grant number BWDU 24105).

Acknowledgement

This work was supported by the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg (grant numbers L75 21107, BWDU20110, L75 22123, L75 22124). The project supervision was performed by the Project Management Agency Karlsruhe (PTKA). In addition, we like to thank Adrian Barwasser and Leonhard Hörstensmeyer of the University of Stuttgart, Institute for Human-Factors and Technology Management IAT who supported the work by their expertise and impulses.

REFERENCES

[1] United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects: The 2012 Revision, Highlights and Advance Tables*. New York: United Nations; 2012.

[2] United Nations Department of Economic and Social Affairs, Population Division. *World Population Prospects 2024: Summary of Results* (UN DESA/POP/2024/TR/NO. 9). New York: United Nations; 2024.

[3] Dahl Andersen A, Marin A. Learning and innovation in natural resource intensive industries. *Innovation and Development*. 2015. doi:10.13140/RG.2.1.1904.0481.

[4] United Nations. Sustainable production and consumption. 2023. Available from: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/. Accessed: 26 July 2024.

[5] Global Footprint Network. Ecological footprint data. Available from: https://data.footprintnetwork.org/. Accessed: 29 July 2024.

[6] WU Vienna. Material flows by material group, 1970-2019. Visualisation based upon the UN IRP Global Material Flows Database. Available from: materialflows.net/visualisation-centre. Accessed: 31 October 2023.

[7] Lentes J, Mandel J, Schliessmann U, Blach R, Hertwig M. Competitive and sustainable manufacturing by means of ultra-efficient factories in urban surroundings. *International Journal of Production Research*. 2017;55(2):480-491. doi:10.1080/00207543.2016.1189106.

[8] Mandel J, Sauer A. *Die Ultraeffizienzfabrik: Ziele – Konzept – Methoden*. Ludwigsburg: LOG_X Verlag; 2020.

[9] Kuhlmann T, Sauer A. Ultra-Efficiency Factory - Framework and Holistic Approach to Increase and Evaluate Efficiency and Sustainability. *Advanced Materials Research*. 2016;1140:481-488. doi:10.4028/www.scientific.net/AMR.1140.481.

[10] Lentes J, Mandel J, Schliessmann U. Competitive and sustainable manufacturing by means of ultra-efficient factories in urban surroundings. *International Conference on Production Research*. 2015;23. doi:10.1080/00207543.2016.1189106.

[11] Sheehan E, Braun AT, Kuhlmann T, Sauer A. Improving Material Efficiency for Ultra-efficient Factories in Closed-loop Value Networks. *Procedia CIRP*. 2016;40:455-462. doi:10.1016/j.procir.2016.01.096.

[12] Miehe R, Stender S, Hessberger N, Mandel J, Sauer A. Improving Manufacturing Systems with Regard to the Concept of Ultra-Efficiency. *Advances in Manufacturing Technology XXXI*. 2017:321-326. doi:10.3233/978-1-61499-792-4-321.

[13] Waltersmann L, Kiemel S, Amann Y, Sauer A. Defining sector-specific guiding principles for initiating sustainability within companies. *Procedia CIRP*. 2019;81:1142-1147. doi:10.1016/j.procir.2019.03.282.

[14] Waltersmann L, Kiemel S, Bogdanov I, Lettgen J, Miehe R, Sauer A, Mandel J. Benchmarking Holistic Optimization Potentials in the Manufacturing Industry – A Concept to Derive Specific Sustainability Recommendations for Companies. *Procedia Manufacturing*. 2019;39:685-694. doi:10.1016/j.promfg.2020.01.445.

[15] Schutzbach M, Full J, Kiemel S, Waltersmann L, Sielaff L, Miehe R, Sauer A. Principles and Design Strategies for Ultra-Efficient Production Systems in the Process Industry. *Chemie Ingenieur Technik*. 2021;93(11):1781-1791. doi:10.1002/cite.202100062.

[16] Schutzbach M, Kögel A, Kiemel S, Miehe R, Sauer A. Principles of Management Systems for Positive Impact Factories. *Sustainability*. 2022;14(24):16709. doi:10.3390/su142416709.

[17] Sielaff L, Waltersmann L, Lucke D, Sauer A. Machine Failures' Consequences – A Classification Model Considering Ultra-Efficiency Criteria. *Procedia CIRP*. 2023;118:982-986. doi:10.1016/j.procir.2023.06.169.

[18] Singh S, Hertwig M, Lentes J. Economic Impact of Ultraefficient Urban Manufacturing. In: Vinod Kumar TM, editor. *Smart Economy in Smart Cities: International Collaborative Research*. Singapore: Springer Singapore; 2017. p. 273-293. doi:10.1007/978-981-10-1610-3_12.

[19] Lentes J, Hertwig M. Towards Ultra-Efficient Industrial Areas. *Procedia Manufacturing*. 2019;39:804-813. doi:10.1016/j.promfg.2020.01.426.

[20] Hertwig M, Bogdanov I, Beckett M, Waltersmann L, Lentes J. Symbiotic loss-free industrial production in ultra-efficient urban industrial parks. *Procedia CIRP*. 2021;98:637-642. doi:10.1016/j.procir.2021.01.167.

[21] Chertow MR. Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and the Environment*. 2000;25:313-337. doi:10.1146/annurev.energy.25.1.313.

[22] Ehrenfeld J, Chertow MR. Industrial Symbiosis: the legacy of Kalundborg. In: Ayres RU, Ayres LW, editors. *A Handbook of Industrial Ecology*. Cheltenham: Edward Elgar Publishing; 2002. p. 334-348. doi:10.4337/9781843765479.00038.

[23] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

[24] ISO 6385:2016: *Ergonomics principles in the design of work systems*. Geneva: International Organization for Standardization; 2016.

[25] Freitag J. *Abschlussbericht des Verbundprojektes UltraELab*. Karlsruhe: Landesanstalt für Umwelt Baden-Württemberg; 2022.

[26] Lentes J, Hertwig M. Towards Ultra-Efficient Industrial Areas. *Procedia Manufacturing*. 2019;39:804-813. doi:10.1016/j.promfg.2020.01.426.

[27] Hertwig M, Zimmermann N, Lentes J. Method for development of sustainable relations of manufacturing companies in industrial estates. *International Conference on Production Research*. 2017;24:715-720. doi:10.12783/dtetr/icpr2017/17697.

[28] Bogdanov I, Hertwig M, Beckett M, Waltersmann L. *Ultraeffizienzfabrik: Symbiotisch-verlustfreie Produktion im urbanen Umfeld; Arbeitspaket 3.4: Ausarbeitung von Anforderungsprofilen an Ultraeffizienzfabriken zum Aufbau stadtnaher Industriegebiete*. Stuttgart: Fraunhofer-Institut für Arbeitswirtschaft und Organisation; 2020.

[29] Hertwig M. *Upgrading of Industrial Parks – Symbiotic Loss-Free Industrial Production in Ultra-Efficient Urban Industrial Parks*. Trent: Sino-German Workshop on Circular Economy; 2021. doi:10.24406/publica-fhg-413457.

[30] Hristov I, Chirico A. The Role of Sustainability Key Performance Indicators (KPIs) in Implementing Sustainable Strategies. *Sustainability*. 2019;11:5742. doi:10.3390/su11205742.

[31] Srinvias AS, Donald AD, Sameena M, Rekha K, Srihith ID. Unlocking the Power of Matlab: A Comprehensive Survey. *International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)*. 2023;3(1):20-31. doi:10.48175/IJARSCT-9005.

[32] Ouyang M. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering and System Safety*. 2014;121:43-60. doi:10.1016/j.ress.2013.06.040.

[33] Gerdes J, Munder M, Sauer A. Evaluation of technical and economic potential of waste heat distribution networks in industrial sites. *3rd International Conference on Power, Energy and Electrical Engineering (PEEE)*. 2022;3:219-226. doi:10.1016/j.egyr.2022.12.112.

[34] IBA’27. Internationale Bauausstellung 2027 StadtRegion Stuttgart. Available from: https://www.iba27.de/en/knowledge/the-iba27/. Accessed: 23 October 2023.

[35] Fellbach. Handlungsfelder, Website of the City of Fellbach regarding the IBA’27 Project. Available from: https://iba.fellbach.de/de/Handlungsfelder-Projekte. Accessed: 07 July 2023.

[36] Dilger U. Impuls zur Gebietskonferenz im IBA’27-Projekt “Manufacturing meets Agriculture” at 14.02.2023. Available from: https://iba.fellbach.de/1032?project_id=31. Accessed: 26 October 2023.

[37] Johnson K. A Long-Term Strategy Suggestion for Renewable Energy Success. *12th European Conference on Renewable Energy Systems*. 16-17 May 2024;12:135-140. ISBN: 978-605-70842-3-1.

[38] Landesanstalt für Umwelt Baden-Württemberg (LUBW). Solar radiation on roof areas. Available from: http://www.energieatlas-bw.de/sonne/dachflachen/solarpotenzial-auf-dachflachen. Accessed: 16 July 2024.

[39] Sado K, Ali I, Hadi L, Sado S. Power loss calculation of Photovoltaics using Python. *Computers and Informatics*. 2021;1(2):74-82. https://dergipark.org.tr/en/pub/ci/issue/64530/952567. Accessed: 16 July 2024.

[40] Deutscher Wetterdienst (DWD). Weather data Germany. Available from: https://www.dwd.de/DE/leistungen/klimadatendeutschland/mittelwerte/nieder_8110_fest_html.html?view=nasPublication&nn=16102. Accessed: 16 July 2024.

[41] Stadtwerke Fellbach (SWF). Wasserpreise. Available from: https://www.stadtwerke-fellbach.de/de/Wasser/Wasserpreise/Wasserpreise/Tarifblatt-Wasser-2023-mit-AVB-und-ergaenzenden-Bedingungenpdf.pdf. Accessed: 16 July 2024.