Total Equipment Energy Effectiveness (TEEE): A comprehensive model to manage energy in manufacturing

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Research

Keywords: Energy Management, Equipment Energy Effectiveness, Renewables, Manufacturing

Posted Date: August 27th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-64745/v1

Abstract

Energy efficiency brings considerable benefits to society and industry through reducing carbon footprint, helping to protect environment and improving energy security and sustainability. It saves money on fuel bills and boosts growth and creates jobs in the economy.

The industry sector is a major contributor to energy consumption and related greenhouse gas (GHG) emissions. It has a lot of potential to further reduce energy use and greenhouse gas emissions.

Total Equipment Energy Effectiveness (TEEE) addresses the current challenge of a distinct lack of a comprehensive model to embrace all potential aspects of equipment, manufacturing processes and energy features for measuring equipment energy efficiency. The model needs to be flexible enough to cater for the needs of every manufacturing firm. It can be used at equipment level, process level as well as the broader level of a factory.

The model is a measure of how efficiently equipment consumes energy compared to its full potential and can be applied as a tool to improve energy efficiency. The comprehensiveness involved might be a potential obstacle to implement a total energy effectiveness method particularly in SMEs. However, the problem is tackled by a novel TEEE Methodology which simplifies its application even for small companies.

TEEE makes the concept of equipment energy effectiveness clearer and more applicable and also makes communication more efficient and easier within manufacturing industry. It provides a sound perspective on improvement to sustainability and also can be used as a benchmark and tool to promote energy awareness in the factory.

Introduction

Globally the industry sector accounts for more than a third of energy consumption (1) and about 35 percent of energy and process related greenhouse gas (GHG) emissions (2). Almost 80% of these emissions is from energy use and energy efficiency is potentially the most significant and economical means for mitigating GHG emissions from industry (3).

The UK Climate Change Act 2008 commits the UK government by law to reducing greenhouse gas emissions by at least 80% by 2050 compared with 1990 levels (4). The UK industrial sector accounts for about 21% of total 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 reductions in GHG emissions are still needed (5). A report in 2018 summarises lessons from the Act, after 10 years, for the UK and other countries, on how climate change legislation can be more effective. According to the report, the Act should be more policy prescriptive, for example by integrating clearer sector targets. Firmer tests are expected as there is concern that the gap is widening between the emissions targets set in law and the policies established to deliver them (6).

The 2015 edition of Energy Technology Perspectives (ETP 2015) shows the vital role of identifying regulatory strategies and co-operative frameworks to advance innovation in areas like variable renewables and carbon capture. It indicates that efforts to decarbonise the global energy sector are lagging further behind for that year. ETP 2015 focuses on setting out pathways to a sustainable energy future and incorporating detailed and transparent quantitative modelling analysis. Energy decarbonisation is under way, but needs to be boosted and recent trends reaffirm the need to accelerate energy technology innovation, including through policy support and new market frameworks (7).

Current models for measuring equipment energy effectiveness focus on factors originate either from equipment or from manufacturing surroundings. The models that consider both aspects are too complicated and ignore energy aspect i.e. thermodynamic efficiency and/or renewables perspective. The TEEE methodology is a comprehensive model that covers all equipment, manufacturing processes and energy aspects. TEEE uses a novel structured data framework to facilitate the measure of how efficiently equipment consumes energy compared to its full potential.

According to ETP 2015, in the medium term, the most effective measures for reducing industrial emissions include implementing best available technologies and energy efficiency measures, switching to low-carbon fuel mixes, and recycling materials. Deploying innovative, sustainable processes will be crucial in the long run (7), and The TEEE methodology can be applied as a tool to achieve these targets.

Background

There are three sources for industry greenhouse gas emissions:

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

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

3- Greenhouse gas 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. (8).

The proposed model covers the use of all types of fossil and non-fossil fuels as a source of energy i.e. sources 1 and 2. Over recent years the share of electricity generation from the renewables has increased. For example this amount in Scotland has increased from 11.7% in 2004 to 42.3% in 2015 (9). Both energy efficiency and renewable energy can contribute to much lower CO_2 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 (10).

International Energy Agency (IEA) estimates that the energy intensity of most industrial processes is at least 50% higher than the theoretical minimum determined by the laws of Thermodynamics (11). Energy efficiency of many processes is very low, and their average energy consumption is extensively higher than the capability of the best available technology (12). The energy intensity of manufacturing in the UK is greater 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 (13).

There are more than 23 million SMEs in the EU which are employing more than 100 million employees and generate 60% of European GDP. They account for a key share of energy consumption and 60–70% of the environmental impact. Financial restrictions such as low capital availability and non-financial barriers such as inadequate in-house skills and information issues effectively limit the application of energy efficiency measures within SMEs (14).

Lu et al. (2010) present a model involving several process metrics and suggest 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 (15). May et al. (2015) propose a 7-step methodology to develop firm-tailored energy KPIs (16). John cogrove et al. (2018) suggest a process mapping method that combines energy management with value stream mapping (17).

Total production costs can be improved by 10–20% via optimal energy management in the manufacturing industry (18). Many industrial companies still lack proper techniques to effectively deal with energy inefficiency (19). 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 (20).

There is a high number of variables that affect energy consumption of equipment. These 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. This approach identifies energy losses during breakdown, setup & 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. This aspect 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.

Teee Methodology

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 measure to determine equipment energy effectiveness. The manufacturing processes aspect should also identify pre-operation 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.

As previously mentioned, there is also an essential need to develop a new broad model to cover the energy aspect of equipment energy effectiveness. This approach considers thermodynamic efficiency of the process to minimise energy losses due to thermodynamic inefficiencies. If there are technical constrains to identify or address these inefficiencies, 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 (21). 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. This aspect monitors the actual energy performance of a machine under optimal energy usage. As shown in Figure 1, the TEEE model is a comprehensive framework that covers all equipment, manufacturing processes and energy aspects. TEEE is a measure of how efficiently equipment consumes energy compared to its full potential.

The level of comprehensiveness can be a possible serious impediment to apply a total energy effectiveness methodology especially in small and some medium size firms. TEEE, as a novel methodology, is designed to solve the problem. The technical data provisions originated from OEE measurement can be used as a solid base to develop an appropriate TEEE measurement system.

Overall equipment effectiveness (OEE), as introduced by Nakajima (1988), is seen to be the fundamental way of measuring equipment efficiency and has been extensively accepted as a major quantitative tool for measuring the productivity of manufacturing systems (22). It is the essential measure of total productive maintenance (TPM) and has become one of the most common used metrics for operations. The concept of OEE is being used increasingly in industry because it quantifies efficiency into a simple number, while revealing the actual effectiveness of a machine.

A high number of manufacturing companies have already developed the appropriate IT structure to collect and analyse data to measure OEE. The system can be simply adapted to meet the requirements of TEEE measurement. As shown in Figure 2 that structured data framework facilitates measuring TEEE. All tiers of both equipment and manufacturing aspects can be integrated to develop four stages of pre-operation, gross operation, net operation and value operation. As mentioned later and shown in Figure 4, all energy factors for gross operation, net operation and value operation can be measured via obtaining results of OEE calculations along with access to the Power consumption during Operation (POPE) quantity.

The energy loss analysis scheme during pre-operation time

A set of manufacturing surroundings affect the energy performance of equipment during pre-operation time. Anvari et al (2010) show that there are considerable time losses before loading time (23). As shown in Figure 3, these energy losses can be categorised under eight headings:

1- Energy consumption during Non-Scheduled Time (NST) related to production consists of: all consumed energy during time spent on any disruption to the production schedule, time spent on carrying out current orders, general preparation and basic maintenance such as cleaning and lubrication. It can be calculated as follows:

Energy consumption during NSTPro = NSTPro × PNST

Where:

PNST= Power consumption during NST

2- Energy consumption during Non-Scheduled Time (NST) related to personnel consists of: all consumed energy during time losses because of shortage of labor due to daily shop floor meetings, and training. It can be calculated as follows:

Energy consumption during NSTPer = NSTPer × PNST

3- Energy consumption during Non-Scheduled Time (NST) related to organisation consists of: all consumed energy during non-operational time due to shift changing, and unscheduled time for holidays and night shifts. It can be calculated as follows:

Energy consumption during NSTOrg = NSTOrg × PNST

4- Energy consumption during Non-Scheduled Time (NST) related to management consists of: all consumed energy during time spent on precautionary periods. It can be calculated as follows:

Energy consumption during NSTMng = NSTMng × PNST

5- Energy consumption during non-scheduled time related to inputs consists of: all consumed energy during non-operational time due to lack of material, electricity and utilities such as water. It can be calculated as follows:

Energy consumption during NSTInp = NSTInp × PNST

6- Energy consumption during Improvement Time consists of: all consumed energy during time spent on R&D, and activities for upgrading plant, equipment and process which need no operation of machines. It can be calculated as follows:

Energy consumption during improvement time= Improvement Time × PIMP

Where:

PIMP= Power consumption during Improvement Time

7- Energy consumption during engineering time consists of: all consumed energy during repair time other than appointed time for preventive maintenance and other regular planned maintenance tasks. It can be calculated as follows:

Energy consumption during Engineering Time= Engineering Time × PENG

Where:

PENG= Power consumption during Engineering Time

8- Energy consumption during Planned Maintenance Time can be calculated as follows:

Energy consumption during Planned Maintenance Time = Planned Maintenance Time × PMAI

Where:

PMAI= Power consumption during Planned Maintenance Time

Hence Energy Consumption during Time Losses Before Loading (TLBL) can be calculated as:

Energy Consumption during å TLBL= (å NST) × (PNST) + (Improvement Time) × (PIMP) + (Engineering Time) × (PENG) + (Planned Maintenance Time) × (PMAI)

Where:

å TLBL=The sum of all Time Losses Before Loading

=å NST + Improvement Time + Engineering Time + Planned Maintenance Time

and

å NST= NSTPro + NSTPer + NSTOrg + NSTMng + NSTInp

Figure 3 summarises the energy loss analysis scheme during pre-operation time.

The energy loss analysis scheme during operation time

A set of machine conditions along with manufacturing processes affect the energy performance of equipment during operation time. Tajiri and Gotoh (1992) classify major time losses during operations into six groups. Breakdown losses, setup and adjustment losses are downtime losses used to determine a true value for the availability of a machine. The third and fourth losses, including minor stoppage and reduced speed losses, are known as speed losses. They are used as a measure of performance rate of a given machine. Rework and yield losses are defined as quality losses that determine the quality rate for the equipment (24). As shown in Figure 4, the energy losses during operation time can be categorised under three headings:

I- Energy Losses during Gross Operation

Breakdown losses are caused by equipment requiring maintenance. One example is the downtime when labour and spare parts are needed to repair the equipment. Setup and adjustment losses are caused by changes in operating circumstances, for example changes in the beginning of production runs or commencement at each shift. These losses include downtime for setup, start-up, and adjustment. Energy consumption during downtime Losses i.e. breakdown, setup and adjustment losses are used to determine Energy-Availability (EA).

II- Energy Losses during Net Operation

Minor stoppage losses are caused by events such as the machine jamming, halting, and idling. Normally a minor stoppage of more than 10 minutes is considered as a breakdown even if no damage has happened to the equipment. Speed losses are caused by decreased operating speed. These losses are calculated on the basis of the ratio of theoretical to actual operating speed. Energy consumption during speed losses i.e. idling, minor stoppage and reduced speed losses are used to determine Energy-Performance rate (EP).

III- Energy Losses during Valuable Operation

Quality and rework losses are caused by defective products manufactured during normal production. Yield losses are caused by unused or wasted raw materials during the early stages of production from machine start up to stabilisation. Energy consumption during quality losses i.e. start up and production rejects are used to determine Energy-Quality rate (EQ).

The energy loss analysis scheme based on thermodynamic efficiency

Thermodynamic methods provide a measure of inefficiencies within a process and accordingly the maximum theoretical improvement potential. Although it is accepted this optimal limit will not be reached in practice, it can still be instructive in showing where differences may arise (5). Thermodynamic analysis can outline the extent of energy inefficiencies within the constraints of the existing process along with potential improvements.

As previously mentioned, the energy intensity of most industrial processes is at least 50% higher than the theoretical minimum determined by the laws of Thermodynamics. Motor systems consume about 65% of electricity in industry. Measures can be aimed at improving the aerodynamics of the motor, its windings and applying higher quality magnetic steel. For example, scrap preheating and oxygen injection in steel industry or better membranes for separation and more selective catalysts for synthesis in chemical industry can decrease energy consumption (3). Energy Consumption due to thermodynamic losses are used to determine Energy-Thermodynamic efficiency (ET).

The energy loss analysis scheme based on non-renewable energy consumption

According to ETP 2015, among energy end uses, heating and cooling systems offer significant potential for decarbonisation that so far have been mostly untapped. They were responsible for 30% of global carbon dioxide (CO2) emissions in 2012 as 70% of heating and cooling demand were relying on fossil energy sources. Broad application of energy efficiency and switching to low-carbon energy sources can lead the fossil share to below 50% by 2050 with renewables (including renewable electricity) covering more than 40% of heating and cooling needs. Direct and indirect CO2 emissions linked to heating and cooling would fall by more than one-third by 2050 (7).

It is vital to improve energy efficiency; however, there is growing concern about global warming, public health, the exhaustion of fossil fuels and energy price stability. This signifies that the suggested model should involve this element of sustainability. A more effective CO2 strategy should concentrate on shifting to renewables. Other substantial benefits such as reliability and resilience and Jobs and other economic benefits can also be derived from renewable energy use. The energy revolution scenario indicates that renewable energy can meet more than 80% of the world's energy demands by 2050 (25).

Some organisations may leave this energy factor and focus on other losses. They can add this factor when they are able to make adequate provisions against non-renewable sources. Non-renewable energy consumption is considered to determine Energy-Renewable rate (ER).

Total Equipment Energy Efficiency (TEEE) structure

Based on the TEEE methodology and the above loss analysis schemes, TEEE structure can be defined.

As shown in Figure 4, six elements of TEEE are defined as follows:

EB = Energy Consumption during Pre-Operation Time / Energy Consumption during Calendar Time

= (Energy Consumption during Calendar Time - Energy Consumption during Time Losses Before

Loading) / Energy Consumption during Calendar Time

=1 – (Energy Consumption during Time Losses Before Loading / Energy Consumption during

Calendar Time)

= 1 - [(å NST) × (PNST) + (Improvement Time) × (PIMP) + (Engineering Time) × (PENG) + (Planned

Maintenance Time) × (PMAI)] / Energy Consumption during Calendar Time

EA = Energy Consumption during Operation Time / Energy Consumption during Pre-Operation Time

= [(Pre-Operation Time – Down time) × POPE] / (Energy Consumption during Calendar Time –

Energy Consumption during Time Losses Before Loading)

= [(Pre-Operation Time – Down time) × POPE] / [(Energy Consumption during Calendar Time –

[(å NST) × (PNST) + (Improvement Time) × (PIMP) + (Engineering Time) × (PENG) + (Planned

Maintenance Time) × (PMAI)]]

Where:

POPE= Power consumption during Operation

EP = Energy Consumption during Net Operation Time / Energy Consumption during Operation Time

= (Cycle time per unit × Processed amount × POPE) / [(Pre-Operation Time – Down time) × POPE]

= (Cycle time per unit × Processed amount) / (Pre-Operation Time – Down time)

EQ = Energy Consumption during Valuable Operation Time / Energy Consumption during Net Operation Time

= Cycle time per unit × (Processed amount – Defects amount) × POPE) / (Cycle time per unit × Processed amount× POPE]

= (Processed amount – Defects amount) / Processed amount

= 1 – (Defects amount / Processed amount)

ET = Energy Consumption during Thermodynamically Efficient Process / Energy Consumption during Valuable Operation Time

= (Energy Consumption during Valuable Operation Time – Energy Consumption due to Thermodynamic Inefficiencies) / Energy Consumption during Valuable Operation Time

= 1 – (Energy Consumption due to Thermodynamic Inefficiencies) / Energy Consumption during Valuable Operation Time)

ER = Renewable Energy Consumption/ (Renewable Energy Consumption + Non-Renewable Energy)

= Renewable Energy Consumption during Calendar Time / Energy Consumption during Calendar Time

Hence TEEE can be calculated as given:

$TEE = EB \times EA \times EP \times EQ \times ET \times ER$

As earlier mentioned, some manufacturing firms may leave ER and focus on other losses. They can add this factor when they are ready. TEEE without considering Renewables can be calculated as given:

$TEEE = EB \times EA \times EP \times EQ \times ET$

All elements of TEE are summarised in Figure 5.

Case Study

Two large international manufacturers were selected for TEEE 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.

A form was developed to gather required data which included 5 parts as follows:

Part A- General information

Part B- Machine, Plant or Process/Duration/Energy Consumption during the above period

Part C- Energy Losses before Loading

Part D- Energy Losses after Loading, if the OEE measurement for the above period is not available

Part E- Energy Losses after Loading, if the OEE measurement for the above period is available

Either Part D or Part E may be skipped based on the availability of data for OEE. A template was also developed and included to make further clarification.

The results show a good practice for both companies. They also present key opportunities for improvement to meet the new sustainability requirements. The case study still continues and the outcome will be presented when the process is completed.

Conclusions

Based on a new scheme for energy loss analysis involving all equipment, manufacturing processes and energy aspects, a new model to measure and analyse equipment energy effectiveness is developed. This comprehensive model covers all aspects but with a novel structure which simplifies its application.

TEEE monitors all major potential dimensions and measures the equipment energy effectiveness for a full process cycle in order to respond to the new sustainability requirements. Also, it provides a sound perspective on energy effectiveness improvement of plants by taking into consideration all energy losses.

The model is flexible enough to cater for the needs of every manufacturing firm and can be applied at equipment, processes and factory levels.

It makes communication more efficient and easier within industry and may be used as a tool of improvement and a benchmark to achieve world-class standard. TEEE can provide an informative tool for training to save energy and improve sustainability. It covers the use of all types of fossil and non-fossil fuels as a source of energy. Further research can consider non-energy uses of fossil fuels. It is important to examine this method over a longer period and within other plants with different environmental and technical perspectives.

The limitation of this research is an incomplete case study due to the COVID-19 pandemic. It is quite important to examine the model within multiple companies from different sectors, and, desirably, both types of factories with batch processes such as car manufactures and continuous manufacturing plants such as oil refineries and steel makers. It would enable us to compare the results and have a deeper understanding of total equipment energy effectiveness in different factories.

Declarations

Acknowledgements

The author would like to thank the European Environment Agency (EEA) Enquiry Service and Ms. Julie O'Brien from the Scottish Environment Protection Agency (SEPA) for their contribution to access to the updated Environment and energy data. He gratefully acknowledge the support of Dr Hari Agung Yuniarto from Universitas Gadjah Mada, Mr Wilhelmus Abisatya Pararta from PT Astra Daihatsu Motor and Mr Yusuf Qaradhawi from PT Kerry Ingredients, Indonesia for the case study.

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Figures

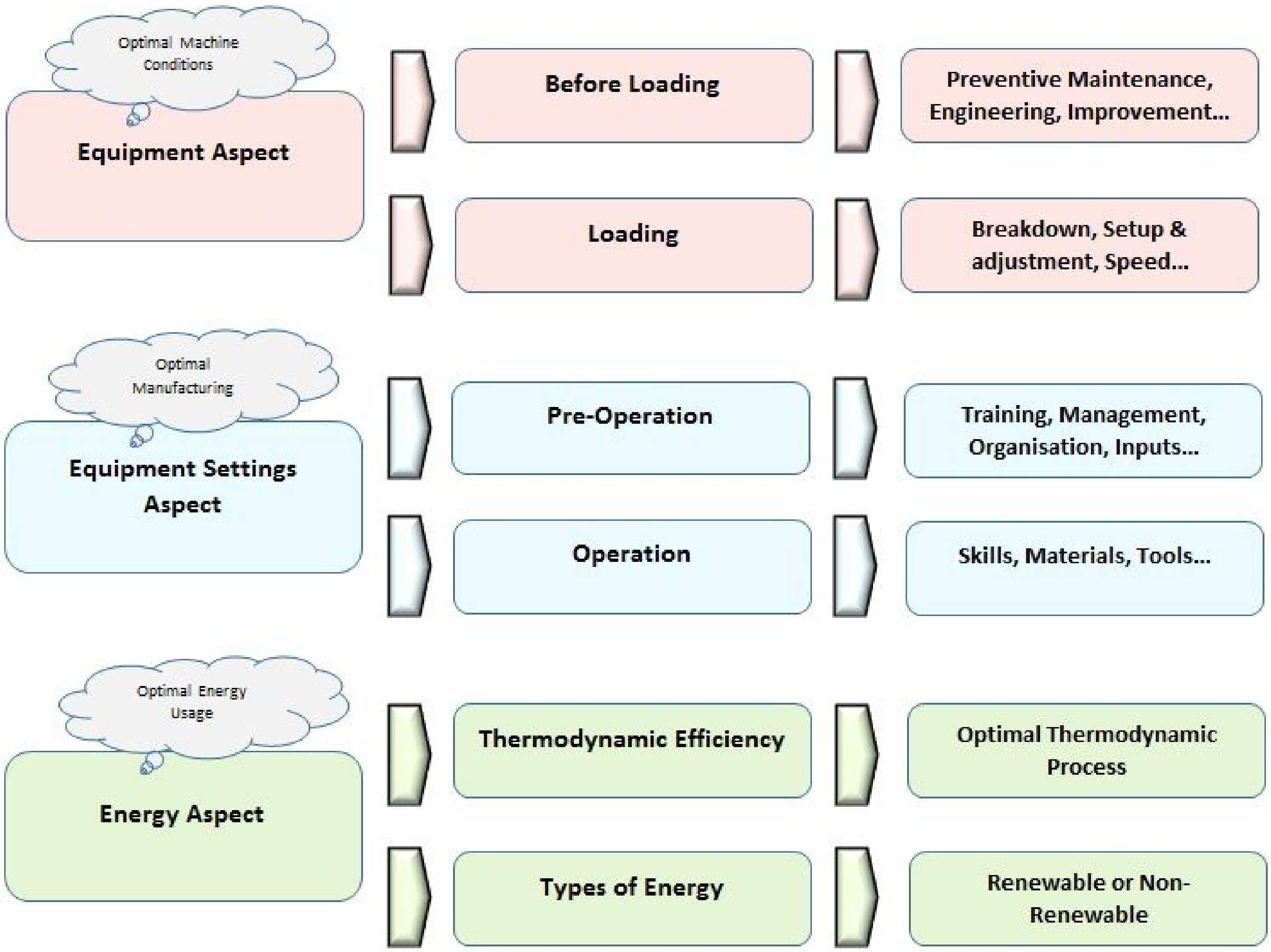

Figure 1

The three aspects of TEEE

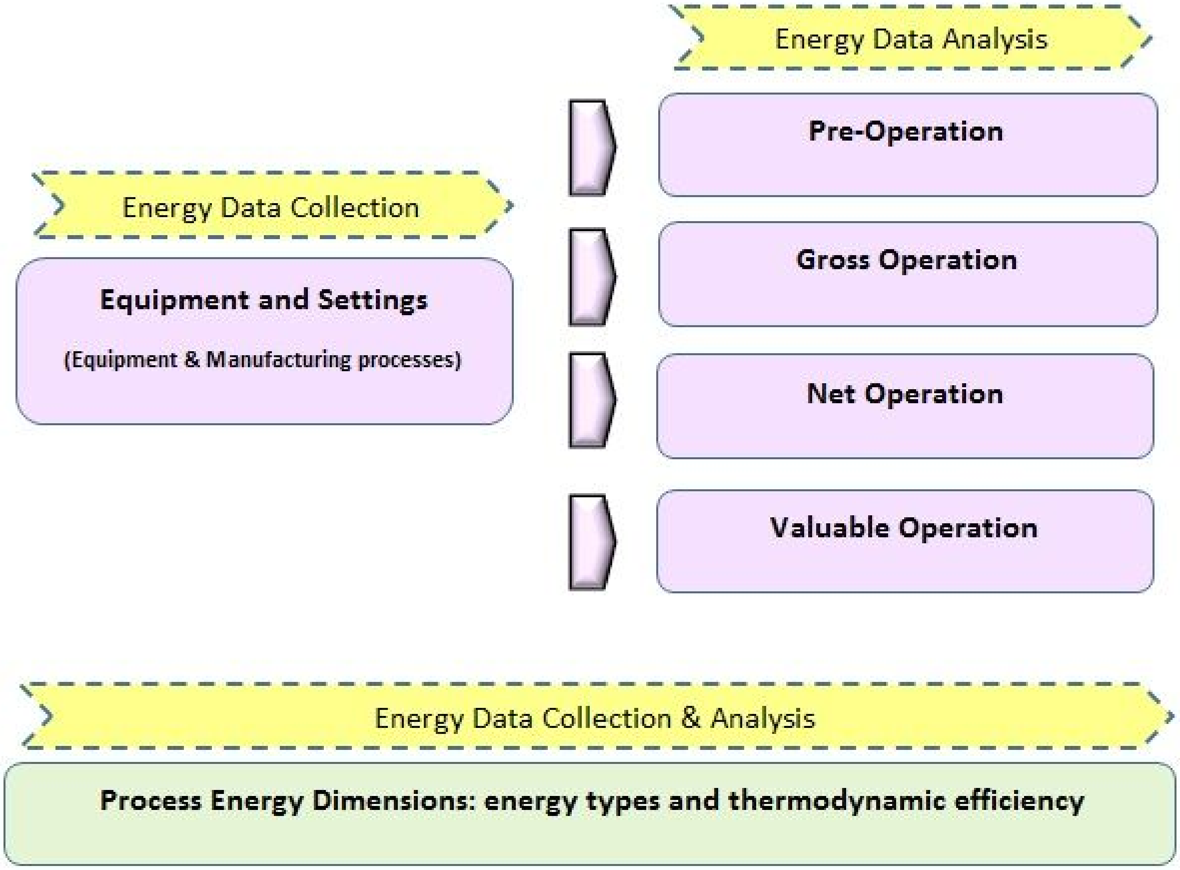

Figure 2

Energy Data: Collection and analysis structure

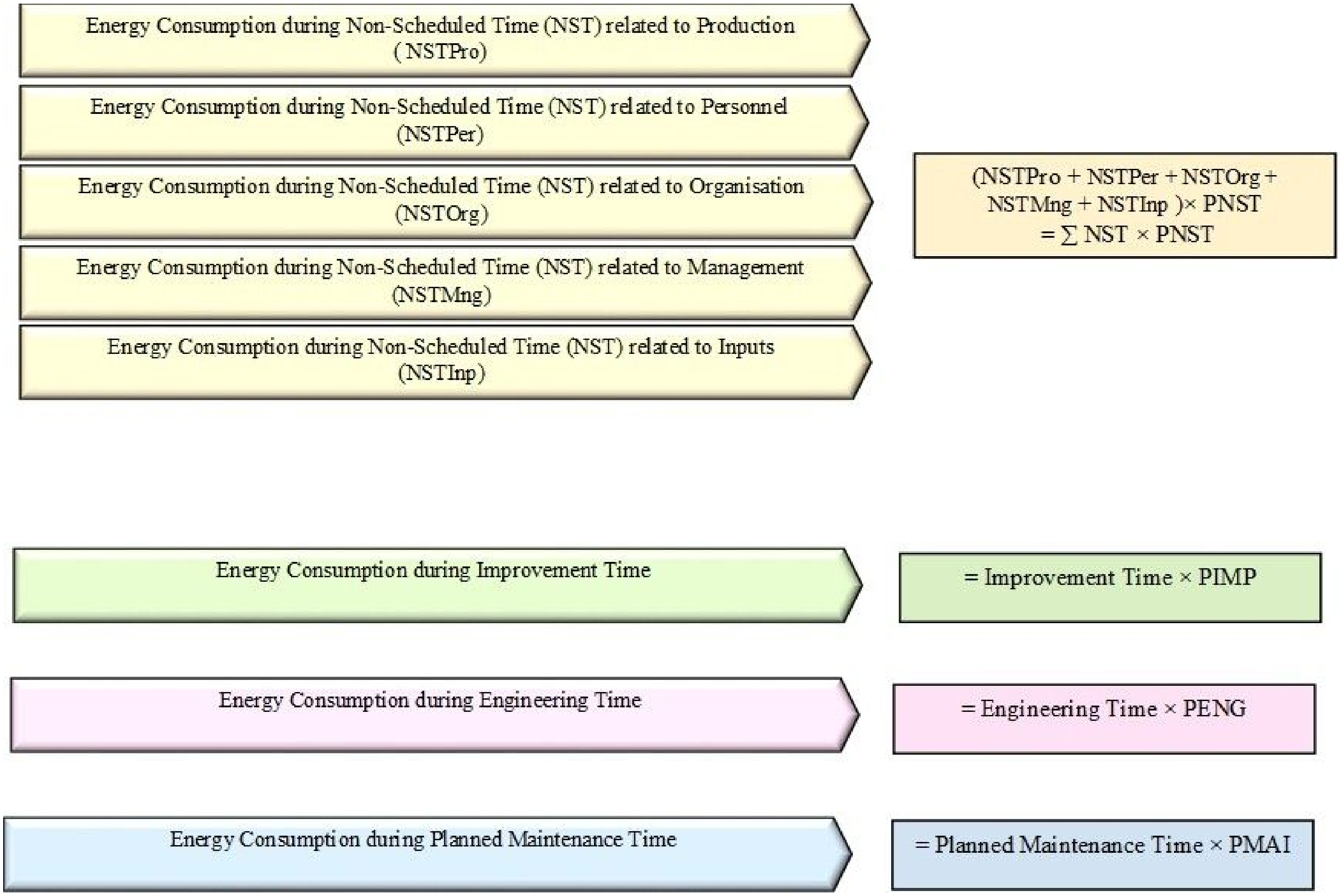

Figure 3

summarises the energy loss analysis scheme during pre-operation time.

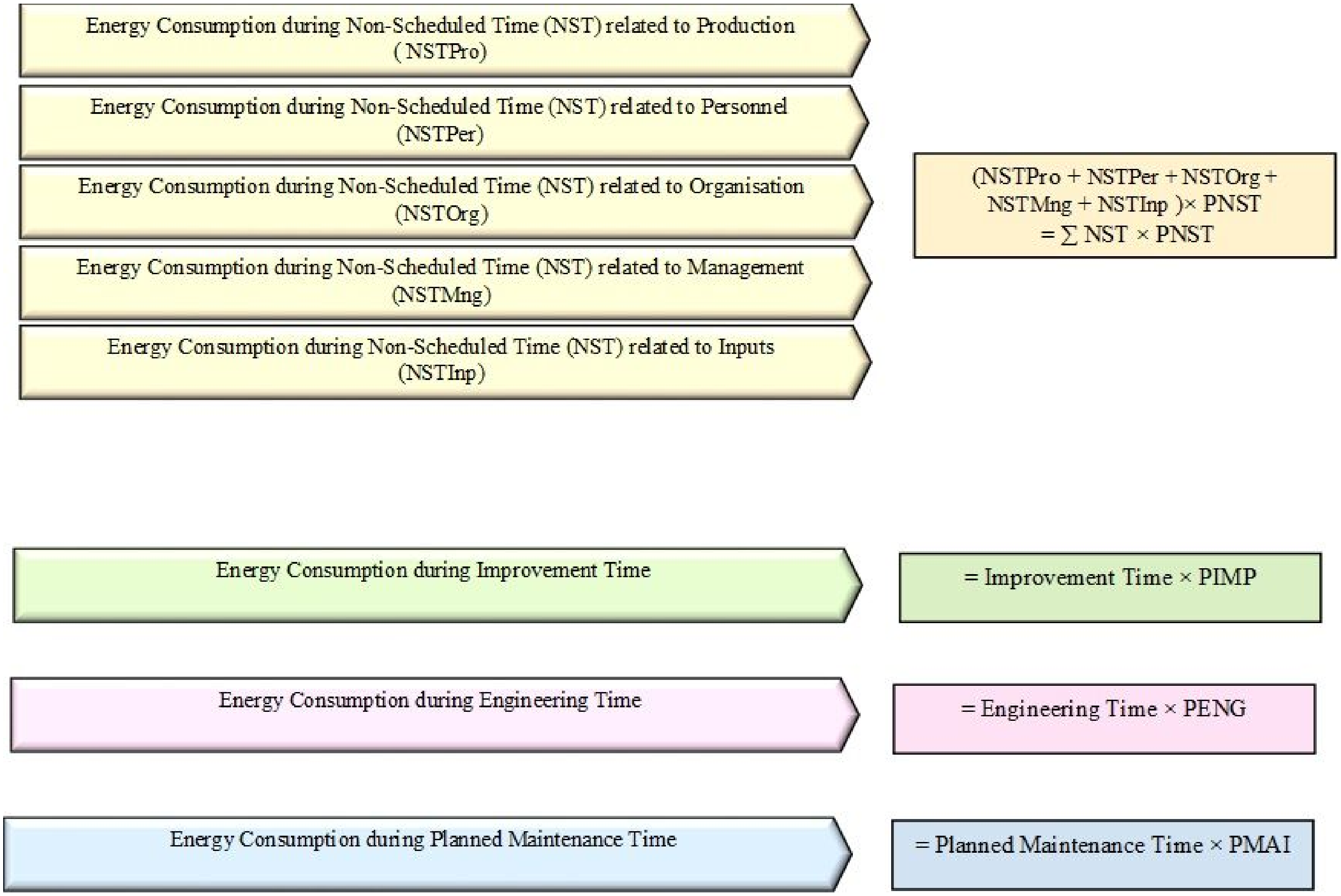

Figure 4

Total Equipment Energy Efficiency (TEEE) structure

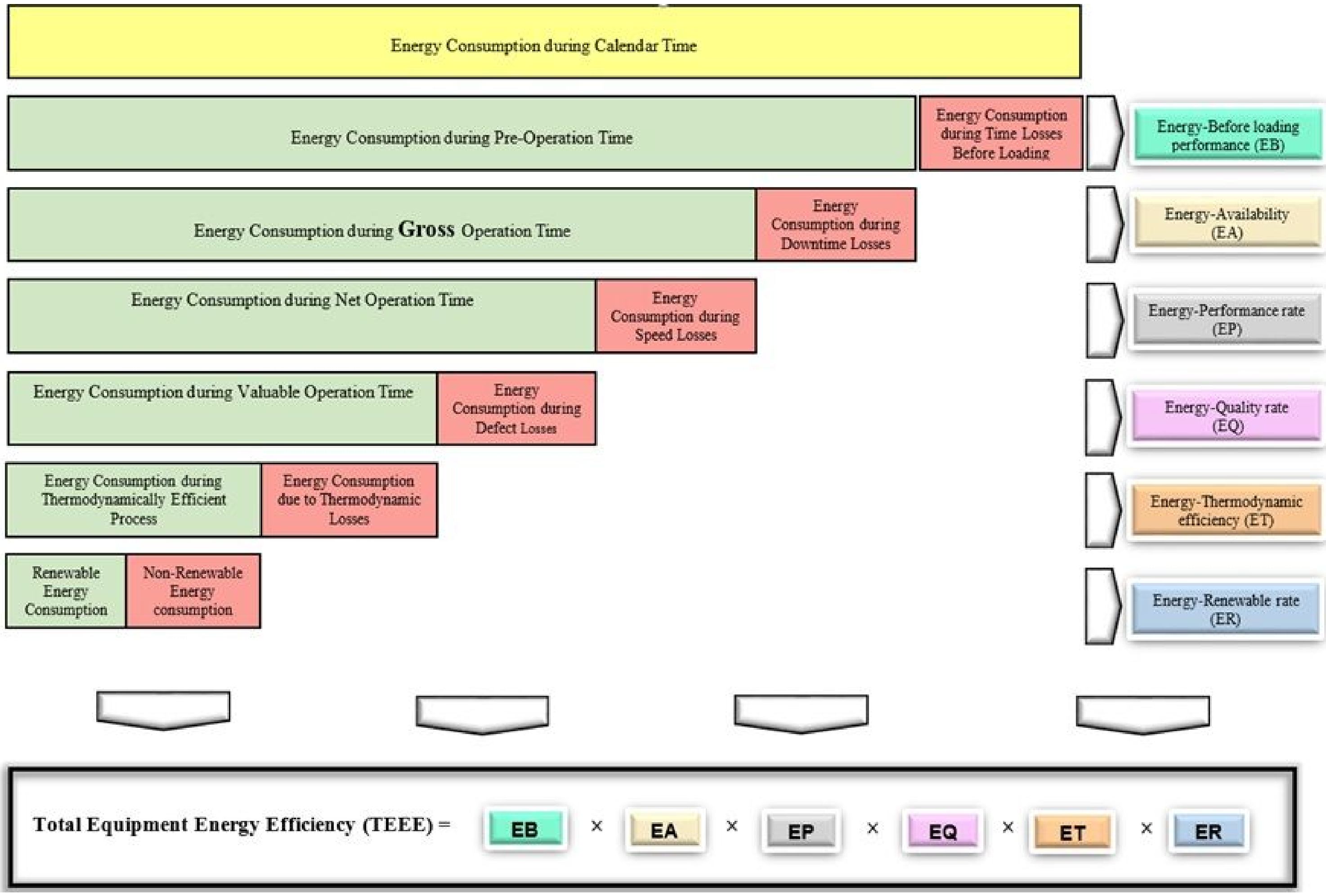

Figure 5

All elements of Total Equipment Energy Efficiency (TEEE)