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# Smart Energy Management and Industrial Sustainability

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A B S T R A C T

The swift advancement of manufacturing, influenced by digital solutions and technological capabilities, aligns with the pursuit of sustainable development goals under Industry 4.0. The research described in the present paper aimed to develop an integrated energy sustainability hub encompassing sustainability, Industry 4.0 technologies, and energy efficiency. Recent studies on energy sustainability do not sufficiently address the in- terrelations between sustainability and energy efficiency, as well as Industry 4.0 paradigm, leaving a gap in understanding of how digital solutions can optimize energy management. Furthermore, there is a lack of plant- centric studies that examine the practical implementation of these technologies in the context of energy sus- tainability. Confronting this gap, the authors` research introduces an interpretive structural framework that merges Industry 4.0 technologies with energy sustainability within the manufacturing sector This framework has been rigorously verified through insights gathered from energy experts working in a dairy company and Focus Group Interviews leading to the harmonization of technology deployment with sustainable energy management practices. The modular framework`s efficacy is demonstrated through a real-world case study on a milk pro- cessing plant operating within a multinational food company. This case study highlights the framework's scal- ability, adaptability, and interoperability, showcasing its potential to digitalized revolutionize energy sustainability in manufacturing.

A R T I C L E I N F O

*Keywords:*
Energy sustainability hub
Energy life cycle-based approach
Digitalization
Industry 4.0

## 1. Introduction

The increasing demand for energy necessitates changes in manufacturing practices, with industrial plants being major energy consumers. Effective energy management for these plants, particularly medium and small ones, depends on a country's energy policy, including factors like electricity prices and carbon emissions (Neofytou et al., 2020; Santika et al., 2020; Jonek-Kowalska, 2022). It aligns with stra- tegic decision-making within manufacturing companies, ensuring a comprehensive approach to energy sustainability (Krysiak and Kluczek, 2021; Melnik and Ermolaev, 2020). Fluctuations in energy prices lead to shifts in operational models (van de Ven and Fouquet, 2017), aiding in achieving sustainable energy performance in the manufacturing in- dustry in line with the UN Sustainable Development Goals (United Na- tions, 2023), highly favor SDG7 (Jayachandran et al., 2022) for "pure" or cleaner energy through sustainable energy transition (Ghobakhloo and Fathi, 2021). Transforming energy systems through Industry 4.0 (I4.0) technology hub, incorporating various energy systems assessment methods (Hottenroth et al., 2022; Junne et al., 2020; Kopfmüller et al., 2021) can facilitate the adaptation of digital and renewable sustainable solutions (Pandey et al., 2023). I4.0 technologies can support plants operations, accelerating the development of new production systems or improving energy efficiency (Mohamed et al., 2019; Zhang and Fu, 2022; Jonek-Kowalska, 2022), and replacing traditional energy tech- nologies (Zhang and Fu, 2022), leading to substantial savings (Monjurul Hasan and Trianni, 2020). However, managing processes within I4.0 technologies require transparent integration of digitalization (Gho- bakhloo and Fathi, 2021; Jayachandran et al., 2022), resulting in opti- mized processes, manufacturing development, productivity, and reduced greenhouse gas emissions (Chen et al., 2020). With the accel- erated deployment of 4.0 technologies in manufacturing, the manage- ment of energy systems is becoming more prominent.[1] In this context, digitization plays a crucial role in developing a suitable, integrated en- ergy management approach through I4.0, addressing economic,

*List of abbreviations:* MDCA, Multi-criteria decision analysis; LCA, Life cycle analysis; LCC, Life cycle costing; LCSA, Life cycle sustainability analysis; SLCA, Social Life Cycle Analysis; DEA, Data Envelopment Analysis; I4.0, Industry 4.0.

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[1] "I4.0 enables and supports sustainability by deploying digital technologies … with a focus on energy efficiency, pollution control." (Suleiman et al., 2022).

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environmental, and social concerns in manufacturing (Mayer and Oosthuizen, 2022), while meeting the companies` sustainable energy demand.

The gap between energy efficiency, digitalization and sustainability must be closed by designing an energy sustainability hub within the I4.0 context. This hub encompasses problem definition, scope, assessment methodologies, measurement, change planning, and technological improvements.

An energy sustainability hub represents a novel approach to energy management integrating data measurement, energy assessment methods, I4.0 technologies, policy, and best practices. It requires a process-level energy management approach tailored to sustainability assessment methods. The description of the energy hub existing in the literature (Qamar et al., 2021) delivers only the mathematical model for various energy types, overlooking the incorporation of sustainable technologies. Similarly, another paper presents an indicator-based mathematical model primarily for measuring energy sustainability at the regional or national level (Grigoroudis et al., 2021).

While numerous publications exist on energy sustainability theory, objective driving policy (McCollum et al., 2011), optimization techniques, or energy transition criteria (Blohm, 2021; Favi et al., 2022; Saraswat and Digalwar, 2021), as well as sustainable models within I4.0 (see Table 1), there is a distinct lack of research discussing high-level interdependencies between I4.0 technologies and energy sustainability. This research gap arises from the need for modifying initial plans to change business environments. Regrettably, previous studies have ignored the synergies between energy management systems, assessment models (see Table 2), advanced technologies (Jayashree et al., 2021), energy transition (Timonen et al., 2021), and policies (Andersson and Thollander, 2019).

Despite these substantial gaps, an accelerated deployment of 4.0 technologies in manufacturing is bringing energy system management into sharper focus. Notably, the literature reports energy-based models, frameworks, management systems in industrial sectors (Blohm, 2021; Çınar et al., 2021; Gökalp et al., 2017; Man and Strandhagen, 2017), as well as technological studies in I4.0 (Bai et al., 2020; Dalenogare et al., 2018). However, the absence of a tangible and intelligent energy sustainability hub remains conspicuous. Additionally, the current research lacks a concrete demonstration regarding the implementation of such a hub. Furthermore, despite the extensive use of sustainability assessment methods, the pressing need is to concretely manifest the hub's capabilities within a realistic context. Therefore, this new model incorporates I4.0 components, addressing baseline and future scenario and making energy-efficient improvements through change planning. To achieve a "structured" digital energy sustainability hub aligned with I4.0, the following elements must be integrated with each other: (1) Smart energy measuring/metering & monitoring; (2) Supoort for digitalisation in energy technologies; (3) Improving processes and systems integratively; (4) Enhancing technology durability (lifecycle); (5) Implementing in-house energy audit practices; (6) Adopting sustainability assessment methods; (7) Promoting more efficient human behavior.

Manufacturing companies are increasingly driving sustainability through assessment methods and digital technologies (Giraldo et al., 2021), aligning growth strategies (Schöggl et al., 2023) with economic (Ghobakhloo, 2018; Ghobakhloo and Fathi, 2021; Buchmayr et al., 2021; Franco et al., 2023), environment and social dimensions of sustainable development (Peters and Simaens, 2020). The transition to a sustainable digital future (Giraldo et al., 2021) requires engagement with I4.0 technologies to measure (positively or negatively) environmental impact (Chen et al., 2020) in terms of energy use, waste, social well-being, and economic growth (Javaid et al., 2022). The impact of I4.0 technologies on sustainability remains uncertain (Bonilla et al., 2018), and there is a lack of structured frameworks for smart energy sustainability. Current literature lacks a process-level industrial case study, I4.0 assessment, and the interrelation/intersection between energy efficiency and sustainability, and digitalization. Challenges and contribution persist at building a hub to manage energy in manufacturing that correlate I4.0 enabling technologies, sustainability, and energy efficiency via assessment methods (Ghobakhloo and Fathi, 2021; Lins and Rabelo Oliveira, 2017; Yang and Gu, 2021).

The goal of this study is to develop an energy sustainability hub integrating sustainability, technologies, and energy efficiency within Industry 4.0. This primary focus on defining components necessary to achieve energy sustainability at the process level. The core feature of this approach is a three-pronged energy sustainability assessment method, serving as a keymodule within the hub, based on its results, the other modules can be linked with each other and described jointly for synergistic view. This comprehensive energy assessment within the hub is an original concept not found in current studies. For reaching the goal, this paper considers an industrial case study from milk processing to dealinate the modules of the energy sustainability hub within I4.0. This integration combines energy-oriented assessment methods, Industry 4.0 functions, and decision-making processes for energy efficiency and sustainability.

The paper`s originality lies in:

**Table 1**
Models and frameworks focused on the digital transformation of companies/smart factories towards adoption of sustainable I4.0.

| Model/framework | Subject areas/study objectives/measurement | Scope/Country | Methods | Reference |
|---|---|---|---|---|
| STS-S4.0 framework for Sustainability 4.0 (S4.0) | Comparison of policies and initiatives from science technology | Government, Organizations and Academy | | (Maisiri et al., 2021) |
| Readiness framework for I4.0 adoption | Assessment of I4.0 adoption through modularity | Automobile manufacturing enterprises/Turkey | four dimensions, five levels, 60 s-level dimensions, and 246 sub-dimensions, and generic F/W with four layers and seven hierarchy levels; | (Çınar et al., 2021) |
| Digital business model innovation | Reconfiguration of traditional business models to embrace I4.0 focusing on shaping of the value value delivery, and value capture | N/A | Literature review | (Ibarra et al., 2018) |
| IoT -based business model | Integration of IoT in corporate business models with focus on the connection between building elements | N/A | Systematic literature review | (Palmaccio et al., 2021) |
| Sustainable business model through Industry4.0 | Development of sustainable business models through potential sustainable business scenarios in the light of I4.0 deliver a new value proposition | N/A | Literature review | (Man and Strandhagen, 2017) |
| SPICE-based Industry 4.0-Maturity Model | Comparison analysis of seven models in terms of their characteristics of scope, purpose, completeness, clearness, and objectivity focusing on the assessment process transformation, application management, governance, asset management, and organizational alignment areas | N/A | Literature review with the identification studies related to I4.0-MMs | (Gökalp et al., 2017) |

**Table 2**
Existing energy sustainability assessment in the sense of I4.0.

| **Energy technology Technology4.0** | **Key contributions** | **Method (s)** | **Strengths (þ)/ Weaknesses (-)** | **Reference** |
|---|---|---|---|---|
| Not applicable | Mathematical model for measuring energy sustainability based on indicators for a given or country | Statistical methods + Fuzzy logic | nonlinear and uncovers some counterintuitive results (-) | (Grigoroudis et al., |
| Various 4.0 technologies | Economic and environment assessment across various industries (automotive, electronics, food, textiles) | Fuzzy set + Cumulative prospect theory + VIKOR | | (Bai et al., 2020) |
| No applicable | Multi-dimensional sustainability assessments and probabilistic ranking of 11 renewable technologies; selection of the renewable energy technology best in terms of (environmentally, technically, economically, and socially) using AHP | MCDA with Monte Carlo simulation | country-scale assessment oriented (+); more robust results and ensure better informed decision-making (+); different forms of data and | (Troldborg et al., 2014); |
| Renewable energy source | Prioritization of the best renewable energy technology based on a consideration of environmental, economic, social, technical, political, quality of energy criteria using AHP-VIKOR | Integrated AHP-VIKOR approach | direction for energy policy in terms of sustainability | (Abdul et al., 2022); |
| No applicable | Performance assessment of processes and technologies based on specific indicators | Qualitative evaluation | conceptual framework for the further development of assessment methods (+); methodically there are conflicts of objective between the different criteria of sustainability indicators are inconsistent (-) | (Grunwald and Rösch, 2011) |
| Energy sustainability model | Measuring and assessing energy sustainability performance index in [0,1] considering the dimensional sustainability structure | Energy LCA-Based Indicators | process-level assessment (+); considers uncertainties, which is not supported by the software (+); similarly sized assessment object (-); | (Kluczek and Gladysz, 2022) |
| Energy sustainability hub | Process-level energy management approach considering sustainability, change management and I4.0 frequently associated to manufacturing. | Three-pronged sustainability assessment approach using LCA-based | well-founded framework based on a detailed process assessment (+); process-oriented energy indicators (+); | Authors |

- Developing a synergistic interpretive smart energy sustainability hub based on a modular framework, which consists of the following elements: definition of scope, adapting assessment methodologies, measurement, change planning, improvement implementation. The model envisages improvement of sustainability perfromance in terms of energy efficiency for the considered industrial plant, triggering methodological enhancement of existing sustainability models towards industrial adoption of sustainable I4.0;
- Broadening analyses of energy efficiency-related manufacturing performance using multidimensional sustainability assessment indicators, not only at a single process level, but also at the industrial plant level;
- Presenting these interlinkages between energy efficiency, sustainability and I4.0 technologies to deeply understand the model;
- Overcoming difficulties and limitations for the integration of the research areas, including energy efficiency, sustainability assessment approaches, I4.0 technologies) along with methodological approaches.

The structure of the paper is designed to set goals accordingly, explicitly justifying and explaining decisions about key elements of this research while Section 2 provides a review of energy transition through technologies of I4.0 and major methods adopted in many scientific papers; Section 2 clarifies/explains the adopted research methodology to illustrate it using a case study in Section 3. The last section discusses the findings and summarizes the whole paper.

## 2. Research approach

Considering the objective of this research, the authors implemented the following research agenda:

1. Literature review: These studies were provided in two dimensions: (a) sustainability assessment methodologies in the context of energy, (b) adoption of I4.0 technologies towards energy sustainability. As a result of this stage, the authors revealed research gaps in the current knowledge regarding the digital transformation of companies towards creating transformative energy sustainability hub. It also led to the development of assumptions for case selection to validate this concept.
2. Framework Proposal: Building on the literature analysis, the authors proposed a three-dimensional framework for the energy sustainability hub, comprising three dimensions: (a) sustainability through energy efficiency, (b) I4.0 technologies (c) change management.
3. Framework Verification: The validation process involved two paths: the case study and the Focus Group Interview (FGI). Through the case study, the authors verified the model by deeply investigating the primary problem effects of the digital and organizational solution's implementation within a studied company. The scope of this research is narrowed to incorporate transition behaviour towards energy sustainability for milk processing. This transformation is expressed in terms of the improvement of existing technologies and their upgrade to work within an I4.0 environment. Although the case study approach is well recognized for theory creation (Eisenhardt, 1989), a qualitative case study is most frequently used by researchers (Rashid et al., 2019) in manufacturing areas, the authors, therefore, considered the case study method in this paper for its effectiveness in collecting and analyzing data, providing valuable insights into the company's operations, and specifically validating the energy sustainability hub's components related to energy data quality, collection, sustainability assessment, monitoring and management within I4.0 to facilitate energy management.
4. Final alignment of the hub: An inherent part of the energy sustainability framework is its assessment, prticularly focusing on sustainability assessment in terms of energy efficiency, generated here for illustrative purposes. Within the energy-related studies, combined LCA with DEA, thanks to its versatility and wide range of applications was identified as suitable for conducting energy assessment by

analyzing energy streams, which is in line with the authors' expectations. The proposed framework and implementation have been discussed Focus Group Interview (FGI). The conclusions drawn from the verification phase influenced on the final alignment of the hub.

The research methodology is presented in Fig. 1.

The authors have verified the designed frameworks of the sustainability energy hub through the use of the case study and then FGI. The focus group consists of scientists and practitioners from the industry and representatives of the company that participated in the case study. Comments and suggestions provided by the focus group were taken into consideration in the framework development process and final version of the hub.

## 3. Results

### *3.1. Desk research on energy sustainability assessment methods*

Numerous opportunities for assessing energy sustainability in industrial plants and smart factories exist through established methodologies based on Life Cycle Assessment (LCA)[2] (da Silva and Amaral, 2009; Singh et al., 2009; Wang et al., 2009; Evans et al., 2009; Santoyo-Castelazo and Azapagic, 2014; Favi et al., 2022). Integrating LCA with advanced I4.0 technologies enables digitization, automation, and enhanced operational efficiency (Bai et al., 2020; Tesch da Silva et al., 2020). The standalone traditional LCA method is questioned due to its inappropriateness in supporting decision-making for facility sustainability (Hauschild et al., 2005). Unlike studies (Tesch da Silva et al., 2020), which consider environmental and economic impacts on a life cycle basis, previous research primarily focused on environmental indicators (da Silva and Amaral, 2009). Expanding the scope of LCA to encompass energy aspects and plant technology improvements could improve sustainability assessments. Energy LCA, for instance, concentrates on energy-related indicators and their interaction with the environment. Furthermore, LCC is designed for evaluating the economic aspect of technologies, while Social Life Cycle Assessment (SLCA), when combined energy LCA and LCC, assesses social aspects regarding energy (energy impact on quality of employees` work enhancement) along the life cycle. Despite their significance emphasised in various studies (Norris, 2012; Pollok et al., 2021; Venkatesh, 2019), these methods primarily focus on life cycle analysis rather than offering a holistic sustainability perspective. Moreover, the simultaneous achievement of environmental, economic, and social benefits is rarely addressed, even when combining various LCA-based methodologies (Ren and Toniolo, 2020). The combination of energy LCA with other optimization methods related to energy concerns is also underexplored (Kluczek, 2019; Kluczek and Gladysz, 2022). Recent advancements in energy approaches have been explored for assessing energy sustainability performance in manufacturing (Cagno et al., 2018; Lucato et al., 2018; Gómez-Camacho and Ruggeri, 2019; Kumar and Mani, 2022; Mahmood et al., 2022), energy usage and industrial performance are significantly influenced by production methods, throughputs, weather conditions, and operating hours, affecting environmental, economic, and social aspects. The most of existing sustainability assessments primarily rely on indicator-based approaches, especially in industrial energy transition (Faria et al., 2021; Franco et al., 2023). While these approaches employ indicators within LCA methods to assess sustainability, combining them with supportive techniques like Data Envelopment Analysis (DEA) and Multidimensional Comparative Analysis (MDCA) allows for predictive decision-making on sustainability (Pope et al., 2017) and assessing eco-efficiency (Kluczek and Gladysz, 2020). However, sustainability measures in manufacturing often concentrate on process efficiency improvements, overlooking energy issues and minimizing the role of the social dimension (Despeisse et al., 2012). While many energy technologies are examined independently for social or environmental indicators (Dong and Hauschild, 2017), selecting the most relevant indicators for assessing sustainability across sectors or technologies remains a challenge.

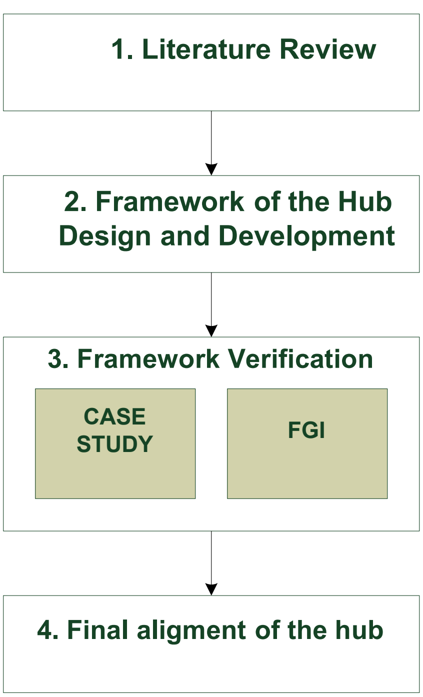


**Fig. 1.** A research methodology.

As an example, using the lifecycle-based framework incorporating the DEA model, energy sustainability in terms of the three sustainability domains is evaluated, Fig. 2.

Given these challenges and the existing fragmented approaches, there is a pressing need to develop an energy sustainability hub within the context of I4.0 technologies. This is crucial for guiding small and medium-sized industrial plants towards I4.0-oriented energy sustainability, aiming to enhance energy assessment capabilities in a standardized, repeatable manner.

### *3.2. Framework of the smart energy sustainability hub*

Following the literature review, the authors proposed an interpretive model (Fig. 3). This energy sustainability framework, described briefly, consists of ten modules framed in three main cycles, aligned with the principles of I4.0 that promote I4.0 technologies.

At all stages of the process, there are interdependencies between perspectives (energy efficiency, change management, and I4.0) in which synergies exist between them. The proposed hub (Fig. 3) illustrates the complexity and richness of interrelations apparent at every stage and in all components of the model. Previous studies were not sufficient in the area, ignoring these dependencies and focusing on a holistic energy-sustainability policy approach or on a definition of energy assessment on a regional/country scale (Grigoroudis et al., 2021) or a process level (Kluczek and Gladysz, 2022). This new hub combines all variants of approaches integrated with Industry 4.0 technologies and aligned with sustainability and applied on a process level I4.0 technologies are the basis for energy efficiency improvements. In order to obtain expected results the change management approach should be used. It is assumed that different stakeholder groups will be responsible for the different

[2] According to ISO14040, LCA is defined a compilation and evaluation of the in/outputs and the potential environmental impacts of production systems throughout its life cycle.

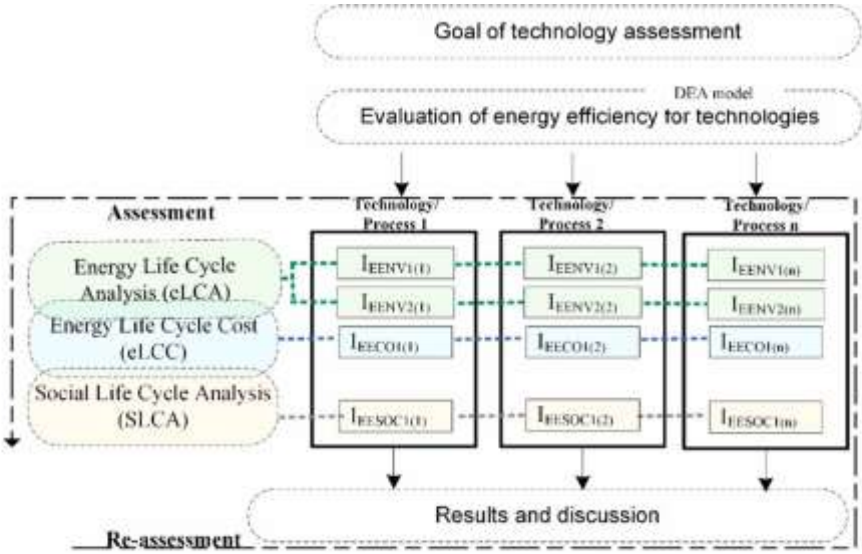


**Fig. 2.** A structural assessment framework within the energy sustainability cycle (own elaboration based on the author`s paper (Kluczek, 2019).

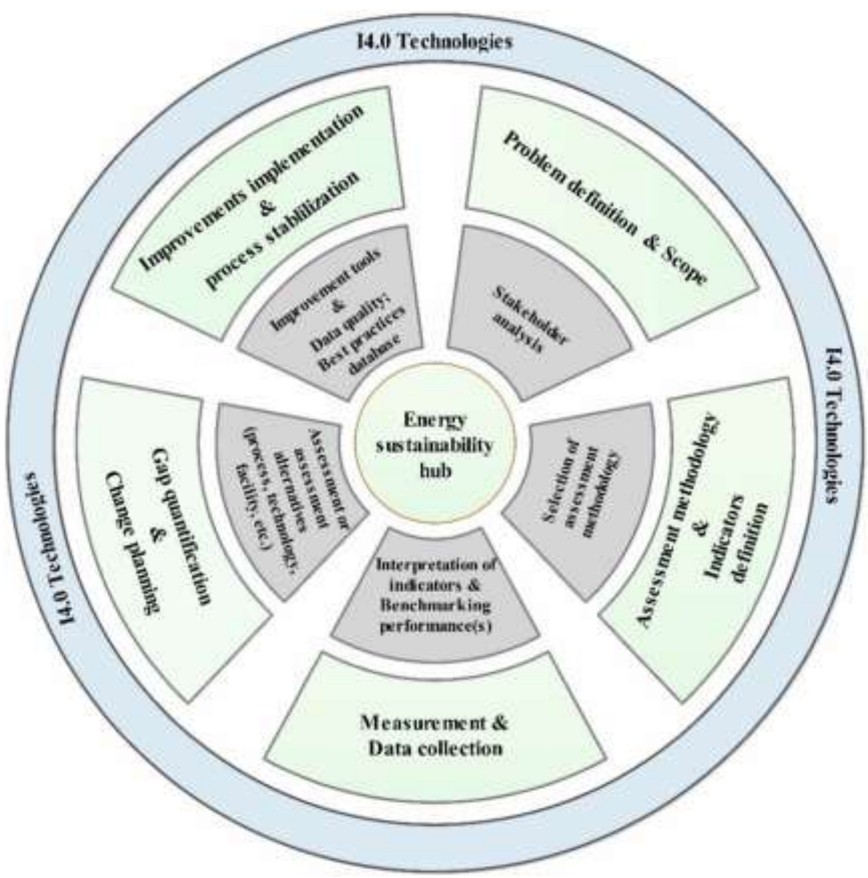


**Fig. 3.** The Energy Sustainability Hub.

lines (perspectives). On the strategic level, the main attention will focus on the energy efficiency topic, on lower levels on change management (tactical) and I4.0 technologies (operational), respectively. However, to achieve sustainable energy efficiency excellence in all perspectives and links between perspectives are essential.

*3.3. Framework verification*

*3.3.1. Case study*

The study results are presented below in the order of the change management cycle. The presentation begins with a description of the model, followed by an overview of the activities related to the case study.

*3.3.1.1. Problem and scope definition.* Problem and scope definition involves identifying stakeholders, analyzing their needs and expectations, and evaluating each of these. This process is followed by a top-down analysis of selected needs, expectations, and energy balance.

The scope of analyses covers manufacturing of boilers which involves interconnected processes such as cutting, bending, welding, cleaning, painting, and final assembly. Technologies employed in producing the boilers utilizes computer-controlled plasma cutting, ensuring precise replication of designs and computer-aided manufacturing (CAD/CAM). This method enables cutting complex-shaped parts with acceptable precision. The dairy plant producing heavy whipping cream, eggnogs, coffee cream, etc. is a major energy consumer. This plant is part of a large international food company with several identical facilities worldwide. An energy audit conducted by experts from Michigan University, as part of the Industrial Assessment Center program, highlighted its energy consumption. The production process involves blending raw and processed milk with other ingredients like sugar and flavors to create the final product. Once blended, the product undergoes thermal processing to ensure the desired quality before being packaged in various forms such as bags, containers, and boxes. The energy flow within this process is illustrated in Fig. 4, and the technologies employed are integrated into the plant's services.

The study is limited to energy technologies used for milk processing. These technologies, which encompass existing technologies, as well as their upgrade are listed in Section 3.1.1.5.

*3.3.1.2. Assessment methodology & indicators definition.* To illustrate the approach to energy sustainability, the study provides energy sustainability assessment based on LCA methods and the input-oriented DEA in the investigated industrial plant. For the assessment, six sections of equipment within milk processing were analysed in the way naturally defined by the functionalities of the considered methodology. The DEA method was employed to evaluate the energy efficiency of six sections used in the dairy plant to differentiate between efficient (with the score of one) and inefficient ones (less than one). The technologies were evaluated as eco-efficient at the process level using a DEA Frontier Software (Cooper et al., 2007), and further they were considered in the energy sustainability assessment framework.

Due to energy diversification, data for developing indicators in terms of economic, economic, and social were aggregated (natural gas and electricity). To assess energy sustainability of technologies, energy sustainability matrices are developed for two scenarios respectively, but results are visualized and interpreted for each dimension separately.

The purpose of this assessment methodologies module is to propose a relevant assessment method and further to define LCA-based indicators for evaluating energy sustainability in terms of the three sustainability dimensions (the three-pronged energy sustainability assessment).

*3.3.1.3. Measurement & data collection.* The data inventory is collected for sustainability assessment in a milk processing plant. In this life cycle inventory analysis, focuses on gathering information related to baseline energy consumption and its corresponding costs at the dairy plant, as outlined in Table 3. The energy measurements were obtained through energy audits and subsequently compiled into a comprehensive plant data inventory containing information about baseline energy usage, estimated savings, the proposed recommendations for the site, and the associated implementation costs. The baseline energy data were used as a reference for assessing energy sustainability by comparing the current and improvement scenarios.

From the data collection, input, and output variables (energy use, estimated savings, implementation costs etc.) were taken for the next stage of the energy sustainability assessment framework. To measure energy consumption accurately, energy experts utilized thermal cameras and relied on the PHAST software for calculating energy savings.

The emission of pollutants was not included in the data inventory. These data are analysed further in Section 3.3.1.4.

*3.3.1.4. Gap quantification & change planning.* An energy-intensity technologies should consider the possibility of improving the existing processes through, for example, implementation of changes, technology improvement and overall manufacturing process optimization. A change plan, integrated with a trade-off analysis of possible solutions, was prepared based on earlier analyses. This plan was also aligned with the company's business and investment strategies, including future solution specifications and verification procedures. The results of the life cycle inventory assessment will be expressed through sustainability indicators within LCA-based methods (eLCA, LCC, SLCA). The integrated three-pronged energy sustainability assessment yields outputs related to economic, environmental, and social impacts, as shown in Table 4.

To better illustrate the approach to the energy sustainability, the study provides indicators including:

- Energy intensity (a sum of natural gas and electricity)

**Table 3**
Baseline energy use at the dairy plant operating approx. 4160 h per year with annual production of 27,913,796.40 liters.

| Energy type | Usage | | Cost |
|---|---|---|---|
| Electricity | 4225,420 | kWh/year | $479,242 |
| Natural gas | 52,500 | MMBtu/year | $234,814 |
| Total | 66,918 | MMBtu/year | $714,056 |

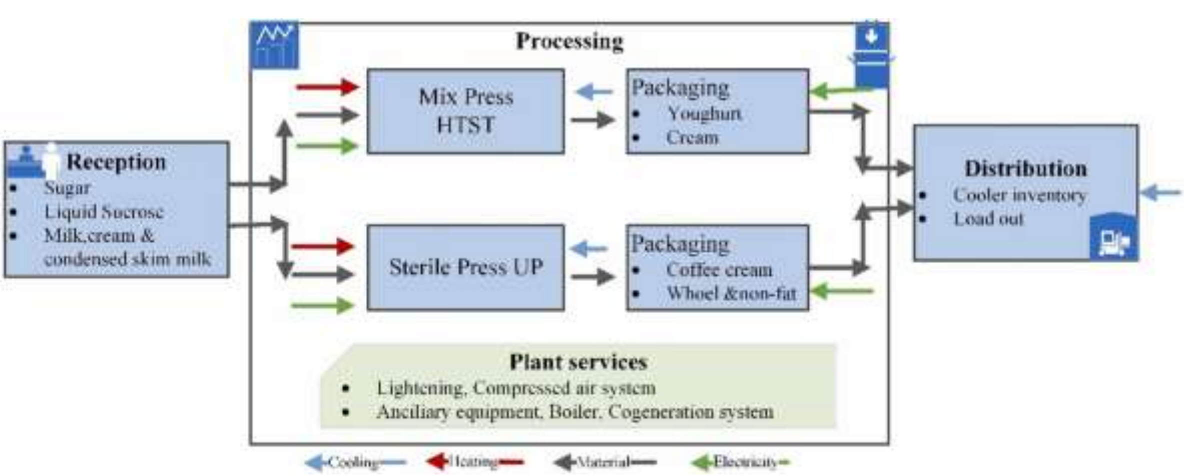


**Fig. 4.** General schematic view of the milk processing.

**Table 4**

Baseline and future scenario.

| Interpretation Dimensions | (methods) | Indicators Improvement | Baseline | (achieved results) |
|---|---|---|---|---|
| Green | % Environmental Sustainability (eLCA); $I_{EENV}$ | Energy intensity GWP | 9.4 | 14.6 |
| Blue | % Economic Sustainability (LCC); $I_{EECO}$ | LCCnet | 2.0 | 2.67 |
| Grey | % Social Sustainability (S-LCA); $I_{ESOC}$ | Energy per employee consumed per annual production | 0.3 | 3 |

- Global Warming Potential (GWP) in terms of release of $CO_2$ due primarily to the human use of fossil fuels, greenhouse gas emissions measure carbon dioxide per kWh of energy consumed [$kgCO_2e/t$]
- Life cycle cost: involving capital investment (I) and operational & maintenance cost (O&M), calculated as follows: (I + O&M) – LCR, where LCR - revenues from energy savings
- Energy per employee consumed per annual production - the worker`s energy used in processes and their exposure to occupational health and safety.

Each sustainability domain is characterized by a set of energy-related indicators of various units, e.g. environmental dimension $I_{EENV1}$, $I_{EENV1}$ etc. Due to the fact that different functional units are used for these indicators, a normalization for the sustainability dimensions is required. The normalization of these indicators for each domain is calculated as the length of the indicators' vectors, expressed by Eqs. (1–3). Hence, the three-pronged energy sustainability can be calculated according to the following formula (1):

$$I_{EENV} = \sqrt{I_{EENV1}^2 + I_{EENV2}^2 + I_{EENVn}^2} \quad (1)$$

$$I_{EECO} = \sqrt{I_{EECO1}^2 + I_{EECO2}^2 + I_{EECOn}^2} \quad (2)$$

$$I_{ESOC} = \sqrt{I_{ESOC1}^2 + I_{ESOC2}^2 + I_{ESOCn}^2} \quad (3)$$

To provide a transparency of the assessment method, a visualization of energy sustainability assessment (Fig. 5) is performed for the environmental, economic, and social dimensions which represent single measures for the energy sustainability.

After the technological improvement, the environmental pillar increased by about 5% compared to the economic dimension. However, this intervention affected the economic dimension only slightly (from 2% to 2.67%). Furthermore, the investments provided through technologies showed a moderate transition towards social sustainability compared to the baseline scenario (3% vs. 0.3%). This is due to the fact that energy was saved by increasing the number of jobs created in the plant.

*3.3.1.5. Improvement implementation & process stabilization.* Improvements have been implemented according to the prepared plans (as detailed in Section 3.1.1.4). The implementation consists of acquiring external suppliers and, in some cases, designing, developing, and implementing dedicated solutions. This process stage involved both hardware (new machines and equipment) and cultural changes such as personnel training and the design of new monitoring and reporting procedures.

In the analyzed case, the company acquired technology from external suppliers, encompassing two categories: energy processing technologies (primarily additional equipment and new machinery) and Industry 4.0 technologies for information processing and process improvement. A comparison of baseline scenario vs. future scenario is presented in Table 5. The implementation of cultural changes has been supported and coordinated by an external consulting company, which adapted initial plans to accommodate shifts in the business environment, resulting in certain task postponements.

Table 6 presents the largest interdependencies related to the analyzed company.

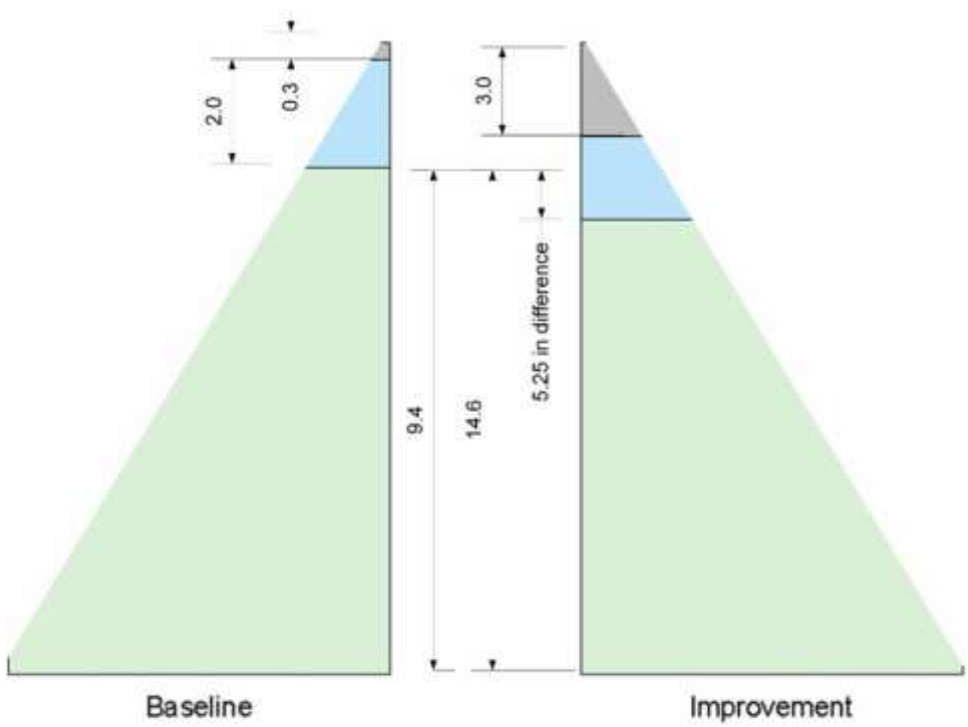


**Fig. 5.** The three-pronged energy sustainability assessment.

**Table 5**
Baseline scenario vs. future scenario.

| Scenario | Equipment / Energy technology | Additional technology | Group of I4.0 |
|---|---|---|---|
| Baseline | Pumps | Pressure sensors | - |
| | Air compressors | Automatic control | - |
| | Steam generators | - | - |
| | Fan, blowers | - | - |
| | Process cooling | Automatic control | - |
| | Lighting | - | - |
| Improved | Pumps | Pressure and temperature sensors, the ability to send operational and maintenance data to external server | Internet of Things, System Integration, Cloud computing, Big Data |
| | Pipeline isolation | - | - |
| | Air compressors | Automatic control, the ability to send operational and maintenance data to external server | Internet of Things, System Integration, Cloud computing, Big Data |
| | Cogeneration | Automatic control, energy measurement sensors, the ability to send operational and maintenance data to external server | Internet of Things, System Integration, Cloud computing, Big Data |
| | Fan, blowers - | Automatic control | |
| | Preheat boilers | Temperature sensors, the ability to send operational and maintenance data to external server | System Integration, Big Data |
| | Process cooling | Automatic control, temperature sensors | - |
| | Recover heat from ammonia cooling | Automatic control, temperature sensors, the ability to send operational and maintenance data to external server | Internet of Things, System Integration, Cloud computing, Big Data |
| | Hight Efficiency Lightening | Motion sensors - | |

*3.3.2. Focus Group Interview (FGI)*

The preparation for the FGI consists of three stages. The initial framework was consulted with academia representatives during an internal seminar at the Warsaw University of Technology. The specialists have expertise in energy and change management, particularly within the context of I4.0. These consultations allowed the authors to narrow their research and the scope of change management approach.

Subsequently, each stage of the framework was consulted with the company's managers. During this stage, the authors focused on the practical aspects of the hub. The managers also provided valuable recommendations for possible solutions (not directly related to the considered case study), contributing to the enhancement of the framework's theoretical foundation.

The final verification was done throughout the FGI session, which included participants from academia and industry (from food processing, automotive, machines industries), all with international experience.

First, the interview facilitator presented the framework; second, the results of the framework implementation and initial conclusions. Based on this, the group evaluated the designed and developed hub, proposing some improvements that have been incorporated into the current version of the hub.

*3.4. Final alignment of the smart hub*

The smart energy sustainability hub was developed to align the final concept as a result of the experts` verification. The presented hub consists of three pillars: sustainability through energy efficiency, change management and the I4.0, closely associated with manufacturing. Functionality descriptions of modules impact energy management, reliant on robust data analysis, measurements, and evaluation methods. The primary goal of the overall approach is to obtain the energy efficiency while achieving horizontal and vertical integration across manufacturing processes, from stakeholders to decision-making, eliminating human intervention. The hub centers around process improvements that synergize with smart manufacturing, bolstered by Industry 4.0 technologies. These changes represent a hierarchical integration considering the transformation of the internal operations activities to align with the proposed improvements. The vertical one refers to embodying smart energy technologies into a hierarchical layer. These technologies, flexible in their application, adapt to different project stages, sometimes spanning multiple phases of change management and sustainable energy perspectives. A graphical representation of the interconnected perspectives of the Smart Energy Sustainability Hub can be found in Fig. 6.

The concept's core of the hub lies in fostering synergy among sustainability dimensions to measure energy improvements across facilities, offering diverse perspectives on regional or national levels. Moreover, the energy sustainability framework boasts a systematic, modular flow of actions and corresponding information, facilitating intuitive and sequential managerial processes. Sustainability-based indicators, derived from established LCA-based approaches and the company's energy audit report, are categorized and allocated to sustainability perspectives to assess energy technologies' sustainability. This approach not only provides a foundational framework for sustainability interventions and technology proposals but also enables benchmarking among similar-sized plants within the same sector, provided data standardization complexities are addressed. The used three-

**Table 6**
Intersection of perspectives.

| **Sustainable energy Perspective** | | Top-down measurement of plant energy use | Energy-related | Energy assessment | Implementation of improvement | Energy managemen |
|---|---|---|---|---|---|---|
| **Change Management Perspective** | | Identification and measurement | Data capture & analysis | Assessment | Implementation & monitoring | Management |
| **I4.0** | Internet of Things | X | | X | | X |
| **Perspective** | System Integration | | X | | X | X |
| | Cloud computing | X | X | | X | X |
| | Simulation | | X | | | |
| | Cyber security | | | | X | X |
| | Additive manufacturing | | | | | |
| | Autonomous robots | | | | | |
| | Augmented reality | | | | | X |
| | Big data, including AI & ML | | X | X | X | X |

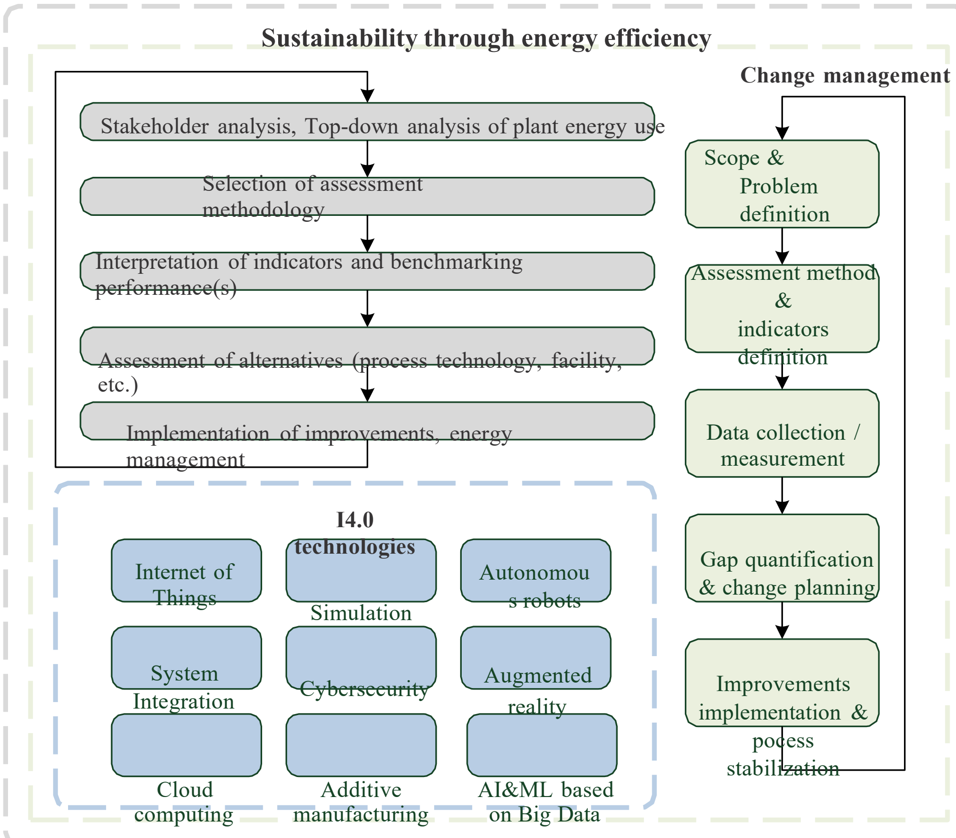


**Fig. 6.** Perspectives of the Smart Energy Sustainability Hub.

pronged sustainability assessment model (SBM-DEA+LCA-LCC-SLCA) relies on existing methods and individual metrics sourced from the energy audit report, offering vagueness in making technology assessment, hence uncertainty in the decision-making process.

The results highlight that energy decision-makers within the company exhibit a stronger focus on social concerns compared to economic outcomes ($I_{EECO}$), potentially leading to imbalances in social and environmental sustainability This a more pronounced emphasis on social factor, $I_{ESOC}$ could potentially create imbalances in the overall sustainability framework. Subsequently, the implementation of specific actions led to substantial improvements in sustainability-based indicators when comparing the baseline and improvement scenarios (Table 5).

Nonetheless, the research show that pro-ecological attitudes and behaviour of the manufacturer have been changing through the adaptation of I4.0 technologies in the food company. Those advanced technologies as highlighted in previous studies (Javaid et al., 2022), have a demonstrable positive impact on sustainability performance outcomes for the food company, especially when integrated with suitable methods, frameworks, and associated indicators. The interplay among sustainability pillars strengthens the potential for achieving social objectives, although the choice of social assessment methods can influence further outcomes. The used three-pronged assessment methods can serve as an inspiration for developing advanced databases with energy-based assessment approaches, facilitating informed decision-making to enhance energy efficiency. Stakeholders can utilize this approach to navigate what to measure and how to assess and interpret findings, thereby boosting energy efficiency and competitiveness within the energy market, while sustaining continuous enhancement of Industry 4.0 for sustainability (Bonilla et al., 2018; Javaid et al., 2022).

However, the proposed framework is not limited to the scope of a single plant; it can be implemented across multiple plants within the same company. Technological aspects, outside the sustainability pillars, are represented by the I4.0 technologies integrated into the improvements module. These technologies drive efficiency and resource conservation through digital advancements, incorporating environmental, economic, and social considerations.

In the context of social issues, companies must cogitate the social effect of technological transformation considering employees' expectations and broader societal implications. Technology's impact on social life is a crucial consideration, as technology alone (such as artificial intelligence or IoT) cannot deliver values without aligning fundamental social values. Additionally, I4.0 technology offers significant environmental benefits through the integration of methods and frameworks. Achieving social goals can be attributed to strong relationships among sustainability pillars. The choice of a social assessment method can impact outcomes, often due to limited social data availability. Research by (Lehmann et al., 2013) demonstrated the feasibility of socially-based assessment methods for analyzing comparable technologies. With the increasing demand for digital transformation towards sustainability, various methods have emerged to assess the performance of I4.0 technology in enhancing sustainability within operational conditions, aiming to evaluate a company's sustainability status, select viable sustainable solutions, address practical challenges, and identify potentially sustainable pathways.

The presented vision can significantly contribute to the future energy evaluation methods, offering practical implications for entrepreneurs. From a manufacturing perspective, companies adopting energy technologies supported by I4.0 components can gain valuable insights into how these technologies impact energy management, aiding their adoption in industrial settings. This study's findings are particularly useful for practitioners seeking to leverage digital technologies to meet sustainable development goals, particularly in energy monitoring and automation (Hussain et al., 2021; Frigerio et al., 2022).

Although the paper provides practical implications, there are also some limitations:

1. Limited Plant and Technology Insight: The results lack in-depth plant or technology profiles due to insufficient or imprecise energy data. Sustainability assessment across economic, environmental, and social dimensions relies on limited information regarding the impact of I4.0 technologies. Furthermore, social indicators should be more focused on human capital enhancement.
2. Implementation Barriers: The study does not delve into the challenges of implementing technological innovations (Zhang and Fu, 2022) or adopting I4.0 technologies, which can vary depending on the economic conditions of the manufacturing plant (Raj et al., 2020).
3. Lack of Detailed Technical Energy Audits: Detailed technical energy audits, including the dismantling of industrial-scale technologies, were not conducted. Such audits could provide valuable insights and may be explored in future research.
4. Limited Industry Scope: The case study is limited to a single food industry company, which possesses unique characteristics. Applying the proposed hub to other sectors would require further research to adapt to different technology profiles. the results do not provide in-depth insight into the plant or technology profile due to the lack of information or precision of the energy data. Sustainability assessment (in terms of economic, environment, and social perspectives) which is a site-specific evaluation is based on too little information to provide a real data on the magnitude of I4.0 technologies. In addition, the social indicators developed must relate to the enhancement of human capital.

## 4. Conclusions

In summary, this scientific paper represents a pioneering effort to fill the research gap regarding development of energy sustainability hubs at the company level and the readiness for implementing I4.0 technologies. Moreover, it highlights the absence of an industrial plant-centric study on the integration of these technologies into energy sustainability. This paper thus attempted to contribute to integrate I4.0 technologies used in manufacturing into energy sustainability. The energy sustainability hub has been verified by energy experts in the dairy company as well as throughout FGI. The digitalization of energy sustainability as a potential new area is a cutting-edge research area presented in this paper, therefore, it can be an engine for combining its efficiency, social progress, economic growth, and environmental demand for developing Sustainability 4.0 (Reis et al., 2021) in compliance with I4.0.

The study revealed that the integrated approach for energy assessment may be treated as an inherent part and objective evaluation of various concepts that allows modifying and then adapting the sustainability assessment method across IoT based energy technologies. More convincing results would be achieved when the energy sustainability hub is applied in a heterogeneous group of facilities and when similar indicators are used to provide a comparison of their sustainability performance. Therefore, it can provide a standardization for companies in the shift to I4.0 in continuous benchmarking in the manufacturing industry. Moreover, the sketch of smart energy sustainability in manufacturing is recognized in the context of decision-making processes identifying a digital path to shift toward Sustainability 4.0. Hence, the development of such a model holds the potential to incentivize a broad spectrum of smart manufacturing companies to select the most suitable I4.0 technologies based on their specific plant requirements.

To energize manufacturing's smart energy sustainability, some critical enablers must be put in place: (1) Decision-makers adopting I4.0 consider economic, social, environmental factors, aligning technology with company`s sustainability strategy. Before making the decision, they must investigate I4.0 technology, the systems to be invested in as well as the infrastructure required to reach directions of energy sustainability. This allows for extending knowledge of how a given technology can work in their operations and, most importantly, for their employees, society, and stakeholders in the light of sustainability; (2) Continuous education of employees about advanced technology to a specific system or sector to implement them in place requires to hire technical talent or IoT-focused expertise.

This energy sustainability hub seems to be unique because it is designed to provide adaptability, interoperability, and scalability.

### CRediT authorship contribution statement

**AK:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **AB:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data Availability

The authors do not have permission to share data.

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