

Technology Transfer for Energy Efficiency in the Industry 4.0 Era: A Systematic Review

Karoline Guedes^{1*} , João Luiz Kovaeski¹ , Regina Negri Pagani¹ 

Abstract:

This paper presents a systematic review of the literature on Technology Transfer and its role in the implementation of Energy Efficiency in the Industry 4.0 era. The main objective was to survey a portfolio using the Methodi Ordinatio 2.0 methodology, in order to understand whether the transfer of knowledge and technologies has contributed to the implementation of energy efficiency practices. The review revealed that technology transfer plays a fundamental role in optimizing the use of energy resources, facilitating the adoption of more efficient and sustainable solutions. Collaboration between different sectors and regions, as well as capacity building and sharing of good practices, were identified as key factors for the successful implementation of these technologies. Furthermore, the research highlighted the importance of public policies to encourage this transfer, especially in areas with lower technological capacity. It is concluded that technology transfer is essential to achieve global energy efficiency and sustainability goals, and that its continued promotion will be decisive for the development of innovative and scalable solutions in the future.

Keywords: Energy Efficiency. Technology Transfer. Anthropotechnology. Industry 4.0. Sustainability.

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Introduction

It is known that energy is an essential resource for human life and its development, as well as for economic growth, especially in the industrial sector, which relies on energy to transform raw materials into products and services. In light of this, the manner in which energy is being utilized is increasingly addressed by representatives of countries, industries, and researchers, particularly concerning the environmental impacts of consumption and climate change (Seow & Rahimifard, 2011; Heideier et al. 2020).

According to the International Energy Agency (IEA, 2024), the energy sector has faced significant challenges in recent years, initially due to the Covid-19 pandemic and subsequently due to the global energy crisis triggered by Russia's invasion of Ukraine, and of escalating risks in the Middle East and heightened geopolitical tensions globally. As highlighted in the World Energy Outlook, both events have had impacts on energy markets, leaving many producers and consumers feeling adversely affected by the volatility of fuel and electricity prices (IEA, 2024).

With the rise in investment in clean technologies and the rapid growth in electricity demand, the world is embarking on its journey towards a safer and more sustainable energy system, and what more needs to be done to achieve its climate targets. However, the world is still far from a sustainable recovery. Only with an increase in changes to how the world produces and consumes energy can the trend of rising emissions of pollutants be altered in the future. According to the IEA report, investments in clean energy are essential to stimulate global economic growth, generate jobs, and reduce emissions of pollutants, along with investments in improving energy consumption efficiency, low-emission electricity, and more sustainable fuels (IEA, 2024).

According to Cantarero (2020), in addition to post-Covid-19 recovery efforts worldwide, the solution to current climate and economic crises may lie in the rapid transition to low-carbon (sustainable and renewable) energy systems, encompassing assumptions of Energy Efficiency (EE), accessibility, reliability, and energy independence. The pursuit of EE has recently grown due to increasing industry concerns about the environmental impacts of energy consumption. In this context, there are aspects related to EE that can guide organizations toward sustainable production: the economic aspect, directly linked to energy resources and costs, including the cost of treating pollutant emissions; the environmental aspect related to pollutant emissions; and the social aspect that connects energy consumption with employability and the energy security policies of the community in which it operates (Fenerich et al. 2023).

The adoption of EE practices can help reduce the threat of global warming (Brunke, Johansson, & Thollander, 2014). According to Patterson (1996), EE involves minimizing the use of inputs (energy) while producing the same amount of products or services, with the primary function of avoiding the need for new energy sources, contributing to loss reduction, rational energy use, and increased sustainability.

In addition to economic benefits in the use of EE practices in industries, related to the reduction of energy costs, there are also social and environmental benefits (Guedes, Fenerich, & de Oliveira, 2025). Social benefits arise from EE making energy more accessible to the population, due to lower prices, as well as investments in technologies creating jobs, thereby enhancing overall economic and societal development. In terms of environmental benefits, EE enables a reduction in energy use and decreases emissions of energy-related pollutants. Moreover, organizations with lower energy consumption present a greener image, which can influence market competitiveness among environmentally and sustainability-conscious consumers (Kamal, Al-Ghamdi, & Koc, 2019).

¹Universidade Tecnológica Federal do Paraná – Ponta Grossa, Paraná, Brazil.

*Corresponding author: karolineguedes@alunos.utfpr.edu.br

Gahm et al. (2016) state that the pursuit of this greener image has led industries to reduce energy consumption and improve the input-output ratio (product) of a production process, resulting in improved EE. One instrument that can be used to achieve sustainability is Technology Transfer (TT), a process in which resources are transferred from one organization to another in pursuit of technological development (Silva, Kovaleski, & Pagani, 2022).

Despite energy management systems presenting sustainable practices in industries, there is still a lack of models that feature TT as a practice for the proper performance of EE. According to Hutchins, Robinson, and Dornfeld (2013), industries often face challenges in measuring the economic, environmental, and social impacts associated with their activities and processes. Therefore, the need for industries to be more sustainable has stimulated the interest of policy developers and decision-makers because, even when sustainability is included in the company's strategy, current production methods cannot be considered sustainable, necessitating significant changes at the organizational, behavioral, technological, and managerial levels (Neri et al., 2018).

Trianni, Cagno, and Neri (2017) point out that, to improve sustainability in industries, effective measures need to be implemented, such as the application of EE practices alongside sustainable practices. A TT tool that aids in achieving sustainability through the application of EE practices in an industrial environment can guide efforts and benefit decision-making, making it more accurate, especially in the era of Industry 4.0.

The primary motivation for TT for this purpose lies in achieving sustainability through the implementation of EE practices. Furthermore, this achievement must be evaluated and examined concerning its short to long-term effects on society, the economy, and the environment (Abu-Rayash & Dincer, 2019). Therefore, this article will focus on industrial activities and will specifically address technology transfer for the implementation of EE practices, and aims to develop a systematic review using the *Methodi Ordinatio* methodology, looking for building the portfolio of articles on the topic, in an effort to answer: How does TT contribute to the implementation of EE practices in industrial activities, and what are the impacts of this implementation on environmental, economic, and social sustainability?

Literature Review

Technology Transfer

According to Silva, Kovaleski, and Pagani (2019), Technology Transfer (TT) is understood as a flow of propagation or preservation of applicable technologies, knowledge, and/or outcomes of their implementation, resulting in the creation of products or other elements shared among participants, which can be companies, individuals, organizations, or entities. According to authors Ismail, Hamzah, and Bebenroth (2018), it is the process of disseminating technologies from their place of origin to a broader audience and diverse locations, shaped by the characteristics of information, which encompasses knowledge and technology.

The importance of TT, especially concerning sustainable development, can have impacts at the socio-economic, environmental, organizational, and political levels (Corsi, Kovaleski, & Pagani, 2021). The incorporation of new technologies demands increasing attention from industries to human factors, as these continue to play a crucial role in operational systems (Silva, Kovaleski, & Pagani, 2019). Organizations must recognize the values associated with human aspects and technological innovations (Pagani et al., 2016).

The development of new competencies becomes essential for both employees and managers, constituting a critical element for success in implementing new Technologies (Corsi et al. 2020). Additionally, effective knowledge transfer becomes crucial given the growing complexity in both technological and organizational aspects. In this scenario, it becomes imperative to provide training courses to empower employees with the necessary skills and competencies (Cannavacciuolo et al. 2023).

According to Barbieri et al. (2023), given the scale and complexity of TT in both sustainable and non-sustainable industries, it is necessary to address the local specificities present in different regions and cities. It is evident that not all territories demonstrate the same level of proactivity, nor do they possess an equal ability to adapt to new technologies and new criteria of environmental sustainability, which often require a significant reconfiguration of production and consumption activities.

In addition to TT, attention to Anthropotechnology is crucial. According to Corsi et al. (2021), through anthropotechnology, certain barriers such as human and adaptability issues can be anticipated and addressed, enabling effective TT. Furthermore, it yields social benefits by facilitating technological development for the population receiving the technology. TT, in turn, is a means of implementing sustainable development, promoting beneficial outcomes not only for the economic realm but also for the environmental and social aspects (Kovaleski, Picinin, & Kovaleski, 2022).

Sustainable development gains significance in this scenario due to the need for sustainable technologies that not only enhance the quality of life for the population but also drive technological and economic progress, taking into account environmental benefits and impacts. The effective transfer of technology aimed at sustainable development promises to bring substantial gains across the three pillars of sustainability (Corsi, Kovaleski, & Pagani, 2021).

Energy Efficiency

The definition of Energy Efficiency (EE) is essentially achieving the same or more using the same amount of resources, aiming to streamline processes and enhance the quality of production operations. ISO 50001, in its initial version, defined EE as "the quantitative relationship between performance output, services, products, or energy and input energy" (Brazilian Association of Technical Standards, 2011).

However, for the implementation of EE practices in industries, it involves analyzing the costs, benefits, incentives, and potential barriers

to this implementation (Guedes, Fenerich, & de Oliveira, 2025). According to Kamal, Al-Ghamdi, and Koc (2019), the application of EE practices yields benefits at economic, environmental, and social levels.

In terms of economic benefits, there is the development of energy generation systems that reduce the cost of purchasing energy and alleviate the need for the creation of new energy transmission and distribution systems. Furthermore, EE reduces the cost of purchasing energy and brings economic benefits such as an increase in the industry's asset value and equipment, energy savings, tax payment savings, increased productivity and yields, improvement in energy infrastructure, energy security, and an increase in the country's GDP. Therefore, EE cannot be merely considered an energy issue but rather an economically fundamental matter (Kamal; Al-Ghamdi; Koc, 2019).

Regarding social benefits, there is a reduction in deaths related to increased comfort, health, and well-being of individuals, leading to reduced health expenditures and lost workforce due to primarily respiratory diseases. Additionally, social benefits include the generation of direct and indirect employment, increased access to energy for the population, and financial savings, which can contribute to building a more extensive energy distribution infrastructure. Such benefits aid in the development of society and the economy, providing competitive advantages to industries through the sustainable image they convey (Kamal; Al-Ghamdi; Koc, 2019).

Methodology

The procedures described here were utilized for searching, selecting, and reading articles. For the systematic review with articles aiming to develop a bibliographic portfolio on the topic of Technology Transfer and Energy Efficiency, the Methodi Ordinatio 2.0 methodology was employed, and the steps are presented in Table 1.

Table 1: Methodological procedures

Theoretical Background	Technology Transfer	
	Energy Efficiency	
Methodological Procedures of Methodi Ordinatio 2.0	Step 1	Set the research intent
	Step 2	Do a preliminary search and find the related words
	Step 3	Define keywords, databases and temporal delimitation
	Step 4	Definitive search in databases
	Step 5	Filtering procedures
	Step 6	Identification of impact factor, year of publication and number of citations
	Step 7	Use the inordinatio
	Step 8	Finding texts in full format
	Step 9	Systematic reading and analysis of articles

Note: Adapted from Pagani et al. (2023).

To relate the themes of Technology Transfer and Energy Efficiency, a Systematic Review was conducted, resulting in a portfolio of relevant scientific articles that will serve as a data source for the topic. For the construction of the article portfolio, the Methodi Ordinatio 2.0 methodology was employed (Pagani; Kovaleski; & Resende, 2015; 2017; Pagani et al., 2023). The methodology is considered a multicriteria decision-making tool, as it ranks articles in scientific journals based on three criteria: year of publication, impact factor, and citation number, determining their relevance (Corsi; Kovaleski; & Pagani, 2021).

The first step in applying the Methodi Ordinatio 2.0 methodology was to define the research intent. Thus, in this work, the research intent is to build a bibliographic portfolio of scientific articles on the to-

pic of Technology Transfer and Energy Efficiency. After a preliminary search, the terms to be used were also defined, along with their combinations to obtain satisfactory results. This included selecting databases with higher returns and, finally, conducting the search in the chosen databases.

During this stage, reference manager JabRef was used, and, additionally, the databases Science Direct, Scopus, and Web of Science were defined, and the keyword combinations, as well as the selected databases and the search results, are presented in Table 2. Due to the combinations: “anthropotechnology” AND “energy efficiency” and “anthropotechnology” AND (“technology transfer” OR “knowledge transfer”) AND “energy efficiency” returning no results, the term “anthropotechnology” was searched alone.

Table 2: Search in databases

Keywords Combination	Scopus	Science Direct	Web of Science
("technology transfer" OR "knowledge transfer") AND "energy efficiency"	340	50	104
"anthropotechnology" AND "energy efficiency"	0	0	0
"anthropotechnology" AND ("technology transfer" OR "knowledge transfer") AND "energy efficiency"	0	0	0
"anthropotechnology"	26	0	15
Total	535		

Note: Created by the author.

After conducting the search in the databases, which resulted in an initial portfolio comprising 535 articles, filtering procedures were initiated to exclude duplicate articles, those not aligned with the theme, and articles from conferences, books, and book chapters. Moreover, the InOrdinatio equation was used to define the portfolio of articles to be read, taking into account the main criteria for selecting an article related to a topic: year of publication, number of citations, and the impact factor (or journal metrics). After collecting the variables, the InOrdinatio Equation (1) was applied, resulting in an ordered portfolio of scientific articles, according to scientific relevance.

$$InOrdinatio = \left(\frac{IF}{1000}\right) + \alpha * [10 - (Research\ Year - Publish\ Year)] + (CI) \quad (1)$$

The criteria used by the equation are: IF (impact factor - a value of zero was assigned to journals with an unavailable IF value); α (alpha value, ranging from 1 to 10, to be defined by the researcher according to the importance of the novelty of the topic; for this study, the value of α was set to 10, as the topic is the subject of study in very recent articles); ResearchYear (the year the research was developed); PublishYear (the year the article was published); and Ci (the number of times the article was cited - was collected from the Google Scholar platform).

A Methodi Ordinatio 2.0 is a methodology that facilitates the researcher's work by constructing a portfolio of ordered articles, allowing the selection and prioritization of the articles (Pagani; Kovaleski; & Resende, 2015; 2017; Pagani et al., 2023). This functionality helps reduce long portfolios to more compact ones, while still maintaining scientific influence on the topic, as it allows for the selection and prioritization of the most impactful articles.

After applying Equation (1), the articles were ranked according to their scores, and another exclusion criterion was applied: only the top 50 articles with the highest InOrdinatio value would make up the final portfolio, as the number of articles in the portfolio was high. Thus, the final portfolio, ordered by scientific relevance, was composed of 50 articles, as shown in Table 6 (Appendix). The obtained results of the filtering procedures are presented in Table 3.

Table 3: Filtering procedures

Filtering Procedures	Deleted Articles
Duplicate papers deleted	132
Deletion of articles outside the theme	121
Exclusion by document type (conference paper; book and book chapter)	49
InOrdinatio	183
The resulting number of articles in the portfolio	50

Note: Created by the author.

The 50 articles ordered in the previous step were found in their full version, allowing the start of the final stage of systematic collection and analysis of the articles. Finally, a bibliometric analysis of the portfolio was conducted using the VOSviewer software, identifying the key authors and main keywords, along with systematic readings of the articles to understand the relationship between the topics of Technology Transfer and Energy Efficiency.

Results and Discussion

Bibliometric Analysis

After the filtering procedures, more than 90% of the articles were eliminated. The first bibliometric analysis examined the distribution of the portfolio's articles over the years. Publications on the topics of Technology Transfer and Energy Efficiency have occurred on the same platforms over the years, but with a significant increase in 2020, showing a growth trend. The last five years accounted for 26 articles in the portfolio, representing over 50% of the total, indicates that the topic is experiencing growing scientific interest, justifying the development of this article, as shown in Figure 2.

Figure 3 presented shows the most frequently used keywords over the years. The words in shades of blue correspond to older articles, while the terms in green, transitioning to yellow, represent more recent publications. It is also evident that the most frequent keyword is “energy efficiency,” followed by “technology transfer,” which are the main topics of this research. Additionally, emerging themes in the field are related to “barriers,” “sustainability,” “facilitators,” and “decision-makers.”

Content Analysis

After identifying the key authors and emerging topics in the portfolio articles, full readings of the texts were conducted for the content analysis phase. From this reading, it is possible to understand how Technology Transfer is applied in the implementation of Energy Efficiency in industries. Based on the content analysis, it was possible to develop a set of practices for using Technology Transfer in the implementation of Energy Efficiency in an industry, as shown in Table 4.

Table 4: Focus of the Articles

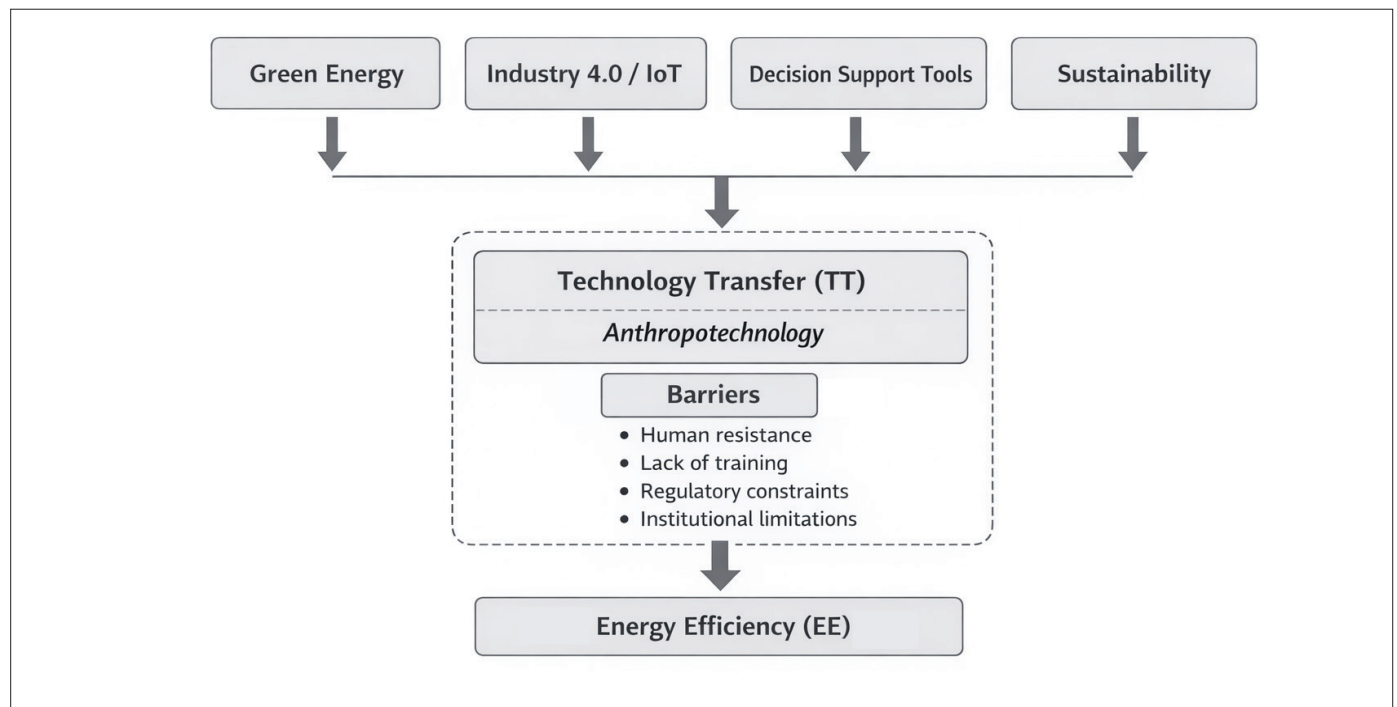
Focus	Autores
Green Energy	Ahmad et al. (2024); Ghorbani et al. (2024); Ghouchani et al. (2021); Njoh (2021); Pang, Deng and Hu (2015); Rani et al. (2024); Sarkodie and Strezov (2019).
Industry 4.0	Huang, He and Su (2024); Lai et al. (2024); Wang, Shang and Lei (2023).
Sustainability	Amaral et al. (2023); Bogaerts et al. (2022); Cui et al. (2020); Decuyper et al. (2022); Durán-Romero et al. (2020); Fořt and Černý (2022); Gutiérrez-Sánchez et al. (2022); Johansen and Werner (2022); Khosla et al. (2021); Martinot, Sinton and Haddad (1997); Jebli and Youssef (2015); Popp (2011); Valenti, Valenti and Staboli (2019); Wang et al. (2020); Yin and Li (2018); Zou and Alam (2020).
Decision Support Tool	Arroyo et al. (2016); Bartiaux et al. (2014); Benedetti, Giordano and Salvio (2022); Chai and Baudelaire (2015); Shove (1998); Ghadaksaz and Saboohi (2020); Hasanbeigi and Price (2012); Luna-Navarro et al. (2020); Ouyang et al. (2018); Salvia et al. (2021); Schlomann and Schleich (2015); Sola and Mota (2020); Stieß and Dunkelberg (2013); Tseng et al. (2017); Wohlfarth et al. (2017); Yin and Li (2018); Wan, Baylis and Mulder (2015).

Note: Created by the author.

To synthesize the literature reviewed in Table 3, Figure 4 presents a conceptual framework in which Technology Transfer for Energy Efficiency emerges from the interaction between Green Energy, Internet

of Things, Sustainability, and Decision Support Tools, while being constrained by financial, regulatory, and organizational barriers.

Figure 4: Conceptual framework of Technology Transfer for Energy Efficiency



Source: (Author, 2026).

Figure 4 presents a conceptual framework that synthesizes the findings of the systematic review. The framework illustrates TT as a dynamic process driving EE through the integration of Green Energy solutions, Industry 4.0 and IoT technologies, Sustainability principles, and Decision Support Tools. The model explicitly incorporates structural, institutional, and human barriers, highlighting anthropotechnology as a transversal element that enables adaptation, learning, and effective assimilation of transferred technologies.

Several studies have addressed TT and Knowledge Transfer KT as strategic mechanisms supporting the implementation of EE across multiple sectors. As illustrated in the proposed conceptual framework, TT for EE emerges from the interaction among Green Energy, Internet of Things (IoT) - Industry 4.0, Sustainability, and Decision Support Tools, while being constrained by structural and institutional barriers.

In the context of green energy, Ghorbani et al. (2024) discuss best practices for the transition to renewable sources, emphasizing that effective knowledge and technology transfer is essential to expand renewable energy adoption, enhance EE, and reduce carbon emissions. Similarly, Ahmad et al. (2024) propose TT models for clean energy production in industrial environments, demonstrating how structured transfer mechanisms can directly improve energy efficiency outcomes. From an industrial perspective, Rani et al. (2024) analyze the transfer of technologies from laboratory to industrial scale using green fuels, reinforcing the role of TT in scaling EE solutions in the era of Industry 4.0.

The contribution of the Industry 4.0, IoT and smart technologies to EE is highlighted by several authors. Lai et al. (2024) demonstrate how the optimization of wireless sensor networks can be enhanced through the transfer of knowledge from previous projects, leading to improved energy performance. Huang, He, and Su (2024) focus on real-time knowledge transfer to optimize energy consumption in urban transport vehicles, aiming to increase EE in the mobility sector. Likewise, Wang, Shang, and Lei (2023) apply knowledge transfer principles to algorithmic optimization of resource allocation, contributing to improved EE and grid stability.

From a sustainability and collaboration perspective, Amaral et al. (2023) emphasize inter-university cooperation as a vector for promoting EE through knowledge exchange. Johansen and Werner (2022) also underline the importance of collaborative knowledge transfer in improving efficiency in district heating systems in Denmark. These studies reinforce the framework's sustainability dimension, showing that long-term EE impacts depend on institutional cooperation and shared learning processes.

However, several studies also identify barriers to technology transfer, which are explicitly incorporated into the conceptual model. Decuyper et al. (2022) discuss the challenges faced by intermediaries in implementing heat pumps for residential EE, highlighting regulatory and institutional constraints. Fořt and Černý (2022) demonstrate how insufficient knowledge transfer can hinder sustainable building retrofits, proposing interdisciplinary cooperation as a solution to

overcome these barriers. In a broader industrial context, Qiu et al. (2022) show that TT can enhance the technological capacity of energy companies, provided that organizational and knowledge-related obstacles are addressed.

The role of decision support tools is also strongly linked to TT for EE. Benedetti, Giordano, and Salvio (2022) focus on heat recovery in textile processes, illustrating how knowledge transfer improves EE in industrial applications. Salvia et al. (2021) present decision-support tools for EE in public buildings, emphasizing capacity building and structured knowledge transfer as critical factors for their effectiveness. Similarly, Luna-Navarro et al. (2020) discuss decision-making processes aimed at making buildings smarter and more energy efficient.

On an international scale, Ghouchani et al. (2021) analyze how TT can enhance Iran's capacity to deploy renewable energy technologies, while Khosla et al. (2021) examine improvements in EE for air-conditioning systems in India. Durán-Romero et al. (2020) propose a circular economy model for sustainable practices, explicitly emphasizing the enabling role of TT. Finally, Wang et al. (2020) and Ghadaksaz and Saboohi (2020) highlight TT as a strategic pathway for reducing greenhouse gas (GHG) emissions while simultaneously improving EE, stressing the importance of international cooperation in deploying clean energy technologies.

An important contribution of this review lies in emphasizing anthropotechnology as a critical enabler of TT for EE. Beyond technical feasibility, the successful implementation of EE solutions depends on workers' skills, behavioral adaptation, organizational culture, and learning processes. Anthropotechnology allows anticipating human-related barriers, facilitating the customization and assimilation of transferred technologies, and reducing resistance to change. This perspective differentiates the present review from purely engineering-oriented studies by positioning EE as a socio-technical process rather than a purely technological outcome (Kovaleski, Picinin, & Kovaleski, 2022).

Overall, the literature demonstrates that Technology and Knowledge Transfer are central enablers of EE, operating across sectors such as industry, buildings, urban mobility, and energy systems. In addition to its theoretical contributions, managerial implications may be relevant for professionals involved in implementing energy efficiency initiatives:

- Managers should invest in continuous training programs focused on energy management and digital competencies to ensure effective absorption of transferred technologies.
- Companies should adopt anthropotechnological approaches when implementing EE solutions, aligning technologies with workers' capabilities, routines, and cultural contexts.
- Strategic partnerships with universities and research centers can accelerate technology transfer and reduce implementation risks.
- Managers should actively engage in policy advocacy to access public incentives and regulatory support for EE and clean technology adoption.

The synthesis of the literature and the proposed conceptual framework demonstrate that the success of TT processes depends not only on technological readiness, but also on managerial decisions related to organizational structure, skills development, and human adaptation. In this sense, managers play a critical role in aligning transferred technologies with operational routines, institutional contexts, and workforce capabilities. The following managerial implications translate the main findings of this review into practical recommendations to support decision-makers in facilitating effective Technology Transfer for Energy Efficiency in industrial environments.

The studies collectively reinforce the proposed conceptual framework, showing that effective TT for EE depends on the integration of technological innovation, sustainability goals, decision-support mechanisms, and collaborative networks among universities, industries, and governments, while actively addressing financial, regulatory, and cultural barriers.

Research Agenda & Future Gaps

Based on the systematic review, several research gaps were identified. While technological solutions for EE are widely explored, limited attention has been given to human adaptation, organizational learning, and anthropotechnological aspects. Table 5 summarizes current knowledge and proposes a structured research agenda to guide future investigations.

Table 5: Research Agenda and Future Gaps in TT for EE

Research Agenda	Research gaps	Suggested future research
IoT applications for energy monitoring	Lack of longitudinal studies	Long-term impacts of IoT-based EE solutions
Technology transfer models	Limited focus on human adaptation	Anthropotechnology-oriented TT frameworks
Policy-driven EE initiatives	Scarce empirical validation	Comparative studies across regions
Decision support tools	Limited integration with social factors	Human-centered Decision Support System for EE decision-making

Note: Created by the author.

The research agenda summarized in Table 4 highlights that, although TT and EE have been extensively explored from a technological and policy-oriented perspective, several critical gaps remain. Current studies predominantly focus on the deployment of digital technologies, such as IoT-based monitoring systems and decision-support tools, as well as on regulatory mechanisms that foster energy-efficient practices (Kornarius et al., 2025). However, these contributions are often limited to short-term assessments and technical performance indicators, overlooking the long-term dynamics of human adaptation and organizational learning.

A major gap identified in the literature concerns the limited incorporation of anthropotechnology as an analytical lens in TT for EE. While technological readiness is frequently addressed, insufficient attention is given to human-centered factors, including workers' skills, resistance to change, training processes, and cultural alignment within organizations. Future research should therefore adopt longitudinal and interdisciplinary approaches to examine how anthropotechnological factors influence the effectiveness, scalability, and sustainability of energy-efficient technologies over time.

Furthermore, there is a lack of comparative empirical studies across regions, industrial sectors, and institutional contexts, particularly in emerging and developing economies. Such studies would contribute to understanding how regulatory environments, institutional capacities, and socio-cultural conditions shape technology transfer outcomes. Integrating qualitative methods with quantitative performance metrics could offer more robust insights into the interaction between technological systems and human behavior.

Finally, future research is encouraged to develop and validate human-centered decision-support frameworks that explicitly integrate anthropotechnological principles into TT processes (Liaudat, Zuckefeld, & Terlizzi, 2025). By bridging technological innovation with social and organizational dimensions, forthcoming studies can provide more comprehensive models for advancing Energy Efficiency and supporting sustainable industrial transitions.

Conclusion

This systematic review provides a comprehensive understanding of how TT serves as a central enabler for EE within the Industry 4.0 era. A primary contribution of this revised draft is the conceptual framework which synthesizes the finding that TT drives EE through the dynamic integration of Green Energy solutions, Industry 4.0 and IoT technologies, Sustainability principles, and Decision Support Tools. This framework explicitly acknowledges that while these elements propel efficiency, the process is simultaneously constrained by financial, regulatory, and organizational barriers.

Central to overcoming these challenges is the critical role of Anthropotechnology, which is presented as a transversal element within the framework. By focusing on human factors such as behavioral adaptation, organizational culture, and learning processes, anthropotechnology allows for the anticipation of human-related barriers. This perspective is vital as it redefines the implementation of EE solutions as a socio-technical process rather than a purely engineering outcome, ensuring that transferred technologies are effectively assimilated and customized to the workforce.

Finally, the study highlights essential managerial implications for practitioners. Success in TT for EE depends not only on technological readiness but on strategic managerial decisions, including investing in continuous training programs, adopting anthropotechnological approaches to align innovations with worker capabilities, and fostering strategic partnerships with universities. Ultimately, achieving global

sustainability goals will depend on the ability of decision-makers to scale these technological solutions through effective, human-centered transfer mechanisms. In summary, the results of this systematic review confirm that TT is an essential factor for the successful implementation of EE in various spheres. The continuous exchange of knowledge, innovation and good practices between stakeholders is essential to achieve global sustainability and energy efficiency goals. The future of energy policies will depend, to a large extent, on the ability to integrate and scale up technological solutions through effective transfer mechanisms.

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Appendix

Table 6: Portfolio

Article	InOrdinatio
Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries	1808,82
Multivariate Granger causality between CO2 emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): Evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries	923,58
The environmental Kuznets curve, economic growth, renewable and non-renewable energy, and trade in Tunisia	790,02
Something is sustainable in the state of Denmark: A review of the Danish district heating sector	553,55
Bridging the gap between circular economy and climate change mitigation policies through eco-innovations and Quintuple Helix Model	513,75
A review of energy use and energy efficiency technologies for the textile industry	480,04
Embracing a diverse approach to a globally inclusive green energy transition: Moving beyond decarbonisation and recognising realistic carbon reduction strategies	406,68
Biohydrogen production through dark fermentation: Recent trends and advances in transition to a circular bioeconomy	373,68
Improving policy making and strategic planning competencies of public authorities in the energy management of municipal public buildings: The PrioritEE toolbox and its application in five mediterranean areas	365,74
Clean energy use and total-factor efficiencies: An international comparison	360,93
A systematic review of environmental determinants of renewable energy performance in Ethiopia: A PESTECH analysis	355,74
Understanding China's carbon dioxide emissions from both production and consumption perspectives	328,21
Adoption of low-cost energy efficiency measures in the tertiary sector - An empirical analysis based on energy survey data	312,75
Objectives, barriers and occasions for energy efficient refurbishment by private homeowners	312,21
Multi-granularity fusion resource allocation algorithm based on dual-attention deep reinforcement learning and lifelong learning architecture in heterogeneous IIoT	301,37
Influencing factors on energy management in industries	299,75
CBR-based negotiation RBAC model for enhancing ubiquitous resources management	297,47
Foreign versus indigenous innovation and energy intensity: Further research across Chinese regions	292,16
Impact of factor price distortions on energy efficiency: Evidence from provincial-level panel data in China	282,29
International Technology Transfer, Climate Change, and the Clean Development Mechanism	246,25
Gaps, barriers and conceptual chasms: theories of technology transfer and energy in buildings	240,97
Occupant-Facade interaction: a review and classification scheme	240,42
Energy-Efficient Scheduling in UAV-Assisted Hierarchical Wireless Sensor Networks	239,68
Regional carbon imbalance within China: An application of the Kaya-Zenga index	234,09
An intelligent full-knowledge transferable collaborative eco-driving framework based on improved soft actor-critic algorithm	222,68
Transitioning to energy efficient housing: Drivers and barriers of intermediaries in heat pump technology	220,05
Limited interdisciplinary knowledge transfer as a missing link for sustainable building retrofits in the residential sector	219,05
Matching management of supply and demand of green building technologies based on a novel matching method with intuitionistic fuzzy sets	218,79
A practice-theory approach to homeowners' energy retrofits in four European areas	214,53
Closing the building energy performance gap through component level analysis and stakeholder collaborations	208,42
How organizational constraints undermine sustainability actions in a university's campuses: A case study	205,37
Choosing by advantages: A case study for selecting an HVAC system for a net zero energy museum	205,16
Developing a perspective on the use of renewable energy in Iran	203,74
Hybrid drying of food and bioproducts: a review	202,74
Understanding the energy efficiency gap in Singapore: A Motivation, Opportunity, and Ability perspective	201,21
Foundations of plasma catalysis for environmental applications	199,05
Engineering Aspects for the Design of a Bicarbonate Zero-Gap Flow Electrolyzer for the Conversion of CO2to Formate	197,55
Energy supply transformation pathways in Iran to reduce GHG emissions in line with the Paris Agreement	197,42

Frontier in dark fermentative biohydrogen production from lignocellulosic biomass: Challenges and future prospects	195,68
Proposal of a thermally-driven air compressor for waste heat recovery	194,96
Impact of inter-sectoral trade on national and global CO2 emissions: An empirical analysis of China and US	189,89
Can CDM projects trigger host countries' innovation in renewable energy? Evidence of firm-level dataset from China	187,42
The obscure link between motorsport and energy efficient, low-carbon innovation: Evidence from the UK and European Union	185,82
Trade-facilitated technology spillovers in energy productivity convergence processes across EU countries	185,30
Technological capabilities development model in Chinese energy service companies	179,05
Learning networks as an enabler for informed decisions to target energy-efficiency potentials in companies	178,58
International technology transfer for climate change mitigation and the cases of Russia and China	175,81
Explorative study on waste heat production intensity and recovery practices in the textile sector: First steps towards the creation of a decision support tool based on real data	171,55
Energy monitoring as a practice: Investigating use of the iMeasure online energy feedback tool	171,25
The what, why, and how of changing cooling energy consumption in India's urban households	170,74

Note: Created by the author.