Productivity Benefits Beyond Energy Savings: An Analysis of Industrial Energy Efficiency Measures and Industry 4.0 Technologies

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Abstract. When energy efficiency measures are applied in industrial enterprises, the implications extend beyond energy savings, generating additional benefits known as productivity benefits. However, there is a knowledge gap concerning experiences in productivity benefits and the extent to which these are recognized by the industry. This study aims to delve into the industrial energy-efficiency measures and productivity benefits, with a specific focus on boiler and steam systems in industrial environments. By exploring the impacts of energy efficiency measures at the operational level, this research aims to provide insights into the broader implications of energy efficiency within industry.

Keywords: Industrial energy efficiency, productivity benefits,

1 Introduction

Accounting for 42% of the world's electricity consumption [1], industry plays a crucial role in decarbonization and creation of a net-zero economy. In particular, increased energy efficiency (EE), in turn, energy efficiency measures (EEMs) – are viewed as the "first fuel" and considered financially viable energy transition way to decarbonization [2]. EE is more important than ever, as the present issues with energy prices and energy security have intertwined with climate as well as geo-political issues. The boiler functions as a critical thermal component, harnessing the power of steam to facilitate essential processes in industries. The boiler plant comprises a substantial portion of a facility's total energy consumption, with the cost of boiler fuel ranking among one of the highest energy expenses. Therefore, even a modest enhancement in the efficiency of the boiler plant and steam system can yield considerable overall savings. Additionally, while the implementation of EEMs in boilers offers significant energy savings, it can also provide additional benefits (e.g. improved equipment performance, reduced maintenance)[3].

Beyond the usual focus on energy savings, studies [3]–[6] have documented few set of benefits, referring to “non-energy benefits (NEBs)” or productivity benefits, stemming from EE. The extent of the productivity benefits can be significant, including a reduction in energy demand by up to 2.5 times [2]. Scholars have delved into the impact of EEMs at operational level beyond energy savings highlighting multiple benefits such as improved maintenance and waste reduction, pointing a correlation involving EE and certain production metrics [6]–[8]. Nonetheless, a broad perspective on productivity benefits at operational level is lacking in these studies.

In a recent time, Cagno et al. [9] discussed the impact of EEM on the company’s operational performance with a shop floor perspective. Similarly, Hasan et al. discussed the implications of energy management services on production resources and productivity features [10]. However, to the best of authors’ knowledge, very little research has been done on industrial EEMs, and productivity benefits inclusively, thus representing a major research gap. Indeed, the lack of a comprehensive consideration for productivity benefits at operational level would represent a major advance to academic knowledge, as it could provide additional insights to support the decision-making process over the adoption of EEMs [10]. Additionally, it would be particularly useful for final users as supporting the uptake of EEMs with beneficial impacts on production activities.

Similarly, the industrial sector is going through a technological transformation recognized as the Fourth Industrial Revolution or Industry 4.0 (I4.0). I4.0 encompasses a suite of technologies, including *Cyber-Physical Systems (CPS)*, the *Internet of Things (IoT)*, *artificial intelligence (AI),* and big data [11]. The advantages of I4.0 technologies extend beyond productivity, and encompasses system innovativeness [11]. While literature extensively confers the implications of I4.0 at the production level, scant attention has been given to the implications of I4.0 technologies on EEMs and their potential to elevate EEMs performance.

Addressing the identified research gaps, this study aims at contributing to academic discourse by highlighting the productivity benefits of industrial EEMs followed by an exploration of the impact of I4.0 technologies on EEMs. By doing this study, we intend to highlight the nexus between EEMs and productivity benefits at the operational level within the shop floor. This study would be beneficial to academics and industrial decision-makers in implementing EEMs throughout industrial organizations. More specifically, the study would assist the decision makers in addressing the improvement opportunities within their respective energy value chains.

2 State of the art

2.1 Energy efficiency measures in boiler and steam

The industrial boiler serves as a critical thermal component, utilizing the power of steam to facilitate essential processes. Its importance lies in the efficient generation of high-pressure steam, which, in turn, propels turbines, energizes machinery, and supports various manufacturing processes. The boiler plant constitutes a significant share of a facility's total energy consumption [12]. Typically, the cost of boiler fuel ranks as one of the largest energy expense for a facility. Consequently, even a modest improvement in the boiler plant's efficiency can result in more substantial overall savings compared to more extensive enhancements in individual energy end-users [13]. Moreover, the majority of boiler plants present notable opportunities for efficiency improvements. Considering these factors, initiating the search for savings in the boiler plant emerges as a strategic starting point.

The US Department of Energy's Industrial Assessment Centre (IAC) provides a detailed list of energy efficiency measures (EEMs) applicable to diverse cross-cutting technologies [14]. For boilers and steam systems, IAC categorizes EEMs into six distinct areas: operation, hardware upgrades, maintenance routines, blowdown optimization, trap efficiency, and condensate recovery. Table 1 presents the EEMs of boiler and steam.

Table 1. EEMs relating to boilers and steam system [14]

Cross Cutting Area	ARC	EEMs	Category	Notation
Boiler	*2.1212*	*Operate boilers on high fire settings*	Operation	EEM 1
Boiler	*2.1221*	*Replace obsolete burners with more efficient ones*	Hardware	EEM 2
Boiler	*2.1232*	*keep boiler tubes clean*	Maintenance	EEM 3
Boiler	*2.1243*	*Use heat from boiler blowdown to preheat boiler feed water*	Blowdown	EEM 4
Steam	*2.2111*	*Install steam trap*	Trap	EEM 5
Steam	*2.2112*	*Use correct size steam traps*	Trap	EEM 6
Steam	*2.2123*	*Insulate feedwater tank*	Condensate	EEM 7
Steam	*2.2162*	*Reduce excess steam bleeding*	Operation	EEM 8

2.2 Non energy benefits/ productivity benefits of EEMs

EE improvements offer additional benefits known as non-energy benefits beyond energy savings. The non-energy benefits are also represented by other terminologies, such as productivity benefits or ancillary savings in industrial context [3], [7]. The benefits form a distinct set of impacts in the industries which are observed in relation to multiple areas (e.g. production, operation & maintenance, waste & emissions).

Improved productivity, equipment's lifetime extension, air quality improvement, and waste reduction are examples of commonly observed productivity benefits in industrial contexts [3].

In this study, we have considered the productivity benefits into overall equipment effectiveness (OEE), labor effectiveness, operation times, throughput, resource utilization, process efficiency and quality, reliability, flexibility, production speed, operation cost, and inventory. Table 2 presents the productivity benefits based on relevant studies.

Table 2. Productivity benefits of industrial EEMs

Attribute	Remark	Notation
Overall equipment effectiveness	A metric used in manufacturing and production industries to review the effectiveness and performance of equipment or a production process. OEE is calculated by multiplying three factors: Availability, Performance, and Quality.	OEE
Labour effectiveness	Refers to the measurement of how efficiently labour resources are utilized in a given production environment.	LE
Operation time	Refers to the duration during which a machine, equipment, production process, or system is actively engaged in performing its intended functions. It is a combination of setup time and run time.	OT
Throughput	Refers to the rate at which a process produces its output or the amount of material or product that passes through a system within a specified period of time	T
Reliability	Denotes to a system whether it can operate as designed and planned	R
Resource utilization	Refers to efficient and effective deployment of production resources to achieve optimal outcomes in a process.	RU
Flexibility	Operational scheme that indicates the speediness in reaction towards any deviation in production system	FLX
Production speed	Ratio of flow time and value-added time in industrial system	PS
Operation cost	Refers to the ongoing expenditure for day-to-day operation within the business.	OC
Occupational health and safety	Occupational Health and Safety, is a field dedicated to safeguarding the well-being of individuals in the workplace by identifying and mitigating hazards to prevent injuries and promote overall health.	OHS
Waste and emission	Waste refers to unwanted byproducts or materials, while emissions encompass the release of pollutants into the air or water during manufacturing processes	WE

3 Impact of EEMs at productivity level

3.1 Theoretical framework showing the impact of EEM

EEMs wield a significant impact on production performance across diverse industries, as discussed by prior studies [9], [10]. Nonetheless, scholars have argued that the influence of EEMs on production performance is not uniform across all aspects. The impact varies, with some aspects experiencing tangible benefits while others may not be as affected. Similarly, researchers emphasize that the integration of I4.0 technologies enhances the operational performance of EEMs [15], [16]. However, the impact of I4.0 on EEMs also vary depending on I4.0 technology set and type of EEM. Scholars also underscore the complex relationship between specific I4.0 technologies and their influence on EEM and production processes [16]. Understanding these distinctions is crucial for implementing tailored and effective strategies in optimizing both energy efficiency and production performance.

This study leverages on the theoretical framework developed by Hasan and Trianni [15] A correlation matrix has been then specifically developed based on the EEMs associated to the boiler system, steam, and selected productivity attributes within the operational context (see Fig. 1). This matrix illustrates the implications of corresponding EEMs on the operational level, and the identified productivity attributes are then evaluated based on direct and indirect impacts of these measures. The relationships are supported by qualitative information and graded as yes, no, or not applicable.

Notation	OEE	LE	OT	T	R	RU	FLX	PS	OC	OHS	W&E
EEM 1	Y	N/A	Y	Y	Y	Y	Y	Y	Y	N/A	Y
EEM 2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
EEM 3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
EEM 4	N/A	N/A	Y	N/A	Y	Y	N/A	N/A	Y	N/A	Y
EEM 5	Y	N/A	Y	Y	Y	Y	N/A	N/A	Y	N/A	Y
EEM 6	Y	N/A	Y	Y	Y	Y	N/A	N/A	Y	N/A	Y
EEM 7	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	N/A	Y
EEM 8	Y	Y	Y	N/A	Y	Y	Y	N/A	Y	N/A	Y

*Legend: Yes (Y); No (N); Not available (N/A)

Fig. 1. Matrix showing the impact of EEMs at operational level

While the primary aim of implementing EEMs is to enhance industrial energy efficiency, their impact extends beyond energy cost savings, encompassing various productivity benefits within the industrial environment. A comprehensive review of scientific and industrial literature has identified these productivity benefits in the context of boilers and steam. This approach aims to offer a more systematic perspective, facilitating improved comprehension.

Importantly, this study does not explicitly determine whether an implication is positive or negative but provides an indication of the impact. For instance, operating boilers at high fire settings (EEM1) enhances boiler performance, improves operation time, and enhances resource utilization [13]. Similarly, while setting up boilers at high fire settings, it may lead to increased production of ash or other combustion byproducts. Besides, if the combustion process is not optimized, it may result in the generation of waste in form of unburnt fuel or incomplete combustion products [13]. Additionally, considering steam, the insulation of the feedwater tank affects equipment performance, resource utilization, and operational cost [13]. Therefore, this matrix aids decision-makers in assessing the impact of EEMs beyond energy savings, particularly at the productivity level within an operational context.

3.2 Case study

The following section illustrates the real-world application placing particular emphasis on industrial boilers and steam system. It highlights the impact of EEMs on operational performance, taking into account selected I4.0 technologies while considering the associated productivity benefits. A textile manufacturing company located in Bangladesh is selected for this study. The textile plant has been manufacturing sportswear since 2008. While discussing the EEMs, it is observed that the plant has applied 5 EEMs in the boiler and steam system (see Fig. 2). Within this sector, significant applications of boiler systems and steam are evident in processes such as dyeing, finishing, and fabric setting. In the textile industry, the Firetube FTXL Boilers are used in producing steam for various applications.

The operational strategy of running boilers on high fire settings (EEM1) is a subject that merits consideration in the industrial system. Literature argues that it enhances boiler performance and efficiency by maximizing the combustion process. The operations manager acknowledges that operating boilers at high fire settings is often seen as a means to match increased demand for steam, offering a quick and responsive solution to fluctuations in production requirements. However, it is crucial to acknowledge that this strategy has its nuances and potential challenges. Critics highlight that sustained high-fire operation may result in accelerated wear and tear on boiler components, potentially reducing the overall lifespan of the equipment [13], as acknowledged by the plant manager. Moreover, the increased combustion intensity has led to higher emissions in the plant (see Fig. 2). When it comes to integrating I4.0 in the plant, the plant manager acknowledges the application of CPS, in particular, sensors leveraging AI in the boiler system since the year 2021. While these sensors and AI algorithms undeniably contribute to enhanced monitoring of the boiler's performance, the underlying EEM1 itself has an inherent negative impact on equipment lifetime and emission levels.

Similarly, the plant manager acknowledged that the maintenance team cleans the boiler tubes (EEM3) in the interval of six months to prevent the buildup of deposits like scale and soot on the tubes. By maintaining the cleanliness of the boiler tubes, the plant aims to optimize heat transfer efficiency, directly contributing to heightened energy efficiency in the overall system. The manager emphasizes that EEM3 not only extends the lifespan of critical components but also minimizes the likelihood of unscheduled downtimes, thereby enhancing operational reliability (see Fig. 2). While looking at I4.0 technologies, sensors are playing very effective role for EEM3. For instance, sensors equipped with advanced monitoring capabilities are detecting the buildup of deposits such as scale and soot in real-time. As outlined by plant manager, this capability enables proactive and targeted cleaning measures, optimizing the efficiency of the boiler system and ensuring peak performance, minimizing downtime and ensuring overall reliability [12].

Literature extensively discusses the advantages of utilizing heat from boiler blowdown to pre-heat boiler feed water (EEM4), a practice that prevents the need for heating water from its normal temperature and enhances energy efficiency within the system [13]. Interestingly, EEM4 has demonstrated a tangible impact on energy costs, leading to a specific 6% and 6.3% reduction in the energy bill in the years 2022 and 2023, respectively.. Furthermore, the application of this EEM in the plant underscores its ability to enhance resource utilization by efficiently capturing and repurposing thermal energy that would otherwise be wasted. Moreover, the adoption of this EEM leads to a reduction in waste and emissions, aligning with environmentally conscious practices in the plant.

Industry 4.0	Notation	OEE	LE	OT	T	R	RU	FLX	PS	OC	OHS	W&E
Sensors, AI	EEM 1	- / -		+/++					+/++			- / -
Sensors	EEM 3	+/++				+/++	+/++			+/++	+/++	+/++
Sensors	EEM 4	+/++					+/++			+/+++		
	EEM 7			+			+			+		
Sensors, AI	EEM 8	+/+++				+/++		+/++				+/+++

Note: First part shows the impact of EEM without I4.0 technology; second part shows the impact of EEM with consideration of I4.0technology; positive impact (+); negative impact (-).

Fig. 2. Productivity benefits stemming from EEMs

The plant has implemented a practice of insulating the feedwater tank (EEM7) since 2018. By doing so, the plant aims to optimize the performance of the boiler system, as the insulated feedwater tank reduces the energy required for reheating before entering the boiler. Alternatively, the operation manager acknowledges that reducing excess steam bleeding (EEM8) is applied to conserve energy in the steam system. It serves as a systematic response to variations in steam demand, aligning with resource management. This EEM contributes to prolonged equipment life, reducing wear and tear, as acknowledged by the plant manager. While discussing I4.0 for EEM8, sensors and AI algorithms are applied in the plant that analyze historical steam consumption patterns, production schedules, and other relevant data to dynamically adjust the steam bleeding rate. By intelligently adapting to fluctuating demand, AI-driven systems ensure that steam is supplied precisely when needed, avoiding unnecessary wastage. However, the plant manager emphasizes the need for careful monitoring to prevent adverse effects on system stability when reducing excess steam bleeding.

4 Concluding discussion

This research adopts an approach aimed at interpreting the productivity benefits derived from implementing industrial EEMs at the operational level. Drawing insights from literature and case studies, the study sheds light on the multiple impacts of EEMs, extending beyond mere energy savings to encompass various operational aspects. This study is pioneering in its empirical exploration of the impact of EEMs on production performance and the subsequent modification of this impact by I4.0 technologies. Unlike previous studies, which lacked empirical evidence in this domain, our study provides critical insights about EEMs, I4.0 technologies, and productivity benefits. The empirical findings are particularly crucial for industrial decision-makers as it contributes to a more informed decision-making process in industrial settings.

An important phase in this study involved identifying EEMs and relevant I4.0 technologies. To achieve this, first two cross cutting technical domains—boiler systems and steam—were specifically chosen. Second, relevant I4.0 technologies are investigated keeping focus about the EEMs. The rationale for focusing on boiler systems and steam emanates from their substantial role as energy-intensive components in industrial settings. The examination of EEMs and I4.0 technologies within these domains revealed a spectrum of impacts at the operational level. Some effects were directly linked to individual equipment, while others addressed aspects such as resource utilization and organizational considerations inherent in industrial environments.

For instance, when considering the implementation of EEM1 (operate boiler on high fire settings), it becomes evident that this practice exerts a substantial influence on equipment. Interestingly, our observations reveal a notable negative impact of this EEM on equipment performance. The intensified combustion process associated with operating boilers on high fire settings may lead to increased wear and tear on critical components, potentially compromising the overall efficiency and longevity of the equipment. Furthermore, it is intriguing to note that the negative repercussions extend beyond equipment performance. Our analysis indicates an adverse effect on waste and emission management. The increased combustion intensity not only contributes to increased waste generation but also leads to a rise in emissions, potentially impacting the environmental footprint of the industrial operation.

Notably, each EEM contributes to productivity benefits in diverse ways. Again, when it comes to I4.0 technologies, the ability to translate operational data into actionable intelligence has notably improved performance in industrial plants, driven by a data-driven approach. While acknowledging the positive impact on EE and operational activities offered by I4.0 technologies, challenges persist in identifying the most suitable I4.0 technology, contingent on specific application needs. While previous studies primarily focused on the impact of I4.0 on production level, the discourse on the explicit productivity benefits of EEMs integrating I4.0 technologies have been relatively understated in literature. A methodological examination, however, unveils the substantial productivity advantages offered by EEMs and I4.0. Therefore, it becomes crucial to broaden the scope of assessing and evaluating EEMs and I4.0 at the operational level, acknowledging their benefits at operational level.

As this study serves as an initial exploration, recognizing the importance for further research in this domain, it empirically illustrates significant impacts of EEMs and I4.0 technologies that reach beyond energy savings to encompass other crucial operational facts, including OEE, labor effectiveness, resource utilization, reliability, operational cost, flexibility, OHS, and waste & emission. Besides, this study contributes to the discourse on industrial EE and I4.0 barriers, introducing a different perspective that diverges from previous studies [1], [17]. Unlike prior studies focused solely on outlining barriers, particularly in process-related decisions, this research encourages companies to broaden their conceptual framework during EEMs and I4.0 technology implementation. By integrating productivity benefits at the operational level, it promotes a crucial paradigm shift that underscores the importance of a holistic understanding of the EEM-I4.0 productivity relationship, marking a significant yet preliminary step in advancing knowledge in the field.

While this study provides an initial overview, its extension to other cross-cutting technical sectors should be integrated in the future study. Additionally, future study should integrate operational performance metrics more comprehensively for a detailed visualization of EEMs on the shop floor. Although this paper represents an initial effort in outlining the nexus between EEMs, I4.0 and productivity attributes, it contributes to enhancing the industrial decision-making process. By adopting a practice-based perspective, it facilitates more efficient management of production-related activities from a resource allocation standpoint.

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