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Knowledge demands for energy management in manufacturing industry - A systematic literature review

Mariana Andrei [a,*], Patrik Thollander [a], Anna Sannö [b]

[a] Department of Management and Engineering (IEI), Division of Energy System, Linköping University, 581 83, Linköping, Sweden
[b] Research & Development Department, Volvo Construction Equipment, Eskilstuna, Sweden

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ABSTRACT

The social context in relation to energy policies and advances in more energy efficient technologies is changing constantly, thus driving a need for change in the manufacturing sector. This study presents a knowledge-based framework that enables the understanding of the model for knowledge that has taken industrial energy efficiency to current levels and the analysis of the model in the current context of industry transition. The framework consists of three broader forms of knowledge and specific knowledge attributes that can capture the knowledge employed in industrial energy management. The framework is applied in a systematic literature review, analyzing the forms of knowledge and main aspects of energy management in manufacturing industries from 157 articles published between 2010 and 2020 in various academic journals. Besides the framework, the results show that the technical form of knowledge is the primary type of knowledge employed in energy management and that a paradigm-changing towards Industry 4.0. is seen. Another employed form of knowledge is process knowledge, which is concerned with the prerequisite information needed to implement energy management. Finally, leadership knowledge is also employed in energy management and a blend in these three forms of knowledge might move us beyond traditional knowledge towards new forms of knowledge that maximize the potential for energy management in manufacturing industries. The knowledge demands brought by Industry 4.0 for all forms of knowledge are identified and discussed.

1. Introduction

Mitigating climate change remains a crucial challenge of our times and energy efficiency is put forward as one of the foremost means to combat climate change. The European Union has set out a clear vision of how to achieve climate neutrality by 2050. Decarbonizing European industries is a critical step towards achieving the EU vision since industry is responsible for about 25% of the total final energy use [1]. The Energy Efficiency Directive therefore pursues an overall objective of at least 32.5% energy efficiency by 2030, and in order to achieve this target, final energy use in the EU will have to be reduced by 20% compared to 2005 levels [2]. In order to improve industrial energy efficiency, the traditional model revolved mainly around technology diffusions [3], where an energy audit is an initial step for increased diffusion of more energy efficient technologies by providing targeted information on improvement measures [4].

However, recent studies have shown that by including energy management practices, e.g. more efficient operations, alongside the implementation of energy efficient technologies, the energy efficiency potential may be even higher [4–7]. The number of industrial companies working with energy management or implementing an energy management system (such as ISO standard 50001:2011) has increased since the introduction of the standard in 2011. Energy management is seen by many companies as an effective tool for enhancing their production systems and operations in pursuit of improved energy efficiency [6]. However, improving industrial energy efficiency is a difficult task, due to the high complexity of the industrial energy systems [6], especially in the current context of industry requiring a fundamental transformation in order to achieve the goal of carbon-neutrality by the middle of this century.

Industry's transformation can be achieved through different incremental and radical innovations in how companies work with energy management and improved energy efficiency. Radical and incremental innovations consist of distinct types of technological process innovations. Radical innovations are root changes that constitute revolutionary changes in technology, while incremental innovations are minor improvements or simple adjustments in current technology [8]. These

* Corresponding author.
E-mail address: mariana.andrei@liu.se (M. Andrei).

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List of abbreviations:

EnM = Energy management
EnMMI = Energy management in manufacturing industries
EE = Energy efficiency
EU = European Union
PDCA = plan-do-check-act
R&D = research and development
Technē = technical knowledge
Epistēmē = process knowledge
Phronēsis = leadership knowledge
CAS = Compressed Air System
CNC = computer numerical controlled
CPS = cyber-physical system
CPES = Cyber Physical Energy System
DSM = Demand side management
DR = Demand response
IOT = Internet of Things
IIOT = Industrial Internet of Things
AIT = Advanced information technologies
AD = Additive manufacturing
MT = Machine tools
SL = System level
(M) = Machine level
(P) = Process level
(L/M-M) = Line/multi-machine level
(F) = Factory level
(O) = Organization level

modes of innovation differ in several ways, such as, complexity, risks, and degree of novelty in knowledge use [8–11]. Throughout the years, successful radical innovations have had a remarkable impact on the development of companies. However, at the same time, the role of incremental innovations in enhancing and sustaining the profit streams of successful radical innovations cannot be neglected [12].

Incremental innovations are described by Refs. [8,9], among others, as gradual and continuous improvements of existing technologies, processes and the organization, containing a low need for new knowledge, and being a strategy with low risks and low returns [10]. Some examples of incremental innovations that industrial organizations implement in order to improve energy efficiency are: i) adopting new routines that lead to behavioral changes, ii) using tools that increase awareness about the organization's production processes, and iii) implementing an energy management system and PDCA (plan-do-check-act) process approach. In particular, the dynamic PDCA cycle is a well-known model for driving incremental changes in an industrial organization's systems, processes and operational activities [13–15]. However, although a high level of efficiency can be achieved through incremental improvements [15], these are not entirely sufficient to achieve a transformation of energy supply and end-use within industry that will lead to fulfilling the environmental goals [4,10,16]. Non-incremental improvements are thus also necessary [16].

Radical innovations are characterized by high risks and high returns [10,11], entailing a fundamental change in the technological regime that involves a high degree of new knowledge and a new organizational structure [8,9,15]. As a result of such innovations, large-scale changes occur in the fundamental technologies of the economy [8,9,15]. Radical changes are not uncommon, and along with replacing norms and standards of product design, performance attributes and production processes, they also reshape how a particular technical function is fulfilled, and involve new systems of suppliers, education and training [9]. The order for the process of radical change starts with awareness of a new technological possibility and is followed by a long-term shift towards process innovation in the new technology. For such a change, leadership skills are necessary to shift resources, e.g., people, equipment, plant, materials, and knowledge, to an era that is new and unproven [17]. One example of radical innovations is the shift towards digitalization in the late 20th century [18]. Whether a consequence or not, the Industry 4.0 research stream is gaining momentum. Advanced Information Technologies (AITs)-enabled Energy Management is of tremendous importance as implementing Energy Management (EnM) is a complex task that must first integrate and consider multiple parameters, conditions, and data and control the use and cost of energy in manufacturing.

A critical factor for innovation is knowledge, both scientific and technological, and sector-specific [19], and extensive knowledge is important for adopting both radical and incremental innovations [8]. Furthermore, it is claimed that radical innovations bring about a full-scale shift not only in scientific and technological knowledge regimes, but also in the associated infrastructures [9]. A study by Ref. [20] has shown that a firm's knowledge characteristics are determinant for increasing that firms' innovations in energy efficiency. These knowledge characteristics are i) prior knowledge in the form of a higher educated workforce, ii) capacity for knowledge development – R&D, and iii) external knowledge cooperation – with universities and competitors. There are studies that discuss the new types of skills (i.e., digital skills, big data analytics) and knowledge (i.e., virtual/augmented/mixed reality, cyber-physical systems, 3D printing, smart factories, industry 4.0, 5G networks) required from young practitioners and questions whether the universities are preparing the new professionals to face the new challenge that industry 4.0 brings in terms of knowledge [21,22]. These are new knowledge demands required to implement energy management and adopt energy efficiency initiatives.

Addressing current industrial transformation requires moving beyond traditional knowledge towards new forms of knowledge that maximize the potential of adopting new and radical innovations. Doing so requires, first, an understanding of the model for knowledge that has developed industrial energy efficiency to current levels, and an analysis of the model in the current context of transition, but also for the future. Recent review studies, e.g., Refs. [6,7,23] have conducted comprehensive analysis of research literature on Energy Management in Manufacturing Industries (EnMMI) and developed frameworks providing a consistent understanding of energy management regarding definition, practices, and objectives. However, to the best of our knowledge, a systematic review paper that provides a review and classification on the topic of Energy Management using a knowledge perspective is lacking in the literature.

With a scarcity of research investigating the forms of knowledge employed in EnMMI, this paper aims to contribute to the literature on the field of EnMMI by adopting a knowledge analytical approach. Hence, the novelty lies in the knowledge-based framework consisting of primary forms and attributes of knowledge that enables the analysis, understanding and categorization of forms of knowledge employed in EnMMI. In following this aim, the particular objectives of the study are as follows:

- Design a knowledge-based framework that will enable the analysis and classification of the literature on EnMMI
- Inductively derive main categories that will define the primary forms of knowledge employed in EnMMI and enable the classification of existing research on EnMMI
- Provide an analysis and classification of the literature on EnMMI based on forms of knowledge to guide researchers in their search for knowledge related perspectives regarding EnMMI
- Explore the knowledge demands for EnMMI in the current context of industry's transition to carbon neutrality

- Explore trends for further research

The structure of the paper is as follows. Section 2 presents the research methodology, and Section 3 the analytical framework. Section 4 presents the results, followed by their discussion on Section 5. Finally, the paper ends by highlighting the study' conclusions in section 6.

2. Research methodology

This paper presents a systematic review inspired by the steps proposed by Ref. [24], described below and illustrated in Fig. 1.

Step 1: Formulate the objectives of the research.

Step 2: Perform the search process by selecting the database, defining search strings and inclusion criteria.

The search strategy consisted of looking for relevant publications in the Scopus and Web of Science online databases, due to their coverage and ability to allow fast and customized searches. Two databases were used to identify all articles published in the field of energy management in manufacturing industries. Fig. 2 illustrates the complete process of the search, with all the performed steps. The review focused on relevant studies (journal articles and conferences papers) published in the last 10 years (between 2010 and 2020). The first search step was performed on the Scopus database using search string 1 (Table 1) in article titles, abstracts, and keywords, followed by filter 1 (Fig. 2), resulting in 158 documents.

After the initial screening of the titles and abstracts, the papers corresponding to subject areas outside the scope were excluded, giving 150 remaining articles. The second search step performed in the Web of Science database used search string 2, and filters 1 and 2, followed by duplicates removal, resulting in 163 articles.

After obtaining these sets of articles, i.e., 150 articles in Scopus and 163 in Web of Science, the relevant articles to be included in the analysis were determined by applying the criteria for inclusion and exclusion illustrated in Table 2, with the relevance criteria for the content of the articles playing a determining role.

After filtering the abstracts using the above-mentioned criteria, 85 relevant papers (75 original articles and 10 review articles) remained in Scopus and 66 (55 original articles and 11 review articles) in Web of Science, giving 151 papers to be analyzed. Furthermore, additional relevant academic studies were identified through manual screening of cross-referencing, thus adding 6 more papers to give a total of 157 journal papers, of which 24 were review papers and 133 were original articles.

Step 3: Perform the review following the systematic process of content analysis based on the following four steps: material collection, use the analytical framework to assess the material, develop categories, and evaluate the material.

The process for category development and selection was carried out in an inductive way, where papers were read again and again, and categories were developed during the coding process to allow identification of main aspects of EnM in manufacturing. Finally, similar main aspects and categories were gathered into overarching themes as illustrated in Fig. 3. These categories are further presented in the results section, under previously published review papers and content analysis sections. Although during the analysis some of the papers partly touched upon more than just one form of knowledge, the aim of this study is not to consider the interrelationships between them. In order to clarify the content analysis communicatively, the categorization of papers on each form of knowledge is based on the main aim of the studies.

Step 4: Construct a data extraction form to enable the coding of articles according to specific criteria.

After all the relevant articles were identified (n = 157), a data extraction form was constructed in a Microsoft Excel worksheet, where articles were coded according to i) knowledge themes, ii) categories, iii) main aspects of EnM in manufacturing industries, iv) year, v) journal, vi) sector, vii) database.

Step 5: Synthesize the results of the literature review and discuss them.

There are a few limitations with this methodology. First of all, it includes a limited sample of studies (n = 157) covering literature on EnMMI within a limited period of time (years 2010–2020). This time span was chosen because the study aims to have a timely overview of the changes taking place in EnMMI due to several important factors, such as the appearance of ISO 50001 in 2011, and updates to the Energy Efficiency Directive in 2012 and in 2018 focusing on increasing the targets for energy efficiency. Furthermore, the relevance criteria for selecting the articles is limited to the studies addressing EnM at the manufacturing organization level, hence excluding papers that have a macro perspective (e.g., region) and are addressing policy issues. The manufacturing system levels are machine, process, line/multi-machines, and factory/organization, and are inspired by the works of [25] on levels for EE in manufacturing systems and [26] on the decomposition of manufacturing systems (as illustrated in Table 3).

Future applications of the methodology could include a different time span, other sectors, e.g. residential or transport, and extend to a macro level perspective (e.g., region) and address policy issues. The methodology presented by Ref. [24] provided a thorough and comprehensive overview of the literature review process and suited the authors' intention in conducting a thorough literature review. There are, of course, similarities with other methodologies, such as the one by e.g., Ref. [27], where five steps are discussed: Question formulation, Locating studies, Study selection and evaluation, Analysis and synthesis, and Reporting and using the results. If one compares these steps with the ones applied in this review (as illustrated in Fig. 1), one can see that the principles are quite similar, as there cannot be that many differences in how to conduct a literature review. However, the choice of using [24]'s steps as guidance was supported by the comprehensive overview of the literature review process.

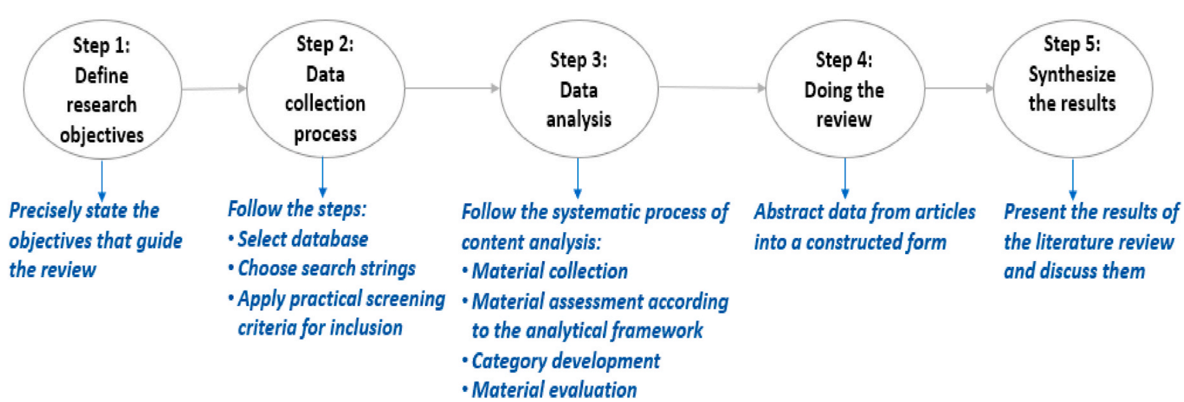

Fig. 1. Steps in conducting literature review adapted from [24].

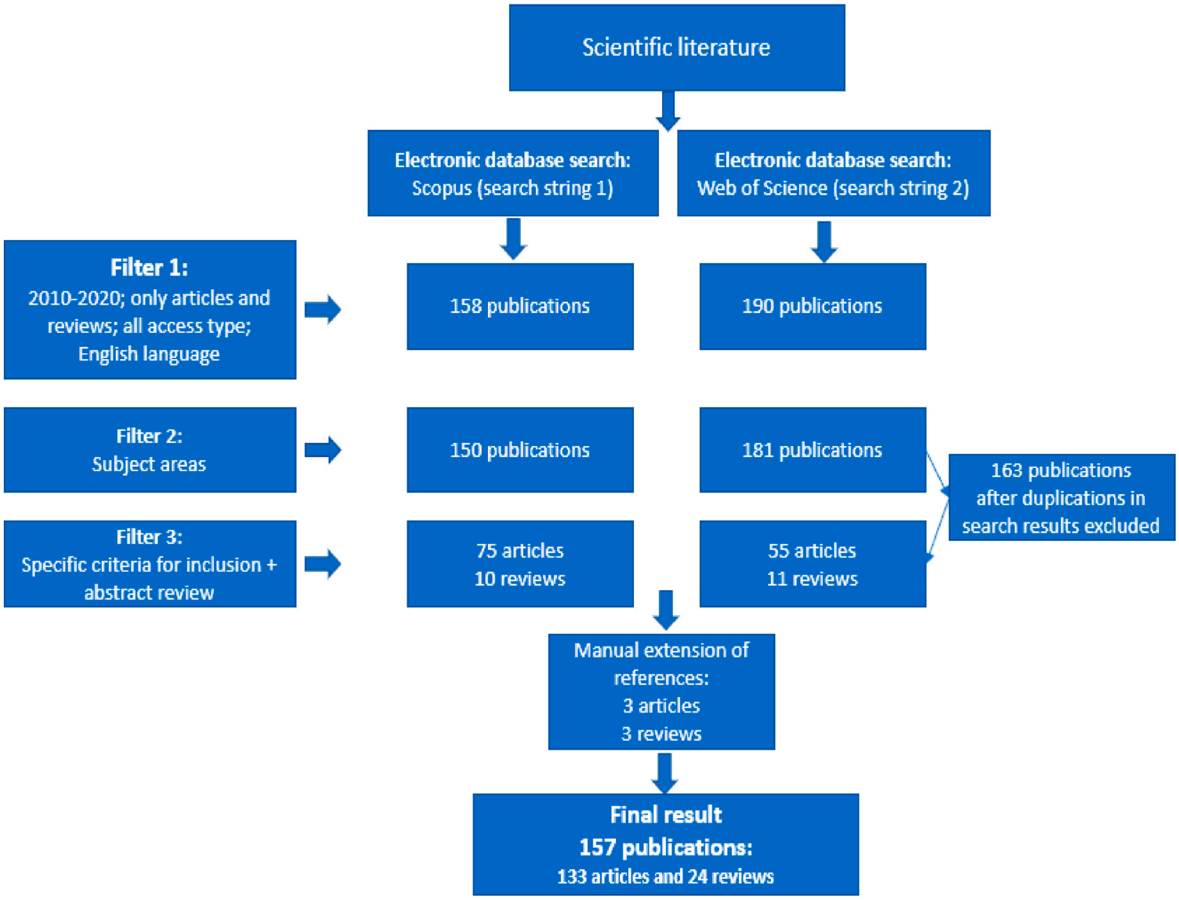

Fig. 2. Search process.

Table 1
Search strings.

Search string #	Search string description
1	"energy management" AND "manufacturing industry" (abstract, title, keywords) AND time period 2010–2020 AND DOCUMENT TYPE (article and review) AND ACCESS TYPE (All (Open Access and Other)) AND LANGUAGE (ENGLISH)
2	"energy management" AND "manufacturing industry" or "energy efficiency" AND "manufacturing industry" (abstract, title, keywords) AND time period 2010–2020 AND DOCUMENT TYPE (article and review) AND ACCESS TYPE (All (Open Access and Other)) AND LANGUAGE (ENGLISH)

3. Analytical framework: knowledge for energy management in manufacturing industry

In order to achieve the aim of the study, a knowledge-based framework has been developed, as illustrated in Table 4, consisting of main forms and attributes of knowledge that supports the analysis of the literature on EnMMI and further enables the categorization of literature on main forms of knowledge. Knowledge has a variety of attributes, and within an attribute knowledge occurs in various ways. Some of the most commonly employed attributes of knowledge are type and mode. Knowledge type concerns differences in the nature of the knowledge itself, where each type can be created, and each type can be used in the creation of knowledge [28]. The most common features for knowledge types are descriptive knowledge, procedural knowledge, and reasoning knowledge [28–30]. Knowledge mode revolves around the notion that meaning is attached to knowledge as a result of a process of interpretation and cognitive construction [31]. In this dimension a distinction is made between tacit and explicit knowledge [32] and reflects the possibility of creating knowledge from one mode to another, and within a specific mode [33]. Furthermore, a contemporary interpretation of the most common Aristotelian concepts of knowledge, such as *Technē*, *Epistēmē* and *Phronēsis* is performed, including these in the analytical framework as main forms of knowledge. Although the Aristotelian concepts of knowledge were developed and applied to individuals, in this study, a step is taken forward by applying them to

Table 2
Selection criteria for the literature review on the field of EnMMI.

Criterion	Inclusion	Exclusion
Document type	Article and review	Other publication types (e.g., books)
Access type	All (Open Access and Others)	No exclusion
Language	English	Any other language
Time period	2010 to 2020	Study published in any other period
Sector	Manufacturing	Any other sector (e.g., residential)
Relevance	• Articles with EnM or EE as the main focus • Articles providing contribution to EnMMI • Articles addressing EnM or EE at manufacturing system level (e.g., organization level, plant/facility/factory/shop level, process level, machine level, equipment level).	• Articles addressing EnM or EE at the macro-level (e.g., region) • Articles addressing policy issues in EnM as the primary focus

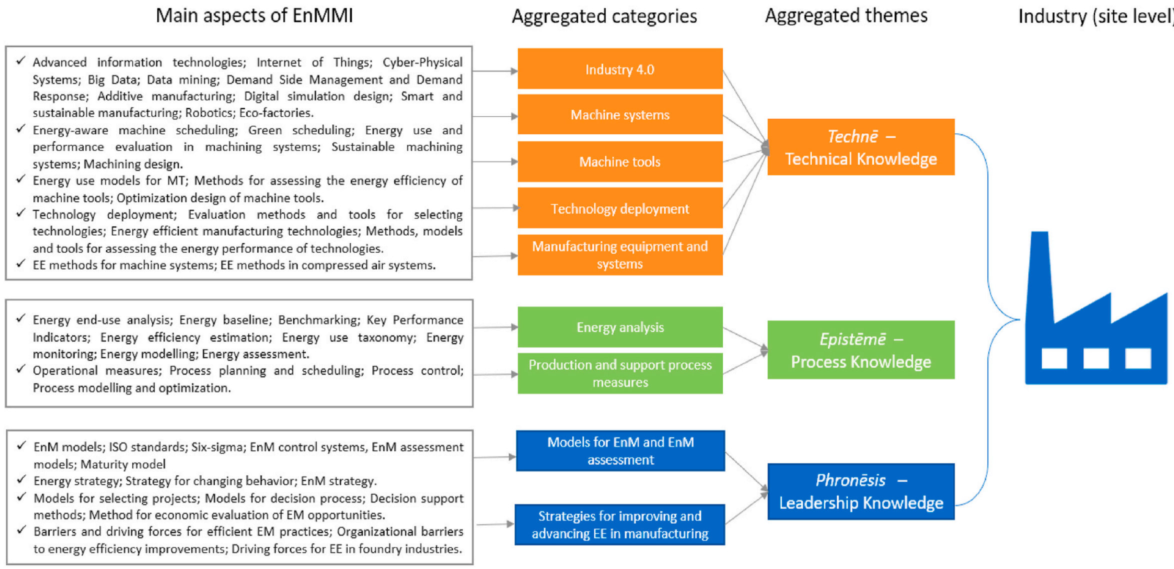

Fig. 3. Structuring the content of the reviewed studies.

Table 3
Decomposition levels considered for the manufacturing systems inspired from [25,26].

System level (SL)	Description
Machine level (M)	Individual device or MT which performs one kind of operation over a piece, incl. peripheral equipment for the auxiliary processes
Process level (P)	Conventional (e.g., turning, milling) and non-conventional processes (e.g., cutting, welding, drilling). Physical mechanisms related to the nature of the process are included
Line/multi-machine level (L/M-M)	Logical organization of several machines and peripheral devices that act either in parallel or in series to execute a specific process
Factory/Organization level (F/O)	Distinct physical entity hosting arrangements of process lines, auxiliary devices, technical building services, and technical personnel

groups of individuals, i.e., organizations.

Technē is translated as the "technical knowledge" used to produce an artifact and the knowledge that goes with it [34]. The technē form of knowledge (e.g., craftmanship) demands a mentor who provides feedback on the welds or other technical installations being attempted to be created, and also helps to show how to improve techne skills. Technical skills vary depending on the field of work and demand training and more training. In connection with Energy Management, technē reflects the practical knowledge that directly informs and develops technical skills in a certain technology, installation, machine, or tool, thus enabling the implementation of associated energy efficiency measures. Technē can be characterized as "descriptive knowledge" or practical "know-how" and "know-what". It encompasses the state of a domain (e.g., a technology or technical system), the key aspects that exist around it, the context in which they exist and the connections that may exist between key aspects and domains [28].

In terms of knowledge mode, technē can be seen as a tacit mode of knowledge. "Tacit knowledge" is gained from experience acquired over several years, rather than produced by formal education and training [35] and resides in people and organizations that have a shared knowledge base resulting in a mutual understanding [35]. It is embedded in routines and procedures [40], but also somehow stored in computerized databases, software programs [36], and institutionalized rules and practices [37]. Tacit knowledge is difficult to articulate or document and is considered by some as true knowledge that can be

Table 4
Main attributes of the knowledge-based framework used for analyzing the articles on EnMMI.

Attributes of knowledge	Translation of Aristotelian concepts for EnMMI			References
	Technē *Technical knowledge*	*Epistēmē* *Process knowledge*	*Phronēsis* *Leadership knowledge*	
Type	Descriptive: *practical "know-how" and "know-what"*	Procedural: *theoretical "know- how"*	Reasoning: *practical and theoretical "know-why"*	[28–30]
Mode	Tacit	Explicit	Tacit and Explicit	[33, 35–38]
Characteristics	Pragmatic, variable, context dependent. Oriented toward production	Universal, invariable, context independent. Oriented toward universal truths about processes	Pragmatic, variable, context dependent. Oriented toward action	[39]
Rationality	Based on practical rationality governed by a conscious goal	Based on analytical rationality	Based on practical value-rationality	[39]

transferred through mentoring [38].

Epistēmē is related to the possession of "scientific" knowledge, i.e., knowledge in the strict sense, as opposed to knowledge acquired in some other way (e.g., practical experience), and is knowledge that is the conclusion of a demonstration [34,39,41]. Epistēmē concerns universals and the production of knowledge and might be gained via receiving information. In most cases it is already successfully dealt with in today's educational systems, e.g., university. In the context of EnMMI, epistēmē represents the knowledge leading to a better understanding and operation, but also, improvement or change in a production process, and it is therefore translated as "process knowledge". The knowledge that informs process knowledge can take several forms, e.g., energy audits, KPIs, taxonomies for energy use, and can be taken from several sources depending on the complexity level of the production process, e.g., technical schools, training, production's manuals, but also from a whole scientific body of literature, technical papers, and textbooks.

Therefore, the epistēmē type of knowledge can be seen as procedural knowledge being characterized by the "know-how" encompassing the steps needed to reach a specific goal [28], in this specific case knowledge of processes. In terms of mode of knowledge, epistēmē is best described as explicit knowledge as it is formal and systematic, easily documented and articulated and is best exemplified by books, manuals and articles [35]. Furthermore, it is argued that explicit knowledge cannot exist independently of tacit knowledge [38]. Explicit knowledge can be created by making explicit and transforming "collective tacit knowledge" into a prototype process or product [42].

Phronēsis is related to "practical wisdom", and it involves judgments and decisions made in the manner of a virtuoso actor [39,43]. Furthermore, phronēsis is the capacity for intellectual perception, being a way of understanding that is at the same time articulate enough to be sensitive to the particulars of the situation in which one must act and discerning of the ethically features, but also flexible and open enough to be determined by deliberation, thus bridging the intellectual virtues and the virtues of character in the soul of a virtuous person [41]. More than anything else, phronesis requires experience, since a person who possesses practical wisdom has knowledge on how to manage a particular situation, interacts between the general and the concrete and requires consideration, judgment, and choice [39]. Reasoning knowledge, which is best exemplified as "know why" [28], is employed in phronēsis, as it includes the practical wisdom specifying the appropriate actions for a certain situation and the expected results and valid conclusions [28]. Therefore, in the context of EnMMI, phronēsis translates as "leadership knowledge", e.g., how to act as a leader.

An important connection between the three types of knowledge is that applying existing procedural (epistēmē) or reasoning (phronēsis) to existing descriptive (technē) knowledge often creates new knowledge [28]. Epistēmē concerns theoretical know-how, technē denotes practical know-how and know-what, while phronēsis involves practical and theoretical know-why. Moreover, the two attribute dimensions (i.e., type and mode) provide different views on the knowledge for EnMMI since, for example, someone can hold descriptive knowledge in a tacit form, meaning that they performed the activity repeatedly, but there is not yet a common language to pass this knowledge onto others. It might, therefore, be advisable to record such knowledge in a manual or procedure, thereby converting a certain tacit mode of technē knowledge into explicit knowledge. Furthermore, the same perspective can be applied for any type of knowledge since the objective of EnMMI should include the constant transfer and creation of knowledge especially in a period of transition.

The framework has been validated for the generalization concept [44], and it's applicability has been tested. This phase focused on the capability of the framework to capture the knowledge employed in EnMMI. To achieve this aim, an expert validation took place to critically discuss with industrial managers and researchers each framework's element, i.e., attributes and forms of knowledge, and to evaluate the framework's potential and applicability to describe the reference list of EnMMI. During the expert validation phase, critical discussions took place with both industrial managers and researchers on the rationale behind the forms and the attributes of knowledge. Furthermore, the experts tested the framework to well-known practices. Regarding the definition of the attributes', each attribute's description is exploited in order to organize the findings from the literature on EnMMI. This phase offers the validation of the theoretical definition of the attributes of knowledge as described in the current section.

4. Results

4.1. Previously published review papers

In this section, the resulting previously published review papers (n = 24) related to EnMMI are analyzed in terms of main aspects of EnMMI and categorized as illustrated in Tables 4–6. From the inductive content analysis of all the review papers, five publications discuss all three forms of knowledge (Table 5).

The review papers considered as the most relevant to our research work are those of [6,23]. However, both review papers differ from our study in terms of (1) the scope of the review, (2) years of publication, and (3) the number of relevant publications. [6] performed a systematic review of the literature and developed a conceptual framework for EnMMI. [23] conducted a comprehensive and systematic analysis of the literature, provided a holistic classification, and developed a reference framework based on different aspects of EnMMI from the leadership point of view. [45] carried out a review on Wire Electrical Discharge Machining showing that the energy-saving and emission reduction methods have focused mainly on the optimized design of machine tools, process modeling and optimization, and production management. [46] performed a comprehensive literature review of the metal forming processes and a hierarchy of the metal forming system, where the connection between the equipment, process, and manufacturing system is presented. [47] reviewed methodologies for analyzing energy use, analyzed the development of Industry 4.0 with emerging technologies and concluded that computational modelling is a powerful tool for energy analysis and an effective decision-making technique.

Another group of review papers focused on particular main aspects of EnMMI categorized under two types of knowledge (Table 6).

From this group, three papers address key aspects from Technē and Epistēmē knowledge themes, such as [48] who focused on aspects from Industry 4.0 (Machine Learning tools), and energy analysis and optimization; [49] quantified the key sources of energy use at the process level, as well as emerging technologies for increasing efficiency; and [50] analyzed the type and share of energy used, and on the EE technologies and measures applicable to the textile industry.

The other four review papers discuss key aspects of EnMMI within the Technē and Phronēsis themes. [21] conducted a review regarding the relationship between Industry 4.0 and organizational learning, while [51] reviewed the potential progress of Industry 4.0, related technologies, and management models. [52] conducted a review on EE in manufacturing systems, the current technologies and strategies for optimizing the use of resources and reducing energy use, and [53] provided a review on the industrial energy savings based on technologies and management.

Last but not least, a final group of 12 review papers touch upon key aspects of one type of knowledge and are briefly described in Table 7.

The Technē theme includes review papers discussing i) technology deployment, e.g., Refs. [54,55], ii) blockchain technology and Industry 4.0 [56], iii) drivers for investments in EE technologies [57], and iv) the characteristics of energy use in the CNC machining process and influencing factors for EE improvement [58]. Under the Epistēmē theme, [59] developed a hierarchical model for better understanding of energy use in machining, [40] conducted a review of energy assessment methods and tools, while [60] discussed current analysis approaches and prediction methods for energy and media in the beverage industry. Finally, the Phronēsis theme includes a review by Ref. [61] on the application of Multi-Criteria Decision Making methods in EnM, two review papers that discuss key aspects such as EnM assessment tools & methods [63,64], and a review by Ref. [62] on the driving forces for EnM programs.

4.2. Content analysis

In order to conduct a standardized and concrete interpretative analysis of the various subjects of EnMMI, the articles (n = 133) were grouped according to common themes. From the inductive content analysis of the articles, the final data is categorized in aggregated themes, i.e., process knowledge, technical knowledge, and leadership knowledge (see Fig. 4) and represents the basis for the current content analysis section. This section presents notable findings identified during

Table 5
Mapping of previously published review papers covering different main aspects of EnMMI from all three knowledge themes and the study's system level.

References	*Technē*				*Epistēmē*		*Phronēsis*				System Level		
	Machine systems	Machine tools	Industry 4.0	Technology deployment	Process measures	Energy analysis	Production & scheduling management	Decision tools & methodologies	Strategies for improving EE	Drivers & barriers	Machine	Process	Factory
[6]				x		x		x	x	x	x	x	x
[23]			x	x	x	x	x	x		x	x	x	x
[45]	x	x			x		x				x		
[46]	x				x		x				x	x	x
[47]			x			x		x			x	x	

the content analysis.

4.2.1. *Technē – Technical knowledge*

Technē form of knowledge predominated in the EnMMI literature, thus showing the focus. Under this theme five main categories emerged: **a) Industry 4.0, b) machine systems, c) machine tools, d) technology deployment,** and **e) manufacturing equipment** (Fig. 5), of which *Industry 4.0* is the most important category having the highest number of publications. The articles related to Technē are listed as references from Ref. [1 to 63] in the Appendix.

4.2.1.1. Industry 4.0. A move towards a higher level of industrial digitalization has been identified in the literature on EnMMI. Alongside with a demand for interconnected, automated, adaptive, and flexible solutions that are shaping the manufacturing system towards Industry 4.0, encompassing Internet of Things, big data, robotics, additive manufacturing, and digital simulation. By Industry 4.0 it is understood the integration of smart technologies and industrial production systems with the support of cyber-physical system (CPS) applications and the Industrial Internet of Things (IIoT). The articles from this category were grouped into several sub-categories, as illustrated in Table 8. The following section presents the notable findings within the research stream.

Predominantly over the last five years of the analysis, EnMMI has involved a rapidly changing paradigm with the aim of transforming the industry into smart and sustainable factories, which are characterized by higher flexibility and sustainability and are at the core of Industry 4.0. Although the research conducted in this area was performed mostly at the plant and production processes level, there are also studies that focus on manufacturing cell, robot, and tool level, proving that AIT applications are being constantly updated in order to reach the complexity of manufacturing systems. At the plant level, AIT applications aim to improve EE, scheduling optimization, and robotics, while at the basic machine tool level, where they are more complex and highly specific, monitoring and control, data-driven tool wear models, and predictive maintenance benefit from AIT.

By applying AIT such as IoT, CPS and manufacturing big data, the industry promotes the implementation of an EnM strategy and improves its sustainable competitive advantage. With the support of IoT, real-time energy data can be easily collected and analyzed to implement EnM. CPS allows interoperability, interaction, and communication between a physical world (e.g., workshop, plant, site) comprised of physical devices and computing objects (e.g., smart sensors), and a cyber world (which is comprised of all the information collected). Nevertheless, the increased energy data generated in manufacturing industries, i.e., energy big data, is being processed with big data analytics. With the rapid development of such AIT, new strategies for EnMMI are being provided, enabling sustainable smart manufacturing.

Integrating CPS with existing energy technologies and AIT-led innovations in the fields of machine learning, manufacturing big data analytics, cloud manufacturing, and IoT, leads the transformation towards Cyber Physical Energy System (CPES) which in turn enables process and systematic efficiency, plus improvements in energy efficiency at machine and factory level. Furthermore, CPES offers solutions for implementing energy-efficient manufacturing strategies and methodologies in a global production network where technical architectures integrate energy-efficient manufacturing modules to assess technical capabilities and energy use in connected virtual factories. Real-time and user-friendly simulation models of factories are being developed, and a big data approach, analysis, and optimization are being applied. Multipurpose digital simulation is a useful tool for developing industry 4.0 scenarios that enable improvements to energy efficiency and productivity while decreasing resource and energy waste, through 3D digital human modelling and discrete event simulation.

Table 6
Mapping of previously published review papers covering different main aspects of EnMMI from two knowledge themes and the study's system level.

References	*Technē*			*Epistēmē*	*Phronēsis*			System Level		
	Manufacturing systems	Industry 4.0	Technology deployment	Energy analysis	Organizational learning	Strategies for improving and advancing EE	EnM models	Machine	Process	Factory
[48]		x		x					x	
[49]			x	x					x	x
[50]			x	x				x	x	
[21]		x	x		x					x
[51]		x					x			x
[52]	x	x	x			x		x	x	x
[53]			x				x	x	x	x

4.2.1.2. Machine systems. A subsequent set of articles belongs to the category of Machining Systems, which refers to the major production and energy consuming equipment used widely in the manufacturing systems. The number of articles on the field suggests an academic interest in reducing energy use in machine systems. Therefore, after conducting an analysis inside the category, it was possible to classify the articles by their common main aspects and system levels, as illustrated in Table 9. The following section presents the notable findings within the research stream.

Energy efficiency improvements at the machine level have been at the center of research for almost the entire period of the analysis and have received academic attention since they cut to the heart of sustainable manufacturing. In order to deal with energy efficiency improvements in machining systems, one first needs to analyze the energy flow in a clear and thorough manner that will enable the understanding of machining systems and the identification of related problems. Research at the machine level breaks down the energy use to look at the energy loss and the potential improvements at a detailed level, with the goal of increasing energy efficiency and productivity.

Within machine systems, energy-aware machine scheduling has the highest number of articles, reflecting the scientific community's interest in the topic, probably due to the fact that it enables energy-efficient production planning and is thus an effective way to improve EE and reduce energy costs. Therefore, models for dynamic machine scheduling and planning are being developed. However, due to the complexity of machining systems in terms of parameters, constructing energy models is not enough to achieve the objectives of energy-efficient machining, since i) models are mainly developed for a certain machine with specific parameters that might not be applicable in a different set-up or context, and ii) knowing the energy use of the machine tool is not enough to reach the objectives of an energy-efficient machining-system, optimization is needed to reach the goal. Therefore, energy optimization studies are conducted mainly in energy-efficient scheduling of production and machining parameters. Optimization algorithms for energy-aware machine scheduling consider not only factors of production, i.e., makespan and machine workload, but also indicators for environmental sustainability.

4.2.1.3. Machine tools (MT). Under MT research, common main aspects and system levels were identified, as illustrated in Table 10. With the focus on reducing the energy use of machine tools, a group of researchers have developed models for the energy use of MT, optimization models for cutting parameters in order to reduce energy use in CNC machining, and models for reducing energy waste in non-cutting activities. Models for the energy use of MT have enabled the development of strategies for designing energy-efficient MT. Furthermore, methods for assessing the EE of MTs have been approached by several scholars, such as exergy-based EE evaluation models, KPIs for evaluating the energy performance of MT and support for the design and selection of MT and prototype system for systematic energy use analysis and evaluation of CNC machining.

4.2.1.4. Technology deployment. Under the technology deployment research stream, the following main aspects and system levels emerged, as illustrated in Table 11. Energy efficiency based on technology deployment is another important research focus for the academic scholars, discussing deployment of EE technology for reducing energy use at industrial scale and closing the EE technology gap, but also determinants regarding technology acceptance and investments in EE technology.

4.2.1.5. Manufacturing equipment and systems. Manufacturing equipment and systems represent another important category in the research area and the subsequent group of articles illustrated in Table 12 indicates that the main focus is around **(i) methods for energy efficiency of equipment systems**, and **(ii) methodologies for monitoring, controlling, and benchmarking the energy performance of compressed air systems**.

4.2.2. Epistēmē – Process knowledge

The Epistēmē research stream is concerned mainly with the prerequisite information and knowledge needed to implement EnM and energy efficiency in manufacturing. While the Technē type of knowledge is rather contextual for each site, Epistēmē knowledge can be generalized from one site to another. Main trends and academic research interests revolve around basic and mandatory tools and methods needed for energy-related analysis and energy efficiency improvements at the production process level. Under this research theme two main categories have been developed: **a) energy analysis** and **b) production and support process measures**, as illustrated in Fig. 6. *Energy Analysis* includes the highest number of studies. Below are presented the main insights from these two categories together with identified key aspects of EnMMI. The articles related to Epistēmē are listed as references from Ref. [64 to 103] in the Appendix.

4.2.2.1. Energy analysis. Energy-related analysis improves energy use awareness and allows identification of where to take action in the manufacturing processes in order to reduce energy use and improve energy efficiency. Moreover, improving energy efficiency in production facilities is a challenge for managers when a shift toward a more energy efficient manufacturing system is needed. However, to conduct an energy analysis, proper tools and methods are required to assess and model energy use. Reacting to this need, the research focus of academia and practitioners worked towards developing efficient and reliable tools and methods for energy analysis. Hence, a significant number of tools and methods supporting energy-related analysis have been identified in this category and were categorized as illustrated in Table 13.

Tools and methodologies for developing i) taxonomies for energy end-use, ii) energy-related KPIs for benchmarking, and iii) energy monitoring systems are among the most researched ones, as they give access to data and information that allows specific energy-related analysis and identification of energy efficiency improvements, thus creating essential and structured process knowledge. Furthermore, monitoring existing rates of energy use in various plants is important

Table 7
Mapping of previously published review papers covering different main aspects of EnMMI from one knowledge theme and the study's system level.

References	*Technē*					*Epistēmē*	*Phronēsis*			System Level			
	Machine systems	Industry 4.0	Machine tools	Drivers for EE technologies	Technology deployment	Energy analysis	Decision tools & methodologies	EnM assessment methods	Drivers & barriers to EnM	Machine	Product	Process	Factory
[54]					x						x		
[55]					x					x			x
[56]		x											x
[57]				x									x
[58]	x									x			
[59]						x				x			
[60]						x							x
[40]						x						x	
[61]							x						x
[58]								x			x		
[59]								x			x		
[62]									x				x

and considered a prerequisite for any EnM activity. Analyzing and benchmarking has its share of attention since it is a recognized analytical methodology that supports the improvement in efficiency and performance of energy use. Furthermore, reductions in energy and GHG emissions can be achieved on manufacturing sites where there is a comprehensive understanding of energy flows and analysis of energy usage. Existing studies design and develop energy baseline and energy benchmarking methodologies that allows analysis and comparison of manufacturing lines and enables realistic targets in individual plants. Energy related KPIs covering different levels in a manufacturing facility are essential tools that enhance and support monitoring, analysis, and benchmarking, as they provide: i) visualization of energy and production data, and ii) assessment of the progress in reaching the energy efficiency goals.

4.2.2.2. Measures for production and support processes. Acting to increase energy efficiency at the production process level is another important initiative, and the documents from this category were classified by common interests under the common subtopics, as illustrated in Table 14. Energy modelling and optimization of manufacturing processes contains the largest number of articles in the category confirming that monitoring is an essential element in identifying energy improvement opportunities. Furthermore, process planning and scheduling have the second highest number of publications showing that energy-aware scheduling and planning is a key aspect of EnMMI, being at the shop level, process level, or at the machine level. And further development of optimization models for specific manufacturing processes enables i) carbon emissions and processing cost models that can achieve carbon efficiency improvement and save related cost, and ii) optimized process planning and scheduling. To conclude, scholars focus on generating new methodologies and tools for manufacturing firms to implement new solutions for energy-efficient production, as well as for improvements to performance in terms of productivity and related cost savings.

4.2.3. Phronēsis – Leadership knowledge

Under this research theme, the articles were classified under two categories: **a) Models for EnM & EnM assessment**, and **b) Strategies for advancing energy efficiency in manufacturing**. EnM Models comprises the highest number of publications in the sampled theme. The key aspects identified under each category are illustrated in Fig. 7. The articles related to Phronēsis are listed as references from Ref. [104 to 133] in the Appendix.

4.2.3.1. Models for EnM & EnM assessment. This category has the highest number of articles in the leadership knowledge research theme. The articles from this category were grouped into sub-categories as illustrated in Table 15. Under the current leadership pattern, the research focuses on models for planning and implementing EnM in organizations. The models address how to get EnM accepted in organizations and integrate it into a company's business plan and production management. Furthermore, models on developing sustainable EnM programs and assessing the maturity of EnM systems are part of the focus. Nevertheless, EnM assessment models represent another researched area alongside the necessary tools for assessing the implementation of industrial EnM and plant EE.

4.2.3.2. Strategies for improving and advancing energy efficiency in manufacturing. The articles from this category were grouped into several sub-categories, as illustrated in Table 16. Strategies for advancing EE in manufacturing address everyday behavior changes, but also adopting LEAN, integrating waste-to-energy, corporate energy policy, and combining investments in energy-efficient technologies with continuous EnM practices. Another researched topic is related to the decision tools needed to be deployed in order to ease the decision process related to selecting energy efficiency measures or industrial resource efficiency

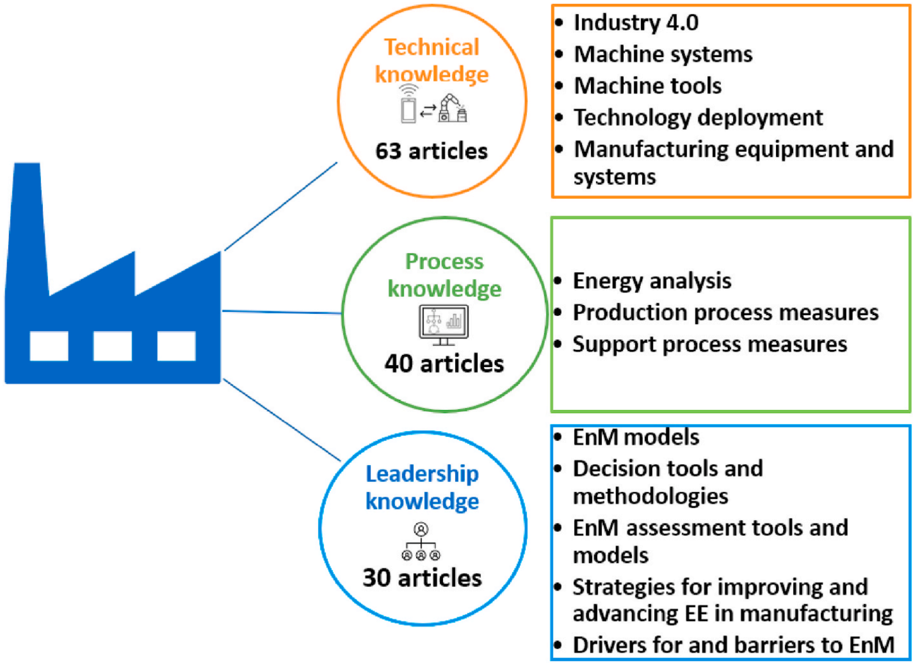

Fig. 4. Content framework for knowledge-based themes of EnMMI.

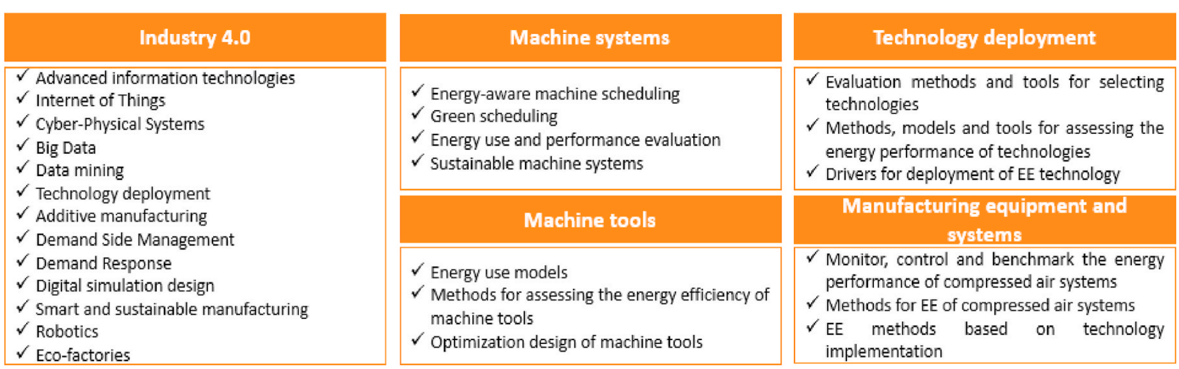

Fig. 5. Categories and main aspects of EnMMI identified under the Technē research stream.

Table 8
Mapping of reviewed papers on EnMMI under main aspects of **Industry 4.0**

	System level	References
Advanced information technologies	(M)	[9,11]
	(P)	[2,4]
	(L/M-M)	[3,12]
	(F)	[1,5–8,10,13,14]
Additive manufacturing	(P)	[15–17]
Demand side management and Demand response	(P)	[19–21]
	(L/M-M)	[18]

Table 9
Mapping of reviewed papers on EnMMI under main aspects of **Machine Systems.**

	System level	References
Energy-aware machine scheduling	(M)	[22–30]
EE evaluation of machine systems	(M)	[31–33]

projects. In the studies of drivers and barriers to EnM, the role of middle managers has been studied as an influencing factor for EnM and EE investments, but also the challenges to and motivating forces for the adoption of efficient EnM practices.

Table 10
Mapping of reviewed papers on EnMMI under main aspects of **Machine Tools.**

	System level	References
Energy use models for MT	(M)	[34–45]
Methods for assessing EE of MT	(M)	[46–49]

Table 11
Mapping of reviewed papers on EnMMI under main aspects of **Technology Deployment.**

	System level	References
Deployment of technology	(M)	[50]
	(F)	[51–53]
Determinants for acceptance of technologies	(F)	[54–56]

4.3. *Descriptive analysis*

This section analyzes the distribution of the papers (N = 133) over a

Table 12
Mapping of reviewed papers on EnMMI under main aspects of **Manufacturing Equipment and Systems**.

	System level	References
Methods for energy efficiency	(M)	[57–60]
	(F)	[61]
Monitoring, controlling, and benchmarking CAS	(F)	[62,63]

decade, by time period, themes, and manufacturing system level of application.

4.3.1. *Distribution across the time period and themes*

The distribution of the reviewed publications within the research period (2010–2020) is shown in Fig. 8. Between 2010 and 2020, research in the area of EnMMI has an increasing trend overall. In 2010 only two papers were identified and until 2015 the trend follows a slow increase in the number of papers identified, with six papers published in 2015. The topic gained momentum in 2016 from which a steep slope can be noticed with a significant increase in the number of publications until 2020, highlighting the growing academic interest in the topic (e.g., the number of papers published between 2010 and 2015 is 21 and is slightly lower than the number of publications from 2020, i.e., 25). So, from the distribution of the papers so far, one can see that research on the subject is increasing, and the focus is on technical knowledge with the highest number of publications (n = 63), as research efforts shift towards the Smart Factory, which is at the heart of Industry 4.0.

4.3.2. *Distribution across the manufacturing system level of application*

Figs. 9–11 illustrate the distribution of the publications categorized under the Technē, Epistēmē and Phronēsis themes across the system level of application. The Technē research stream has the largest proportion of studies under machine level (35 articles representing 56%), the Epistēmē theme address EnM at process level in more than half of the publications (58%), and under the Phronēsis theme, half of the publications address EnM at the organization level.

5. Discussion

5.1. *Knowledge demands for energy management in the manufacturing industry*

In this section, the knowledge demands for the adoption of more

Table 13
Mapping of reviewed papers on EnMMI under main aspects of **Energy Analysis**.

	System level	References
Measuring energy performance	(M)	[65]
	(P)	[64,66–69,71,73]
	(L/M-M)	[70]
	(F)	[72,74–76]
Monitoring	(M)	[78], [79]
	(P)	[77], [81]
	(L/M-M)	[80]
	(F)	[78], [80]
Models for energy use analysis	(M)	[84]
	(P)	[82], [85], [87]
	(F)	[83], [86]
Energy assessment	(M)	[89]
	(P)	[89]
	(F)	[88], [90], [91]

Table 14
Mapping of reviewed papers on EnMMI under main aspects of **Measures for Production and Support Processes**.

	System level	References
Energy modelling and optimization	(P)	[92–96]
Process planning and scheduling	(P)	[97,99,100]
	(F)	[98]
Operational measures	(P)	[103]
	(L/M-M)	[102]
	(F)	[101]

Table 15
Mapping reviewed papers on EnMMI under main aspects of **Models for EnM & EnM Assessment**.

	System level	References
EnM models	(O)	[104], [105], [108], [109], [110], [112], [114]
	(F)	[106], [107], [111], [113]
EnM assessment tools and models	(O)	[116]
	(F)	[115], [117], [118], [119]

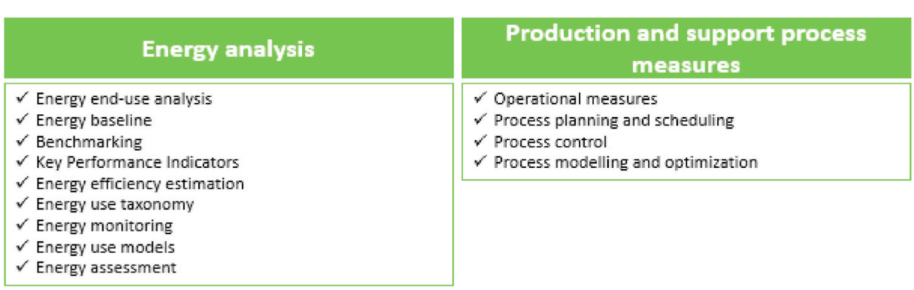

Fig. 6. Categories and key aspects of EnMMI identified under Epistēmē theme.

Fig. 7. Categories and key aspects of EnMMI identified under Phronēsis theme.

Table 16
Mapping of reviewed papers on EnMMI under main aspects of **Strategies for advancing energy efficiency in manufacturing**.

	System level	References
Strategies for EnM in manufacturing	(P)	[126]
	(O)	[132], [133]
	(F)	[124], [125]
Decision tools and methodologies	(P)	[130]
	(O)	[131], [129]
	(F)	[127], [128]
Barriers to and driving forces for efficient EnM practices	(O)	[120], [121], [122], [123]

radical innovations in EnMMI, such as Industry 4.0 that supports the transition towards climate neutrality, are discussed under each form of knowledge. Furthermore, the knowledge creation process for EnMMI including the knowledge demands is illustrated in Fig. 12.

5.1.1. Epistēmē – Process knowledge

If EnMMI is analyzed in terms of required steps for implementation, then the tools and methods discussed in the Epistēmē stream should be the first step in implementing EnMMI since one actually learns i) about one's own processes, ii) about how energy is used within the processes, and iii) what type of energy efficiency improvements are possible. Thus, specific process related information creates process knowledge, which potentially leads to increased EE. This theoretical finding is strengthened by the findings of [20]'s empirical study showing that additional higher educated staff is needed to reach high levels of EE-innovation adoption. This general finding is of key importance in the transition towards decarbonization since higher education across any nation, country, and sector is key to a successful transition.

In another study, [8] claimed that investing in human capital such as technical specialists is a significant facilitator for the adoption of technical process innovation. Furthermore, re-educating staff might be necessary when radical innovation steps such as Industry 4.0 are being approached, since the model that helped parts of the manufacturing industries to develop by transmitting knowledge from generation to generation [54] cannot be applied to the creation of new knowledge. Training professionals in the new skills needed once Industry 4.0 takes over is also discussed by Refs. [21,22]. However, re-education of staff might also be needed due to an ageing population within the staff, as people used to working in production are retiring and taking with them the process knowledge and experience gained during their careers [10, 65–67].

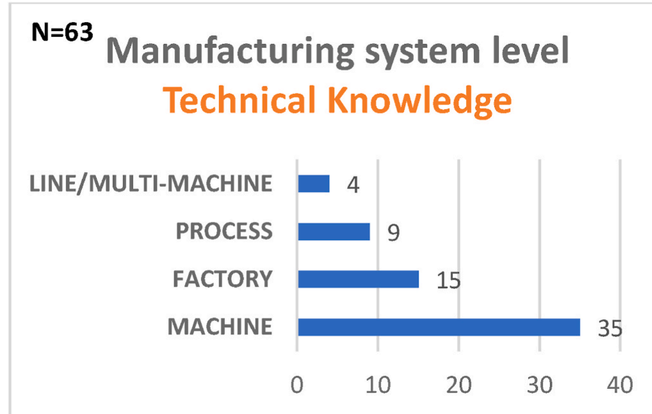

Fig. 9. System level distribution across Technē.

However, what would happen if one decided to take direct steps towards a technē way of measuring and monitoring in Industry 4.0? Will that knowledge about the process be lost, replaced by the computer capability, and if this is the case, what will happen with the epistēmē type of knowledge? On the other hand, the knowledge that practitioners possess will still be relevant for building the EnM when Industry 4.0 is

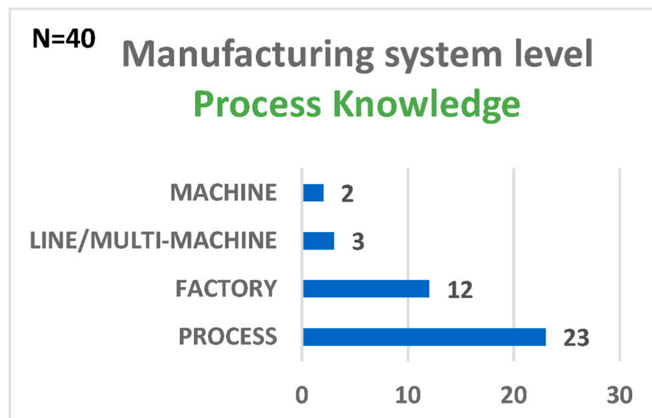

Fig. 10. System level distribution across Epistēmē.

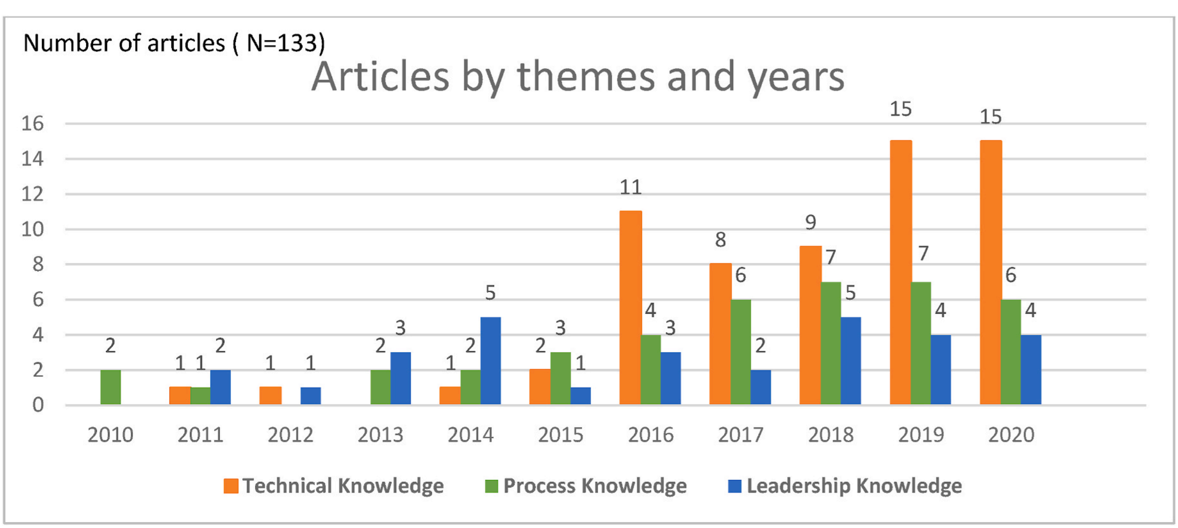

Fig. 8. Distribution of articles per themes and across time period.

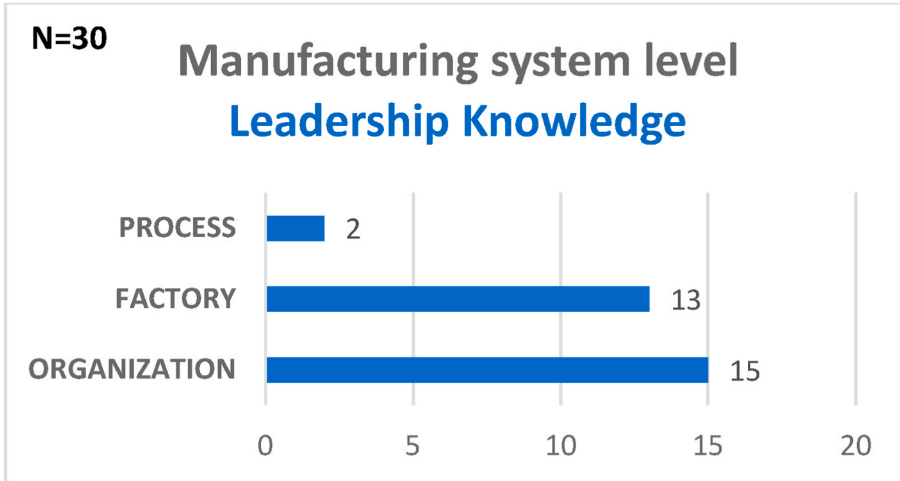

Fig. 11. System level distribution across Phronēsis.

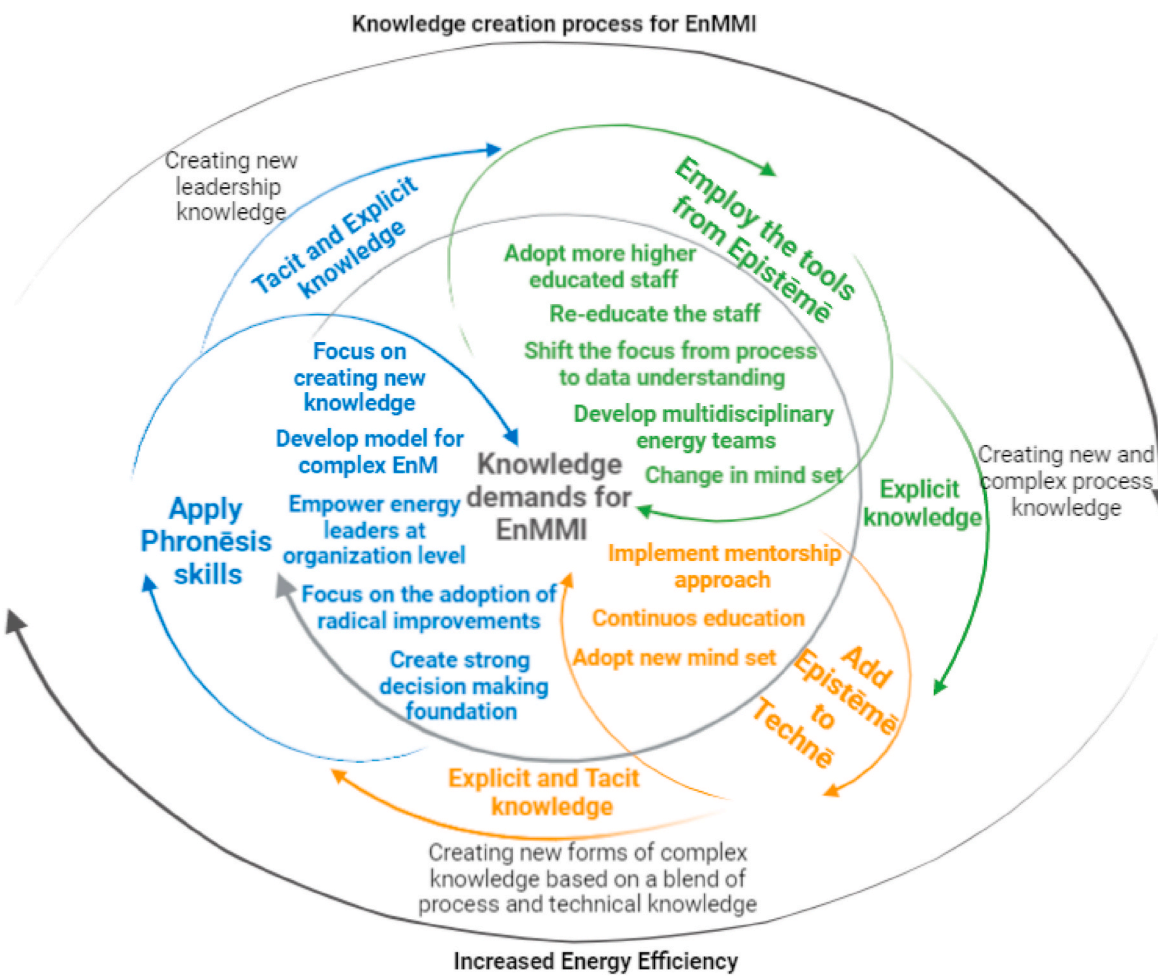

Fig. 12. Knowledge creation process and knowledge demands for the adoption of radical and incremental innovations in EnMMI.

deployed on a large scale? A possible scenario is envisioned, in which epistēmē knowledge as it is now will start to also include technē knowledge from Industry 4.0, in the sense that it will move from understanding the process to understanding the data. In such a scenario, different type of epistēmē knowledge and a new type of skills, i.e., data and digital skills, will be needed in the Industry 4.0 transition. Another possible scenario is that digitalization takes over EnM to a large extent and serves the processes so that it enables more complex process knowledge to be gained.

Although this might create difficulties in drawing a line between process and technical knowledge, such a blend in forms of knowledge might enable the adoption of radical innovation. However, in order to develop such complex process knowledge, an organization's experts in process knowledge would need to share their expertise with the experts in digitalization, i.e., the movement towards more cross- and multi-disciplinary teams. Moreover, adopting digitalization services in the production floor requires a change in mind-set, and this has been shown in a previous study by Ref. [68] to be a challenge in the organization. These are some of the new knowledge demands for EnM brought by Industry 4.0, which need to be discussed and tackled. However, irrespective of the type of knowledge or skills needed, in this study is argued that information creates epistēmē knowledge (being process type of knowledge or digital type) which in turn paves the way to improved technē knowledge, in the current context of EnMMI but also within the Industry 4.0 framework.

Once digitalization becomes fully mature in EnM, process knowledge might become more complex; hence, multi-disciplinary teams with different skills and expertise are required to respond to the current knowledge demands and adopt new radical innovations in EnM. The structuring for a successful transition could be the creation of such multi-disciplinary energy teams, comprehending scientific knowledge (e.g., academia), process knowledge (e.g., experts in specific processes) and technical knowledge (e.g., digitalization and Industry 4.0), but not only at the company level, also at sector level, since knowledge for the transition is highly sector specific. At the incremental level of innovations, there is a history of working in energy teams [69]. However, when implementing innovations at the radical level, where the complexity to change the technology and the production is higher, it will require new skills and technology, more investment and better understanding of how the energy efficiencies will influence the overall process. Therefore, there is a greater need to develop multidisciplinary energy teams at the company level that will include personnel from operators to management level. Such multidisciplinary teams could make effective use of existing knowledge regimes, ensuring continuous education to meet the increased need for new knowledge, and efforts to enhance multi-disciplinary teamworking.

5.1.2. Technē – Technical knowledge

As seen in technē research stream, the paradigm is changing towards Industry 4.0. Digitalization will give access to more real-time energy-related data, enhancing advanced analysis that requires more advanced technē and process knowledge. Therefore, things are getting more complex and new types of knowledge need to be created. To create new technē knowledge, one needs mentorship within the organization in order, first of all, to fully embrace the new mind-set [70] that the adoption of Industry 4.0 requires. The concept of mentorship or mentoring to enhance technē knowledge is not heavily explored in the scientific literature for EnMMI as opposed to the grey literature on lean manufacturing, e.g., Ref. [71]. However, in EnMMI, mentorship can be used to transfer the knowledge from an expert from the organization to a more novice individual through instruction and active learning [38].

5.1.3. Phronēsis – Leadership knowledge

The general finding from phronēsis research stream, is that implementing a complex energy management model is needed in order to adopt radical innovations and advance towards climate neutrality. The key to success is having qualified and operational energy leaders at different levels, from site level, to organization, global and regional level, as stressed by e.g., Refs. [72,73]. Apart from this, strong leadership that enables the creation of new knowledge might further enhance the possibility to adopt new radical innovations. However, the EnM models developed to be implemented in organizations could be improved by aiming to capture the vast amount of knowledge needed especially when a technical development or radical innovation needs to be implemented. The leadership knowledge needed for radical innovations requires a strong decision-making foundation that has both the authority and skills to connect all three forms of knowledge in a way that will lead to the implementation of both incremental and radical innovations in EnMMI. The question that remains to be answered is whether the leaders from the organization level possess the needed structure, i.e., authority at the organization level, to enable strong decision-making type of leadership for EnMMI.

To summarize, this paper has addressed a knowledge perspective on energy management that previously has not been thoroughly described, one exception being [20]'s paper that showed that higher education has a positive effect on energy efficiency innovation. Furthermore, the findings show that technical knowledge is the main form of knowledge employed in EnMMI, as previously discussed by, e.g., Refs. [74,75] under the term of "technology diffusion model". Moreover, the technology knowledge paradigm is shifting towards Industry 4.0. as previously discussed by, e.g., Refs. [51,76]. Also, operational energy leadership at the micro (site and organization) and macro (regional and national) level is found to be key for implementing a complex energy management model, as stressed by e.g., Refs. [72,73]. Such a complex model is needed to meet the current needs of an industry transitioning towards climate neutrality. These findings build upon previous research on energy efficiency and energy management and shed light on the importance of various forms of knowledge. One limitation of the paper is the choice of the method where a literature review was used. Therefore, further research should aim towards also doing field study research and interviews that further explores the knowledge dimensions of energy management.

5.2. Recommendations for further research

Recommendations for further research are being discussed and illustrated in Table 17. While energy efficiency improvements at the machine level have taken us so far, in order to fully integrate energy efficiency within manufacturing systems and make bigger energy savings, research should also focus on system level challenges, where machining, processes, line/multi-machine, and the factory are integrated in order to make the shift towards sustainable decarbonized manufacturing. This change would entail shifting the focus from energy improvements at machine level to energy improvements at system level. Therefore, more comprehensive studies that cover all levels of energy flows in a manufacturing plant are recommended in order to reach the overall energy goals.

Incorporating environmental indicators alongside production factors in the optimization algorithms for energy-aware machine scheduling is a further step towards achieving sustainable machining systems, and therefore more research is recommended. One emerging topic connected with Industry 4.0 that is gaining importance and has been implemented into a wide range of industries is the Cyber Physical Energy System. However, it deserves more research since it takes a further step towards sustainable smart manufacturing. Improving the energy efficiency of industrial robots is another researched topic. However, there is room for scholars to advance more research on the topic and to consider the technological and social challenges and opportunities for EnM connected with a new division of work between humans and

Table 17
Recommendations for further research within each form of knowledge.

Form of knowledge	Recommendations for further research
Technē	EnMMI with a system level perspective Cyber Physical Energy System for EnMMI Energy efficiency of industrial robots Technological and social challenges, and opportunities related to a new division of work between humans and machines Challenges and opportunities offered by 5G network for smart EnM
Epistēmē	Designing of low-cost non-intrusive sensors for energy monitoring Developing production tailored KPIs Effects of manufacturing industries on carbon emissions
Phronēsis	Leadership for EnM Decision support tools for EE and EnM Culture and values in manufacturing organizations

machines.

Finally, due to the evolution of internet networks, especially with the latest 5G network, IoT can now connect more things that are no longer limited to the industry. Covered by the possibilities offered by cloud manufacturing, new and better solutions for improvements in EnM can be developed in such a way as to keep the industry competitive in a time of transition and beyond that. Such networks offer real-time information about everything happening in a plant and allow real-time control. Together with cyber-physical systems and a complete Industry 4.0, the manufacturing plant can be customized and productized according to the needs and tailored solutions required by the market. In this sense, online design tools are a characteristic of Industry 4.0, enabling tailored solutions for manufacturing, which can be met by more flexible and automated processes. Flexible robots and the collaboration between robots and humans in a virtual reality is crafting the possibility of such tailored solutions. Hence, more research on the challenges and opportunities offered by 5G enabled manufacturing for Industry 4.0., allowing smart EnM, could be a timely research topic worth exploring by scholars.

Under epistēmē, methodologies for energy monitoring have been highly studied, as opposed to the design of low-cost non-intrusive sensors for monitoring, which is worth exploring more due to the increase in digitized processes and the economic advantage. Also, more research should be conducted on methodologies for production-tailored KPIs, since this could even further enhance knowledge of the energy and production processes as it can provide more information on i) abnormal production events, ii) weak spots and improvement areas related to production and operations, and iii) cause-effect relationships. There is a trend towards analyzing the consequences that energy have on other environmental pressures such as carbon emissions. Studying the effects of manufacturing industries on resources other than energy (e.g., carbon emissions) can lead to the transition towards more sustainable energy systems and improved EE in manufacturing processes, making this a topic worth exploring.

Regarding phronēsis, more research is recommended on the methodologies for capturing and studying leadership in energy management for manufacturing industries. Another important topic is related to the decision support tools needed to facilitate the decision process connected with the implementation of energy efficiency projects and EE measures, and more research should be conducted in this area. Strategies for advancing EE by addressing everyday behavior changes on the production floor are another topic worth exploring. Moreover, leadership influences organizational and technical processes, and also behaviors, in order to raise awareness of energy issues, reduce operational energy use and improve resource efficiency. Leadership is a complex activity based on the interaction between humans and technologies, thus making it challenging to capture it all in one model. Excellence in phronēsis knowledge will require, as prerequisites, some level of technē and epistēmē knowledge together with an understanding of the culture and values and relationships in the particular company that the leader operates in, and hence more research is recommended on the subject.

6. Conclusions

This study has designed a knowledge-based framework consisting of main forms (i.e., Technē, Epistēmē and Phronēsis) and attributes (i.e., type, mode, characteristics, rationality) of knowledge. The framework was applied to analyze and categorize a total of 157 studies on EnMMI, from which 133 original articles and 24 review studies. Furthermore, the knowledge creation process for EnMMI and the knowledge demands for the adoption of radical and incremental innovations in EnMMI were identified and discussed. It is the first literature review on EnMMI to develop and adopt a knowledge-based lens for analysis.

The analysis of the original articles shows that in the literature on EnMMI, particular attention is given to the technical knowledge, as seen in the 63 articles out of 133. Technical knowledge is comprised of five major knowledge areas: i) Industry 4.0 (the predominant one with 21 studies out of 63), ii) machine tools (discussed in 16 studies), iii) machine systems (covered in 12 studies), iv) technology deployment (7 studies), and v) manufacturing equipment and systems (7 studies). Under process knowledge (represented in 40 articles out of 133), two main knowledge areas emerged: i) energy analysis (highest number with 28 studies), and ii) production and support processes measures (12 studies). Under the last form of knowledge, leadership (covered in 30 articles), two main areas have been identified: i) models for EnM & EnM assessment (16 studies), and ii) strategies for advancing energy efficiency (14 studies).

The major implication at this point for practitioners is that leadership should be implemented to use this body of knowledge in promoting the integrated and joint adoption of knowledge forms. Furthermore, their synergies should be considered, with a focus on increasing the adoption of radical innovations in EnMMI that can determine the successful transition towards a sustainable energy system and maintain or improve competitiveness. To conclude, beyond all these considerations, research should also focus on i) the opportunities that the knowledge forms and attributes employed in EnMMI offer regarding the adoption of both incremental and radical innovations, and ii) further developing the framework to better enable the adoption of knowledge at sector level and organization level through multi-disciplinary cooperation.

Credit author statement

Andrei, M: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing -Review & Editing, Validation, Project administration. **Thollander, P:** Conceptualization, Validation, Supervision, Writing – review & editing, Funding acquisition. **Sannö, A:** Validation, Writing – review & editing, Supervision.

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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.

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Appendix A. Supplementary data

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