Pathways to Energy Efficient Manufacturing through Digitisation

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Abstract
This article presents the outcomes of a collaborative activity across four EU funded projects, under DT-FOF-09-2020 - Energy-efficient manufacturing system management, focused on establishing innovative ways and best practice for leveraging digital technologies to implement more energy efficient manufacturing systems. The outcome of this work is the definition of a pathway towards energy efficiency that allows industry to understand their current situation and to stimulate the definition of a strategic road map to incorporate energy efficiency as a key criteria in operational and organisational decision making. This research presents the findings and the design of such a pathway.

Keywords
Digitisation; Energy Efficient Manufacturing; Pathways; Energy Management

Plain Language Summary

Manufacturing is one of the largest energy-consuming sectors and responsible for approximately a third of the global energy demand. Therefore, energy management is key to ensuring that manufacturing remains competitive as well as being sustainable as part of the global energy transition. Digital technologies will play a significant role in helping the manufacturing industry by providing the ability to automatically monitor and optimise energy usage, while continuously informing stakeholders with regard to the environmental and economic impact of the decisions made at all stages of the manufacturing process. This involves the integration and embedding of advanced digital services including secure-edge connectivity, the Internet of Things (IoT), data analytics, digital twin and automation within existing business roles such as process optimisation, production planning, facilities and energy management. However, this combined green and digital transition is a multi-faceted and complex task for any organisation as such this article explores approaches to reduce the barriers and minimise risk of making this transition. This results in the definition of an innovation pathway for energy efficiency through digitisation.

Introduction

As the demand for industrial products has increased significantly in the past two decades so to has energy consumption and CO2 emissions. According to the International Energy Agency (IEA), the industry sector accounted for 37% (157 EJ) of total global final energy use in 2018, representing a 0.9% annual increase in energy consumption since 2010 [1]. Across some sectors modest improvements have been made in reducing energy consumed through the uptake of renewable energy, policy enforcement and innovation in automation. Nonetheless, there is significant scope for further improvement and a need to accelerate efforts to ensure industry can maintain a sustainable trajectory. The primary characteristic of Industry 4.0 (I4.0) is the digitisation of manufacturing processes, this offers significant opportunities for energy saving through the optimisation of or replacement of technologies, the application of new software tools for energy efficiency management or adaptation in existing business processes [2]. Energy efficiency remains one of the most effective short to medium term targets to reduce industry carbon footprint and needs to be considered at

all stages of the manufacturing process. Improving industrial energy efficiency requires enhancing existing production management systems through the integration of energy related data, such as historical energy usage data, real-time data through metering and real-time predicted energy demand and cost. Manufacturing systems are highly complex involving many components and parameters that collectively impact energy performance of production processes (e.g. components, materials, machines, cells, lines and supply chains). To address this challenge the European Commission under the Horizon 2020 Framework Programme have funded four actions that are focused on the integration and development of new tools and mechanisms as enablers for factories to improve and manage energy-related flows and data more effectively.
Collectively these projects address the following aspects:

- The integration of advanced ICT tools to enable a proactive approach to control and manage the consumption of energy in manufacturing. These include digital twin, big data analytics, Industrial internet of things, cloud technologies and artificial intelligence
- Extract, collate, aggregate information linked to the environmental footprint of a given manufacturing process/plant across the entire value chain
- Demonstrate the impact of these innovative approaches and technologies across different manufacturing sectors and scenarios
- Promote best practice and standardisation activities related to the proposed solutions.

The following briefly describes each of the projects:
DENiM - Digital Intelligence for collaborative ENergy management in Manufacturing: The overarching objective of DENiM is the development of an interoperable digital intelligence platform to enable a collaborative approach to industrial energy management. DENiM provides an integrated toolchain to provision advanced digital services including secure edge connectivity, data analytics, digital twin, energy modelling and automated control culminating in the delivery of continuous energy impact assessment, together with optimisation across existing production facilities, processes and machines.
ECOFACT - ECO-innovative Energy FACTory Management System based on enhanced LCA and LCCA towards resource-efficient manufacturing: ECOFACT is developing an ECO-innovative Energy FACTory Management platform based on improved dynamic LCA and LCCA towards holistic manufacturing sustainability. The focus is on the effective combination of various ICTs for advanced data collection and processing, which enabling a streamlined decision-making process within the production chain. Also enhancing interoperability and flexibility to maximize the replication, upscaling and standardization potential within different plant sizes and manufacturing sectors.
E2COMATION - Life-cycle optimization of industrial energy efficiency by a distributed control and decision-making automation platform E2COMATION aims at providing a cross-sectorial methodological framework and a modular technological platform to monitor, predict, evaluate impact of the behavior of a factory across energy and the life-cycle assessment dimensions, in order to adapt and optimize dynamically not only its real-time behavior over different time-scales, but also its strategic and sustainable positioning with respect to the complex supply and value chain it belongs to.
ENERMAN - ENERgy-efficient manufacturing system MANagement: ENERMAN envisions the factory as a living organism that can manage its energy consumption in an autonomous way. It will create an Energy sustainability management framework collecting data from the factory and holistically process them to create dedicated energy sustainability metrics. These values will be used to predict energy trends using industrial processes, equipment, and energy cost models. ENERMAN will deliver an autonomous, intelligent decision support engine that will evaluate the predicted trends and access if they match predefined energy consumption sustainability KPIs.

Motivation

The maturity of available digital technologies and their application to energy management varies dramatically across different manufacturing sectors and industry scales. While many have embraced I4.0 technologies others lag behind in their capabilities to deploy and implement data-driven services. As a result this hinders progress in their bid to be more energy efficient, as without the right information in the right context it is very difficult to make informed decisions. To address this need, a joint activity was organised by the four projects listed above to bring together key stakeholders (e.g. industry, research, solution providers etc) to explore and reach consensus on the key enablers and targets that can facilitate the use of advanced digital tools to accelerate towards energy efficient manufacturing systems. A design process as presented in Fig. 1 was undertaken as part of a collaborative workshop. This involved four steps:

1. Readiness Assessment: explore different dimensions to define the baseline status of companies
2. Milestone Definition: specify the levels of maturity along the pathway
3. Key Enablers: identify the cross-cutting technologies to help achieve progress along the pathway

4. Pathway Definition: align the constitute components and construct a single guiding pathway for the manufacturing sector

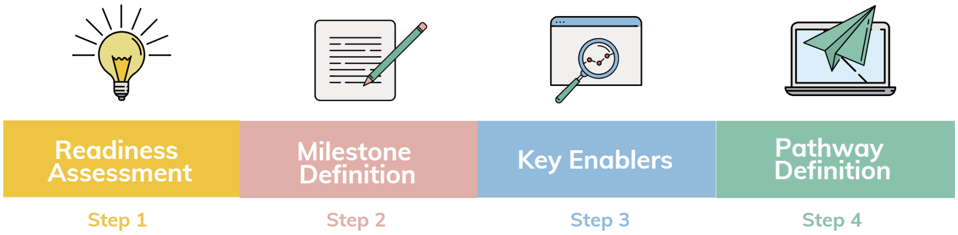

Figure 1. Pathway Design Approach

The outcome of this collaborative activity was the definition of a pathway for energy efficient manufacturing. A pathway consists of a set of progress levels or milestones that represent the evolving steps that act as a guide for users to move towards the most advanced situation. From the perspective of the work presented here, the focus is on defining the pathway for energy efficiency through the use of digital technologies. The benefit of such a pathway is multifaceted, from one side an organisation can use it to define and align strategic innovation decisions towards advancing their capabilities and maximising the impact of these across different dimensions. In addition, the pathway can be leveraged to facilitate and stimulate discussions surrounding company/sector-specific scenarios. From a research and development perspective, it allows for the demonstration of how project outcomes are contributing to the realisation of future manufacturing solutions. Pathways are generally supported by cross-cutting aspects and technologies that enable progress along the pathways, e.g. digital tools, skills, training, infrastructure, cyber-security etc.

The remainder of this paper is structured as follows, firstly an overview of the current barriers and drivers will be presented to establish the current status of industry through a readiness assessment. This will be followed by the presentation and description of the digital enabled pathway for energy efficient manufacturing. Finally, a summary of the findings and recommendation on how the pathway can be used in practice will be provided.

Readiness Assessment for Energy Efficient Manufacturing

To establish the baseline for the proposed pathway, the project team explored the current situation from three dimensions outlined as follows:

- **Motivational Readiness:** This is utilised to establish what is driving the need for change. This incorporated the identification of key stakeholders involved in energy efficient manufacturing, their impact and role. In addition, motivational readiness involved exploring external driving factors that motivate change.
- **Technology Readiness:** Involves understanding the current level of maturity with regards the application of existing digital technologies with in the manufacturing sector. This explores the current levels of integration across systems and product life cycle. A focus was placed on identifying the key barriers and risks that is hindering the uptake and application of new solutions (both digital and energy related).
- **Organizational Readiness:** The final dimension looks to identify the the status of current manufacturing companies from the perspective of appropriate organisational structures, skills and resources that are required to support energy efficiency. It is important to identify the commitment and understanding of organisations to take energy efficiency as a key aspect of their manufacturing process

The following outlines the findings under each of these dimensions as identified during the workshop process. Beginning with motivational readiness a discussion was had to identify external factors and drivers that can or are motivating change in the industrial sector. The items identified by participants included: Taxes; regulation compliance; carbon neutrality targets; corporate social responsibility; request for environmental friendly products from customers; environmental and climate change awareness; growing business potential; increase in energy costs (some industries only); common data sharing; demand for carbon accounting across the value chain actors and the need for transparency; reduce the quantity of scrap and a push for more circularity of products. These factors are viewed as common across all industrial sectors and are driving an increasing awareness of the responsibilities as an organisation to adapt existing approaches to be cognisant of their impact on the broader environment.

Table 1 provides a summary of the key stakeholders that were identified and their role to influence change relating to incorporating energy efficiency in the manufacturing systems. It can be seen that these stakeholders span broad roles

Table 1. Key stakeholders and their role

Key Stakeholders	Role to influence change
Technology Solution providers	Provide enablers for understanding energy and increase accessibility to energy related data
Individual Workers and Operators	Knowledge and Expertise of processes, sharing information with others
Finance Departments	Investment in low carbon projects
Energy Managers	Push low energy intensive production management and understanding of overall facilities performance
Regulators	Drive change through incentives and legal requirements and compliance monitoring
Marketing Team	Market "greener products"
Customers	Green purchase power, awareness and sensitive to impact on environment
Standards Bodies	Solutions to provide common approach for managing energy data, support scalability and replicability.
Utilities	Demand response programmes

within and external to an organisation, from technical providers to regulation and compliance. As such highlighting the need for an open collaborative approach and requirement for information sharing between these key stakeholders.
For technology readiness, the participants were presented with a number of leading questions that were used to understand the current level of digital technologies in use and their integration within organisations, the barriers and risks foreseen and from their experience what level is their corporate digital strategy at. The questions put to participants were as follows:

- What are the levels of integration between systems across the product life cycle?
- What are the barriers & risks to embracing new technologies in the manufacturing sector (consider both Digital & Energy Technologies)?
- Is there a digital strategy in place within your organisation or organisations you have dealt with?

Table 2 presents a summary of the responses received from participants.

Table 2. Current Barriers, Risks and Strategy

Levels of Integration	Barriers and Risks	Digital Strategy
Limited, ad-hoc integration in many cases. Data is often fragmented with very limited view on energy related performance. Lack of appropriate knowledge and skills to handle and manage large data sets. Data privacy and security remains a challenge	Diverse technologies that do the same thing make it challenging to know best route. Proprietary v's standards based technology adoption. Cybersecurity (and data privacy) is a risk, especially at the intersection of IT and OT operations. Reluctance to embrace innovative technologies, old/validated technologies are preferred to minimise risk.	This varies across different organisations, SMEs are often just focused on getting orders out. Generally there is more awareness and a digital strategy in large enterprises as well as capital investment. Strategies are often not transversal across all business roles, parallel but detached development plans appear.

Finally, the focus was placed on understanding organisational readiness, this encapsulated exploring aspects such as skills, support needs and strategic vision, Table 3 provides the outcomes of the feedback received. The following guiding questions were used to solicit inputs:

- What skills & resources are required to enable effective Energy Efficiency Management of manufacturing processes
- What supports and resources are needed to incorporate digital technologies to support energy management of manufacturing systems?

Table 3. Organisational Readiness Outcomes

Skills and Resources needed	Additional Support Required	Strategy for Energy Efficiency
Understanding of processes and what affects them at different levels (operator v's management). Data analysis skills Ability to interpret lifecycle analysis and lifecycle cost analysis results and trade-offs The integration and use of digital tools to augment and support existing job roles and activities	Organisations require expertise to manage complexity of data integration There is scope for dedicated services and solutions to support energy efficiency User friendly interfaces, visualisation and decision support – ease integration of data analytics Capabilities to correlate production processes with product variability – identifying opportunities	Energy efficiency must be linked to production efficiency. Most often, targets come from outside the company (e.g. regulation or sector practices) Must companies beginning to align their strategy with carbon and sustainable development goals targets. With increasing external pressures for industry to address energy and environmental challenges, this offers an advantage for forerunners.

- Do organisations understand the challenges facing them to achieve energy efficiency?
- Do organisations have a strategy, targets & time frame to reduce energy consumption of their processes?

The outcomes of the readiness assessment provides valuable insight to help define the appropriate responses needed both from a technolgical perspective but also from a strategic stand point. Key findings indicate that collaboration and in particular the sharing of information across the many different organisational roles that can exist in a manufacturing context is critical. As such, the core of any innovation should overcome fragmentation of performance related data and make it easy for an organisation to collect, analyse and leverage data to make evidence-based decision making. Finally, cyber-security and data privacy are a major concern for companies and should be addressed but in the design, provision and operation of supporting digital tools and services. This assessment will inform the design of the pathway in a way that alleviates some of these concerns and challenges.

Digital Pathway for Energy Efficient Manufacturing

Pathway Structure

The need to leverage and adapt existing systems with digital innovation is already well accepted by many companies, however there are still challenges to realising this in practice. While many large companies are already adopting I4.0 concepts in various aspects of their businesses, SMEs particularly have many difficulties (technical, skills, financial and business focus) to take these steps. From the perspective of the work presented here, the objective of defining a pathway is to offer a common structure to capture how a manufacturing organisation can continuously evolve existing processes and procedures to embrace digital technologies that support energy efficient manufacturing.

Aligned with the approach taken in the ConnectedFactories project [3], a pathway to energy efficiency is defined as a maturity assessment model encapsulating a set of levels, milestones and enabling technologies. Fig 2 presents a template structure for defining the pathway. Each level represents a target state of an organisation. An organisation can reside in more than one level at a time with the intention that by achieving the milestones as set out in the pathway they will be able to transition across these maturity levels in a structured and systematic way based on their current status and ambition. Traversing the pathway will rely on key enabling technologies and influenced by cross-cutting factors, all of which should be captured as part of the pathway (left of Fig 2. Levels are set based on the identification of the different ends of the spectrum for the domain being considered, specifying the most basic maturity level, the most advanced solution and intermediate steps in between both. For each of these levels a pathway must set out clear milestones that can be achieved to reach the appropriate level of maturity. These can be technical, organisational or social dimensions that should be taken into account.

Pathway Definition

The pathway for energy efficiency has been defined to include five milestones/levels of maturity, under each of these specific activities are used to characterise the position in the pathway, these include:

1. *Limited Visibility on Energy Performance:* visibility regarding energy performance is low, where data is available it is collected manually and while some reporting may be done on energy usage, it is generally spreadsheet based reporting at facility level (site-level energy metering). In general no impact assessment if in place.

Figure 2. Pathway Template Design

2. *Process Level Energy Performance Monitoring:* at this milestone the collection of data is more structured and formalised, sub-metering (potentially IoT sensors) is utilised to understand energy profiling at facility and process level. Impact assessment is done on an ad-hoc basis at process level.

3. *Energy Performance Insight:* visualisation of energy flows is part of the management procedures on the shop floor, energy data is analysed and trends, patterns and baseline analysis is carried out at appropriate levels. A systematic approach to impact assessment is in place at this milestone and the formal application of energy auditing standards are utilised within the factory.

4. *Energy Efficiency Informed Decision Making:* traditional key performance indicators (KPIs) are enhanced to incorporate energy efficiency specific indicators and metrics. These are manually tracked across the manufacturing site. Energy models are deployed and used to predict and forecast energy demand and consumption. A quasi-realtime impact assessment is done leveraging live data from manufacturing processes. An Energy efficiency benchmarking methodology is applied at the site (e.g. EN 16231:2012).

5. *Online Continuous Energy Management:* the most advanced milestone involves the automated tracking and integration of energy related KPIs, energy-centric digtial twins are used to support online process optimisation. Impact assessment is extended to complete value network and is online. A continuous energy management system is utilised across the site (e.g. ISO 50001).

Figure 3 presents a visual representation of the final pathway utilising the template definition.

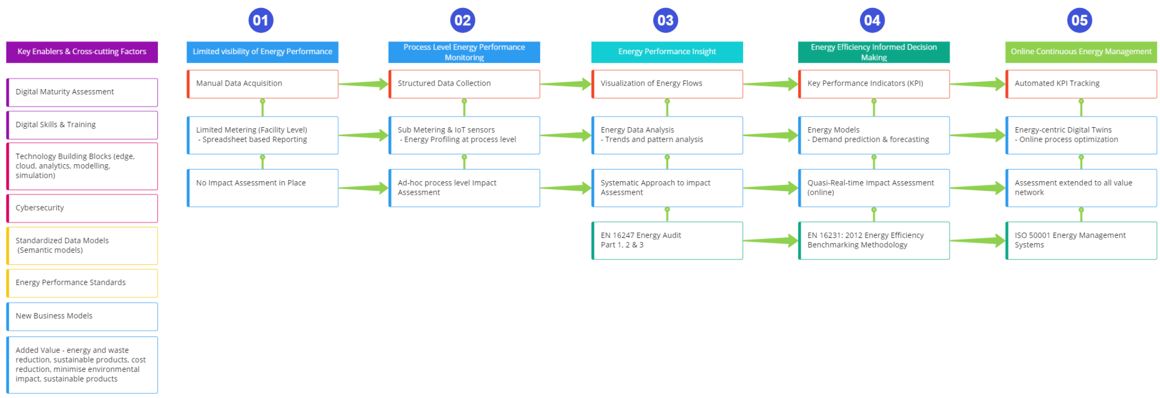

Figure 3. Pathway For Energy Efficient Manufacturing

As previously stated, to successfully achieve the milestones across the different levels of maturity consideration of cross-cutting factors and key technological enablers is required. An initial set of factors have been defined, these include but are not limited to, the ability to formally capture the current state of an organisation (i.e. digital maturity assessment), considering the promotion of digital technologies and tools as enablers there is a need to ensure appropriate digital skills and training is provided to maximise the potential of their application. New business models and added value are essential to motivate the transition from milestone to milestone, for example being able to demonstrate energy and waste reduction, development of more sustainable products, cost reduction and minimising the overall environmental impact of a manufacturing process. Energy performance standards, EU policy and national directives will also play a key role in driving internal innovation. Technology building blocks such as edge and cloud computing, data analytics, machine learning, modelling and simulation are vital for success as the need to convert raw data into insight is a must. Standardized data models, privacy preserving technologies and cyber-security tools and mechanism are important

building blocks to motivate data exchange and participation in a collaborative approach to the energy transition is critical.
The activities of the presented pathway is focused on providing digital technologies, these can be grouped together under three categories, i) Data Management, ii) Performance Monitoring and Assessment iii) Best Practice and Standards. The next step for this pathway is the application and specification of industry specific use case scenarios that demonstrate the evolution across the pathway milestones. The validation of the designed pathway is a key focus for the next phase of collaboration for the projects.

Summary and Conclusion

The defined pathway offers an initial starting point for dialog and engagement with industry on how to maximise the use of digital tools and services to embed energy efficiency in their current operations. The pathway however should not remain static, as new innovations emerge and companies advance in their capabilities the pathway can be updated and adjusted to fit the specific needs of a particular sector or industry. The pathway can be utilised in a number of different contexts, from a company perspective it can be leveraged to inform goal setting and strategy definition based on the representation of the maturity of an organisation towards energy and digital transformation. For a solutions provider the pathway can be leveraged to map enabling technologies or services to milestone activities that allow an organisation to achieve the required level of maturity. From a researcher organisation point of view, the pathway can be utilised as a common frame for project outcomes and impact creation. The role of the four funded DT-FOF-09-2020 projects is to collectively contribute solutions to the pathway milestones, each project aims to provide new innovate solutions that are evaluated and validated across different industrial sectors, promote best practice and share knowledge and lessons learned to help accelerate the digital and green transition for the manufacturing industry. Future work will involve validation of the defined pathway and the expansion of this over-arching pathway to provide more specific pathways in relation to the challenges that industry are facing. These could be viewed as sub-pathways that can support achieving the milestones identified, some examples currently being considered are:

- Pathway for building and integrating energy-centric Digital Twins
- Pathway for up-skilling to support energy efficiency
- Energy Efficiency through energy technology integration (greening the production processes, renewable generation, storage)
- Energy Flexibility – demand response, raw material supply, production flexibility

Grant information

These projects received funding from the European Union's Horizon 2020 Research and Innovation program under the following Grant Agreement numbers: 958339 (DENiM), 958373 (ECOFACT), 958410 (E2COMATION) and 958478 (ENERMAN).

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