

Energy Management in Sustainable Smart Manufacturing

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ABSTRACT

Total Equipment Sustainability (TES) is a novel model to address the current challenge of a distinct lack of a comprehensive framework for measuring equipment sustainability. It comprises all potential aspects of equipment, manufacturing processes, energy and environment. It provides a sound perspective on improvement to sustainability and can be used as a benchmark and tool to promote energy and environmental awareness in the factory.

Industry 4.0 can offer many essential opportunities to advance energy efficiency and sustainability of manufacturing in smart factories. This paper investigates these benefits and suggests a novel and enabling architecture to measure and improve all technical dimensions of equipment sustainability. The architecture involves an integrated, intelligent and dynamic network based on Industry 4.0 and facilitates TES implementation.

TES applies a structured data framework within smart factories derived from Cyber-Physical Systems, Internet of Things and the cloud computing to facilitate the measure of how efficiently equipment consumes energy and contributes to sustainability compared to its full potential. It shows how much equipment is environment friendly.

TES covers both features of energy and environment and considers energy losses, thermodynamic efficiency, renewables, greenhouse gas emissions, recyclables and water use for the entire life cycle of all products and machines.

International trade of industrial products creates a global flow of virtual energy, gas emissions and water. Applying TES in smart factories makes this concept clearer and implies concern for the reasonable sharing of the costs and benefits of the flow and participatory attitudes to develop sustainable policies and effective strategies.

Keywords: Sustainability, Energy Management, Equipment, Manufacturing, Industry 4.0, Smart Factory



1. INTRODUCTION

Energy efficiency offers substantial advantages to society and industry via reducing carbon footprint, helping to protect the environment and improving energy security and sustainability. It saves money on fuel bills and enhances growth and creates jobs in the economy.

The manufacturing segment is a main contributor to energy consumption and related GHG emissions. Globally, manufacturing accounts for about 33 percent of energy consumption and about 38 percent of energy and process related GHG emissions [1]. Almost 80% of these emissions is from energy use and energy efficiency is possibly the most significant and economical ways for mitigating GHG emissions from industry [2]. There are various concerns about the different aspects of energy such as security of supply, socio-economic outcomes of the energy mixes, business development, and job creation [3] which are particularly apply to manufacturing as well. Manufacturing has a lot of potential to further decrease energy use, GHG emissions and address the above concerns.

A report in 2018 summarized lessons from the UK Climate Change Act 2008, after 10 years, for the UK and other countries on how climate change legislation could be more effective. According to the report, the Act should be more policy prescriptive, for instance by integrating sharper sector targets. Firmer tests are expected as there is concern that the gap is extending between the emissions targets set in law and the guidelines established to deliver them [4].

There have been many research projects and improvement arrangements to tackle this major sustainability challenge and the hope is to achieve 100% renewable energy as a long-term solution. However, realizing this hope with reasonable cost requires more research and advances in energy developments, energy storage systems, circular economy, environmental issues and others [5].

Current approaches of manufacturing are unsustainable and considerable technological, managerial, organizational and behavioral changes are required to make them more sustainable [6]. Total production costs can be improved by 10-20% via optimal energy management in the manufacturing industry [7]. Many industrial companies still lack proper techniques to effectively deal with energy inefficiency [8]. Boosting energy efficiency is one of the top priorities of the EU energy strategy, and manufacturing is one of the sectors with significant potential to improve energy efficiency [9].

Despite key progress in sustainable energy and environmental protection, more research and developments are needed to achieve the target of sustainability in terms of renewable energy with reasonable cost, not just in the developed countries but with most of the developing countries as well [10]. It is a critical challenge to achieve a sustainable development in terms of energy, however, there are many concerns in terms of sustainable supplying and using materials and fresh water as well [11]. There is a substantial potential for improving energy efficiency in industry [12] and the priority should be assigned to energy efficiency and renewable energies in the future agenda of the global industrial sector [13]. There is an essential need to develop new broader models to fill the gap and cover all major dimensions of sustainability for equipment and plants.



On the other hand, the fast ever-increasing global competition that most manufacturing companies have been facing over recent years is associated with rapid technological changes. Industry 4.0 has been considered to be a new industrial stage in which several emerging technologies provide digital solutions. It involves a very complicated technology structure of the manufacturing systems, which is one of the key concerns and the effective realization of Industry 4.0 technologies is still a subject of research [14].

Industry 4.0 brings various advantages for decreasing energy consumption and these potentials will assist considerably in reducing both GHG emissions and manufacturing costs [15]. The development towards Industry 4.0 provides major opportunities for achieving sustainable manufacturing [16]. How can Industry 4.0 help to deploy a novel and comprehensive model to measure and improve equipment sustainability? The following sections will suggest a model and then will address this critical question.

2. BACKGROUND TO PROBLEM

The 2015 edition of Energy Technology Perspectives (ETP 2015) illustrates the crucial function of recognising regulatory strategies and co-operative frameworks to improve innovation in fields like variable renewables and carbon capture. It shows that efforts to decarbonise the worldwide energy sector are lagging further behind for that year. ETP 2015 concentrates on setting out pathways to a sustainable energy future and integrating detailed and clear quantitative modelling analysis. Energy decarbonisation is under way but needs to be improved and recent trends confirm the need to speed up energy technology innovation, in part through policy support and new market frames [17].

The UK Climate Change Act 2008 commits the UK government by law to decreasing GHG emissions by at least 80% by 2050 compared with 1990 levels [18]. The UK industrial sector accounts for about 21% of whole delivered energy and 29% of CO2 emissions. Although major improvements have been in the energy intensity of manufacturing (defined as energy use per unit of economic output), significant decreases in GHG emissions are still required [19].

There is an essential need to develop a comprehensive model to address all major dimensions of sustainable manufacturing. Current models for measuring equipment energy effectiveness or its level of sustainability concentrate on factors derived either from equipment or from manufacturing surroundings. The models that reflect both aspects are too complex and ignore energy and environmental aspects. The energy aspect i.e. thermodynamic efficiency and renewables perspective, and the environment aspect i.e. GHG emissions, water use, recyclable and non-recyclable materials are essential concerns of sustainability model that includes all equipment, manufacturing processes, energy and environment aspects of equipment. TES applies a novel structured data framework to facilitate the measure of how efficiently equipment consumes energy and contributes to sustainability compared to its full potential. It measures how much equipment is environment friendly.

According to ETP 2015, the strongest applicable elements for an intermediate plan to improve industrial emissions comprise applying best obtainable tools and energy efficiency methods, moving to low-carbon energy combinations, and recycling. For a long-term plan, applying novel and viable developments will be imperative [17] and The TES methodology can be applied as a tool to achieve these targets.



The comprehensiveness involved can be a potential obstacle to implement a total sustainability method within a manufacturing company which involves many machines. However, the problem is tackled by applying the concept of Industry 4.0 to develop smart factories.

3. RESEARCH METHODOLOGY

The scope of the research intends to propose a framework to address the lack of a comprehensive model for measuring equipment sustainability and then investigate the potential support from Industry 4.0 for its development and deployment. A fourth-stage method for the research was applied as follows.

Stage 1. There is a high number of variables that affect energy consumption and sustainability of equipment. TES method was suggested to include all crucial variables. It applies a structured configuration based on four aspects i.e. equipment, equipment settings, energy and environment.

Stage 2. The systematic process of content analysis with four main steps to revive the litrature was followed. May et al. [20] and Mey et al. [21] apply the systematic process of content analysis based on the following steps:

"Step 1: Material gathering - definition of unit of analysis and constraining potential material Step 2: Descriptive analysis - definition of formal features and assessment of material

Step 3: Category assortment - definition of analytical categories and application to material Step 4: Material evaluation - analysis of material based on defined categories".

The prime terms for the search in article titles, keywords and abstracts were identified as "Industry 4.0" and "Smart factories". The publications in the last 7 years were searched on Scopus and Science online databases due to their ability for tailored and quick searches.

These steps provided a comprehensive picture of smart factories and their key elements i.e. Manufacturing Cyber-Physical Systems (MCPS) based on Industry 4.0.

Stage 3. The key characteristics of MCPS that potentially facilitate the applications of the TES model and the components of MCPS that support the application of the above tools were identified.

Sathge 4. A case study with the involvement of multiple companies from different sectors will examine the model in different smart factories. The next sections will provide more details.

4. FUNDAMENTAL CONCERNS FOR A MANUFACTURING SUSTAIABILITY MODEL

There are three sources for industry GHG emissions:

1. GHG emissions from industry mainly come from using fossil fuels for energy. The industry may outsource energy generation to suppliers that are burning fossil fuels - normally coal and natural gas.

2. GHG emissions from manufacturers such as cement and lime sectors that use alternative non-fossil fuels derived from a wide range of sources, including tyres, plastics, paper and dried sewage sludge, etc.

3. GHG emissions from non-energy uses of fossil fuels in certain chemical reactions necessary to manufacture products from raw materials in steel making, chemical processing, etc. [22].

A comprehensive model needs to cover the consumption of all types of fossil and non-fossil fuels for both energy and non-energy uses.



Over recent years the share of electricity generation from renewables has increased. For example, this amount in Scotland has increased from 11.7% in 2004 to 42.3% in 2015 [23]. Both energy efficiency and renewable energy can contribute to much lower CO2 emissions and significant employment opportunities. A clean energy industry can improve energy security, environmental protection and economic benefits. Renewables and energy efficiency create more jobs per unit energy than fossil fuel technologies and can be applied as an engine for economic growth [24].

International Energy Agency (IEA) estimates that the energy intensity of most industrial processes is at least 50% higher than the theoretical minimum defined by the laws of Thermodynamics [25]. Energy efficiency of many processes is very low, and their average energy consumption is extensively higher than the capacity of the best obtainable tools and machines [26]. The energy intensity of manufacturing in the UK is bigger than that of the economy as a whole: while gross value added in manufacturing was 11.2% of GDP in 2010, it accounted for 16.5% of final energy demand [27].

According to the Organisation for Economic Co-operation and Development (OECD) "water is the perfect example of a sustainable development challenge-encompassing environmental, economic and social dimensions" [28]. The sustainable management of water resources implies not only the unlimited continuation of physically and biologically stable systems but also concern for the other dimensions of sustainable development, such as the economic efficiency of water use, the equitable distribution of the costs and benefits of water resource developments and sharing approaches to policy-making and decision-taking [29-31].

Kissock and Eger [32] suggested a general framework to measure industrial energy savings. The method applied multivariable piecewise regression models to characterise baseline energy use based on weather-dependent, production-dependent and independent components. Lu et al. [7] presented a model involving several process metrics and suggested in-line energy use (kWh/unit), energy use for maintaining working environment (kWh/unit) and energy consumption for material handling (kWh/unit) as examples to measure energy consumption in sustainable machining. Fleiter et al. [33] classified energy efficiency measures based on the published literature and analysed twelve features of energy efficiency measures that are independent of the type and size of the company. The suggested method studied the relative advantage, technical and information context.

Hackl and Harvey [34] proposed a model to examine options of improving energy efficiency in industrial clusters. Müller et al. [35] introduced the "Energy Efficiency Model", a methodology that decomposed the problem and defined the fundamental causes and factors for energy consumption to describe vital energy efficiency approaches. Trianni et al. [36] considered six groups categories of economic, energy, environmental, production-related, implementation-related and possible interaction with other systems and proposed a framework based on them.

May et al. [37] designed a 7-step methodology to develop firm-tailored energy KPIs. Svensson and Paramonova [38] developed a framework to outline potential energy savings in manufacturing units based on theoretical research and included all different stakeholders. Cosgrove et al. [39] suggested a process mapping method that combines energy management with value stream mapping. Caldera et al. [40] evaluated the experience of experts and presented a methodology to analyse the main features of sustainable measures for SMEs. The model evaluated efficiency practices by establishing nine features under three themes: environmental stewardship, process excellence, and a sustainability-oriented culture. Trianni et al. [41] suggested a framework for the assessment of industrial Energy Management based on the benchmarking of Energy Management Practices and Zarte and Pechmann [42] illustrated a project-based learning model to deliver a learning experience that supported the progress of Industry 4.0 capabilities.



5. TES METHODOLOGY

There is a high number of variables that affect energy consumption and sustainability of equipment. The proposed model to cover all essential variables, applies a structured configuration based on four certain aspects (Figure 1).

1. Equipment Aspect: The variables may originate from equipment conditions or manufacturing surroundings. A methodology based on the equipment aspect can be developed from energy losses within loading time. It identifies energy losses during breakdown, setup and adjustment, speed and so on. However, there are other hidden energy losses before loading time which are crucial to measure to determine equipment energy effectiveness. The model should also cover energy losses before loading during preventive maintenance, engineering, improvement and non-scheduled times. This aspect monitors the actual energy performance of a machine relative to its performance capabilities under optimal equipment conditions.

2. Equipment Settings Aspect: A methodology based on the manufacturing processes aspect can be developed from energy losses during operation time. This approach considers energy losses due to lack of skills, materials, tools and so on. However, there are other hidden energy losses pre-operation which are vital to determine equipment energy losses during time losses due to management, organisation, personnel, and inputs and so on. This aspect monitors the actual energy performance of a machine relative to its equipment settings under optimal manufacturing processes.

3. Energy Aspect: There is an essential need to develop the new broad model to cover the energy aspect of equipment. It considers thermodynamic efficiency of the process to minimise energy losses due to thermodynamic inefficiencies. This aspect is used to analyse energy efficiency based on the second law of thermodynamics. It measures specific industrial processes (e.g. industrial ammonia synthesis, petroleum refining) or specific aspects of production process (e.g. HVAC and cooling system, solar collector systems) where energy transformation is a significant component of the system's energy consumption [43]. If there are technical constrains to identify these inefficiencies and for other processes, Best Practice Energy Per Unit (BEPU) can alternatively be applied.

Combustible fuels accounted for 67.3% (of which: 65.1% were fossil fuels) of total world gross electricity production in 2016 [44]. The energy aspect should also cover the types of energy i.e. renewable or non-renewable to tackle the major problem of reducing GHG emissions. It considers all energy data such as types of energy and prices from all potential suppliers. This aspect monitors the actual energy performance of a machine under optimal energy usage.

4. Environment Aspect: The model to assess the level of sustainability needs to cover the environment aspect of equipment. What amount of GHG is produced to manufacture the product? What amount of materials is used to manufacture it? Is the product recyclable? What percentage is recyclable? How much water evaporated and/or polluted in manufacturing? Water use is measured in water volume consumed and/or polluted per unit of product. This aspect monitors the actual level of sustainability for a machine under optimal eco-friendly factors.





Fig. 1. The four aspects of TES

As shown in Figure 1, the TES model is a comprehensive framework that covers all equipment, manufacturing processes, energy and environment dimensions. It is a measure of how efficiently equipment consumes energy and operates sustainably compared to its full potential. The model can be applied for the whole life cycle of a product from the mines, suppliers, manufacturers, during its services until the end of its life.

The comprehensiveness involved might be a potential obstacle to implement a total sustainability effectiveness method. Developing smart factories based on Industry 4.0 can facilitate and expand its application.

6. SMART FACTORIES BASED ON INDUSTRY 4.0

The first industrial revolution started with the introduction of mechanical manufacturing machines mainly through the use of water and steam-powered engines. It followed by the second revolution with the use of electricity and mass production in factories. Beginning in the late 1950s, the digital revolution i.e. third industrial revolution slowly started when manufacturers incorporated more electronic, IT and eventually computer technology into their factories.

Industry 4.0 brings a more advanced interconnected and comprehensive approach to manufacturing. Emerging smart technologies such as Internet of Things (IoT) and new business environments lead manufacturing industries to move toward developing high-tech systems such as smart factories. IoT is simply the network of interconnected physical items which are embedded with sensors, RFID chips, etc. that enables them to collect and exchange data [45]. IoT has offered promising opportunities and solutions to transform the operation and role of many existing industrial functions and build powerful industrial systems and applications [46]. The increasingly growing application of smart components has resulted in the generation of high volume data. Smart components include self-aware and self-predict 'Sensors', and smart machines such as self-aware, self-predict and self-compare 'Controllers' and smart production systems such as self-configure, self-maintain and self-organise 'Networked systems' [47]. Cyber-Physical Systems (CPS) is a transformative technology to manage the high volume data know as Big Data. CPS manages interconnected systems between its physical assets and computational capabilities [48]. CPS is strongly linked to big data in nature, for example, it will uninterruptedly produce a huge amount of data that requires the big data techniques to process and help to improve system scalability, security, and efficiency [49].

CPS integrated with Production, Engineering, Maintenance and Logistics will transform current factories towards an Industry 4.0 factory. The smart factory will totally be equipped with smart sensors, actors and autonomous systems [47, 50].

Smart suppliers provide smart factories with smart inputs via IoT and Internet of Services (IoS). Smart manufacturing is a decentralised and self-organised process embedded with smart elements. It includes dynamic, automate and real-time communication for the management of a highly dynamic manufacturing environment including smart engineering and smart maintenance [51]. Smart engineering includes product design and development and smart maintenance focuses on predictive maintenance. Smart factories are supported by smart external and internal logistics which include smart logistics tools and processes. Self-organised logistics is an example of logistics management that respond to unexpected changes in production, such as bottlenecks and lack of material [52].

A continuous manufacturing process usually involves more compound items than a typical batch process. Figure 2 shows a general perspective of a CPS architecture for smart factories based on Industry 4.0 applied to a continuous manufacturing process such as a steel, plastics and fertiliser plant that consumes natural gas (NG) as raw material as well. A smart TPM approach can be applied to preventive maintenance in critical infrastructures and the energy (electricity and gas) transmission and distribution network. Figure 2 shows a simplified 5G structure with secure IoT and drones remote control to implement preventive maintenance for gas pipelines [53].

The stream of smart data between all value creation elements such as smart factories, smart manufacturing, smart engineering, smart maintenance, smart logistics, smart suppliers, smart grids, etc. in Industry 4.0 is interchanged through the cloud computing [16]. Fog computing is the extension of the cloud and its nodes are physically much closer to CPS. They are able to provide instant connections and perform the computation of big data on their own,

without sending it to distant servers. The main difference between fog computing and cloud computing is that cloud is a centralised system, while the fog is a distributed decentralised infrastructure. Some advantages of fog computing for CPS are low latency, no problems with bandwidth, high security and improved user experience [54].

Smart factories can be supplied with renewable energies from smart grids as well as supplied with NG if required. A smart grid is a vital enabler of low-carbon electricity generation and efficient energy use [55]. Smart grids dynamically and efficiently match generated energies from suppliers with the demand of smart factories and other consumers. Smart factories can be energy suppliers within a smart grid [16].

Smart factories can dynamically compare all potential smart energy suppliers via smart grids to choose the most competitive one. They need to securely, economically and properly share information and make smart agreements among themselves [56]. Blockchain is a growing list of associated records, named blocks, connected and secured applying encryption algorithms [57]. The key to the effectiveness of this list is the links that are generated from one block to the next, therefore it would be difficult to change any block after it is added to the list. Blockchain can generally provide many advances for Industry 4.0 applications. This includes improved techniques for reliable information exchanges, automated and efficient negotiation processes and efficient smart agreements among enterprises [15].

As shown in Figure 2, the relationship between customers and smart factories is defined and enabled by IoT and IoS. The smart factories deliver smart products and smart services linked to the internet to their customers. The smart factories will then gather and analyse data originating from the smart products and linked applications. This real-time Voice of the Customer (VOC) allows the factories to better understand customers' experiences, needs and expectations. Customers can also contribute on product/service development and improvement via IoT and IoS capabilities [51].

A CPS architecture for smart factories based on Industry 4.0 provides many opportunities for reducing energy consumption, GHG emissions, water use and increasing the use of renewable energies and recyclable materials.

Fig. 2. A general perspective of a CPS architecture for smart factories based on Industry 4.0

7. RESULTS AND DISCUSSIONS

7.1 Energy Management and Sustainable Manufacturing in Smart Factories

Energy, materials and water are key resources that need to be considered for sustainable development. The achievement of energy sustainable development is a huge challenge. Energy resources are vital and drive much of the worldwide economy and they contributing to good living standards. But most countries are dependent on non-sustainable energy resources, particularly fossil fuels. These limited resources negatively contribute to environment and efforts are accordingly required to develop sustainable energy systems. As already mentioned, similarly, there are many concerns in terms of sustainable supplying and using materials and fresh water [11].

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Corporate sustainability has three main pillars of economic, environmental, and social. This research focuses on the environmental pillar of manufacturing sustainability. Figure 3 shows a sustainability data structure that includes all major parameters in manufacturing. It involves 2 main features of energy and environment data collection and analysis.

The energy feature focuses on collecting and analysing all key energy consumption data derived from equipment (before loading and loading), equipment settings (pre-operation and operation) and process energy dimensions (energy types, prices and thermodynamic efficiency). The environment feature focuses on collecting and analysing all essential data on environmental perspective i.e. GHG emissions, recyclable or non-recyclable materials and water use.

Fig. 3. Equipment Sustainability Data Structure

Smart factories which are supported by smart suppliers provide their customers with smart products and services. They are backed by smart logistics. Data collection and analysis for both features of energy and environment can be considered for the entire life cycle of all products, machines, plants and logistics.

The level of comprehensiveness can be a possible serious impediment to apply a total sustainability methodology in many traditional firms. MCPS based on Industry 4.0 can facilitate this application. First, a seamless method to manage data acquisition and transferring is needed. Then proper sensors should be selected. Data to information conversion brings self-awareness to equipment. Information from every connected machine is pushed to the central information hub and the analytics bring self-comparison to equipment.

TSE can be applied as a comprehensive tool to measure and analyse equipment, process or factory sustainability. Some key components of smart factories such as CPS, IoT, cloud, big data, augmented reality, simulation, digital processes, analytical elements, additive manufacturing, smart grid, actor- data and sensor-data [15, 47, 50, 51] can facilitate the application of TES for the entire product life cycle.

IoT and IoS generate smart data for equipment (before and during loading), equipment settings (pre-operation and operation), energy (thermodynamic efficiency, types of energy and prices) and environment (GHG emissions, recyclable or non-recyclable materials, and water use). Also, smart factories can dynamically compare all potential smart energy (including inhouse) suppliers via smart grids to choose the best one. Smart grids provide smart data for energy aspect.

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Smart energy systems assist us to integrate electricity and gas infrastructures. They include the entire energy system and cover suitable energy infrastructure designs and operating strategies. The typical smart grid mainly concentrates on the electricity sector, however the most efficient and effective approaches can be deployed when the electricity sector is integrated with the heating and transportation sectors via smart energy systems [58].

Digital product memories collect, save and distribute data for the entire product life cycle. Applying analytical components for big data coming from IoT and IoS can provide TSE in real-time and suggest essential improvements. Based on TSE results, the smart elements of CPS can improve sustainability and energy effectiveness, both automated and dynamically.

This model can be applied to the entire the equipment life cycle from designing, mining, raw material acquisition to manufacturing, commissioning, operation, maintenance, engineering, upgrading and the equipment end of life. Industry 4.0 also provides a major facility of measuring, monitoring, managing and improving all sustainability parameters of products manufactured by smart equipment in smart factories. The sustainability parameters for the entire product life cycle cover from designing, raw material acquisition to manufacturing, engineering systems, the use and the product end of life.

Figure 4 shows a sustainability-oriented value stream map for smart manufacturing. Energy and environment data for the logistics between all stages are also measured. The smart elements of CPS, big data and cloud computing offer an intelligent tool to make sustainable decisions at the end of life for equipment and products. Industry 4.0 provides all required information to compare available alternatives i.e. reuse, remanufacture, recycle, recover or disposal and select the most sustainable choice.

Products are not always consumed in their place of origin. International trade of industrial products creates a global flow of virtual energy, GHG emissions and water. TES applied in smart factories assists us in clarifying this flow and improving it. All required sustainability information about energy, GHG emissions and water for the entire product life cycle can be measured. It helps to optimise the allocation of resources and implies concern for the reasonable distribution of the costs and benefits of the flow and participatory approaches to make sustainable policies and develop effective strategies.

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Fig. 4. Sustainability-Oriented Value Stream Map for Smart Manufacturing

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7.2 Case Study

As shown in Figure 1, the TSE model is a comprehensive framework that covers all equipment, manufacturing processes, energy and environment dimensions. Two large international manufacturers have been selected for the initial step of TSE application. The firms are PT Kerry Ingredients Indonesia, which is a global food company, and PT Astra Daihatsu Motor, which is the largest car manufacturer and second best-selling car brand behind Toyota, in Indonesia.

The research at this stage focuses on measuring sustainability of equipment (before loading & Loading), equipment settings (pre-operation & operation) and process energy dimensions (energy types and thermodynamic efficiency). The results show a good practice for both companies. They also present key opportunities for improvement to meet the new sustainability requirements. Due to the COVID-19 pandemic, the case study is suspended, and the outcome will be presented when the process is completed.

8. CONCLUSIONS

Based on a new scheme for energy losses and sustainability analysis involving all equipment, manufacturing processes, energy and environment aspects, a new model to measure equipment sustainability is developed.

TSE monitors all major potential dimensions and measures the equipment sustainability and energy effectiveness for a full process cycle. Also, it provides a sound perspective on energy and sustainability improvement of manufacturing systems by taking into consideration all energy and technical sustainability losses. It can be applied at all different levels of manufacturing from equipment to the whole factory. TES applies an intelligent structured data framework within smart factories derived from CPS, IoT and cloud computing to facilitate the measure of how efficiently equipment consumes energy and contributes to sustainability compared to its full potential.

This model measures the energy efficiency and sustainability of products, machines, processes and factories for the entire life cycle. It makes communication more efficient within industry and can be used as a tool of improvement and a benchmark to achieve world-class sustainability standard. TSE can provide an informative tool for training to save energy and improve sustainability.

Further research required to answer the following questions. How can the global flow of virtual energy, GHG emissions and water, particularly by applying the concept of industry 4.0, be managed and optimised? How can a simplified version of TSE be deployed within traditional factories which do not benefit from smart components of Industry 4.0?

The limitation of this study is the conceptuality of the model and potential support from Industry 4.0 for its application. Due to the COVID-19 pandemic, this mapping is based on the definition of measures and characteristics, and authors' experience. A comprehensive survey containing 'Levels of Importance' questions with the involvement of multiple companies from different sectors for stage 1 and a Delphi study for stage 3 should be carried out. It is quite important to complete the case study for stage 4 which is suspended due to the pandemic.

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