Applied Energy 149 (2015) 46–61

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Energy management in production: A novel method to develop key performance indicators for improving energy efficiency

Gökan May [a,*], Ilaria Barletta [b], Bojan Stahl [a], Marco Taisch [a]

[a] Politecnico di Milano, Department of Management, Economics and Industrial Engineering, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
[b] Chalmers University of Technology, Department of Product and Production Development, SE-41296 Gothenburg, Sweden

## HIGHLIGHTS

- We propose a 7-step methodology to develop firm-tailored energy-related KPIs (e-KPIs).
- We provide a practical guide for companies to identify their most important e-KPIs.
- e-KPIs support identification of energy efficiency improvement areas in production.
- The method employs an action plan for achieving energy saving targets.
- The paper strengthens theoretical base for energy-based decision making in manufacturing.

## ARTICLE INFO

*Article history:*
Received 18 November 2014
Received in revised form 11 March 2015
Accepted 14 March 2015

*Keywords:*
Energy management
Key performance indicators
Sustainable manufacturing
Cleaner production
Energy efficiency
KPI method

## ABSTRACT

Measuring energy efficiency performance of equipments, processes and factories is the first step to effective energy management in production. Thus, enabled energy-related information allows the assessment of the progress of manufacturing companies toward their energy efficiency goals. In that respect, the study addresses this challenge where current industrial approaches lack the means and appropriate performance indicators to compare energy-use profiles of machines and processes, and for the comparison of their energy efficiency performance to that of competitors'. Focusing on this challenge, the main objective of the paper is to present a method which supports manufacturing companies in the development of energy-based performance indicators. For this purpose, we provide a 7-step method to develop production-tailored and energy-related key performance indicators (e-KPIs). These indicators allow the interpretation of cause-effect relationships and therefore support companies in their operative decision-making process. Consequently, the proposed method supports the identification of weaknesses and areas for energy efficiency improvements related to the management of production and operations. The study therefore aims to strengthen the theoretical base necessary to support energy-based decision making in manufacturing industries.



## 1. Introduction

The revolution in industry has come along from pure cost to quality and productivity efficiencies and is in the transition toward environmental performance efficiency [1–3]. Closely related to significant improvements in environmental and economic terms, the energy efficiency topic has become important as a field that concerns businesses worldwide, going beyond traditional energy-intensive industries such as the steel, cement, and chemical industries [4,5]. Over the last few years, policies and private households have also been stirred up by energy efficiency topics due to emergent media coverage and drivers such as climate change, scarcity of resources and rising energy prices ([6–9].

Energy efficiency, in the theme of sustainable corporate behavior, is seen as a lever for global competitiveness in the future [10–12]. Manufacturing accounts for 37% of primary energy use worldwide [13], and for 40% of electricity consumption in Europe [14]. Accordingly, policymakers and industry are beginning to prioritize the topic on their agenda [15], examples include the development of the ISO 50001 Energy Management Standard and the Europe 2020 Strategy that aims at achieving 20 percent reduction in overall energy use by 2020 compared to the 2005 baseline [16]. Consequently, avoiding energy waste through energy-aware and optimized production is of utmost importance to cope with

* Corresponding author. Tel.: +39 02 2399 4836; fax: +39 02 2399 2700.
*E-mail addresses:* gokan.may@polimi.it (G. May), ilaria.barletta@chalmers.se (I. Barletta), bojan.stahl@polimi.it (B. Stahl), marco.taisch@polimi.it (M. Taisch).

http://dx.doi.org/10.1016/j.apenergy.2015.03.065
0306-2619/

increased global competitiveness and adverse environmental impacts. Improving firms' technological and business processes as well as structures and infrastructures have become crucial in order to adequately address these challenges [17–19]. Guided by this paradigm shift, it becomes essential to adopt a continuous improvement process for using energy resources more efficiently.

Energy-related information allows the assessment of optimization and improvement potential of energy efficiency measures. Hence it becomes important to provide knowledge that highlights the overall state of the factory and its performance regarding energy consumption. In this regard, performance indicators serve as a measure to decide whether a system is working as it is designed for and helps define progress toward a pre-set target. This enables better monitoring and control of energy consumption which is of utmost important both for current and future enterprises to improve energy efficiency in production [20].

While absolute values and aggregated measures like energy consumption per year or per product or similar measures provide an overview on the status quo, it fails to provide decision-making support, transparency and clear identification of action items. Decision-makers in production require tailored energy-related Key Performance Indicators (e-KPIs) in order to (i) identify firm-specific energy drivers in their production system, (ii) make the energy behavior profile of the production system transparent, (iii) recognize cause-effect-relationships, (iv) prepare actions for improvement measures, and (v) communicate status quo adequately with other inter- and intra-functional areas. Thus, the main objective of the study is to present a method which supports companies independently from the sector or product to develop firm-tailored energy-related KPIs.

The proposed e-KPI method serves as a successful example on how to transfer scientific and research knowledge into industrial value. First, it serves as a practical guide for companies to identify and integrate their most important e-KPIs in the steering and reporting system. Second, the method is developed based on the current state-of-the-art in the field of energy-efficient production engineering by backing each step of the procedure with scientifically valid formulas, diagrams and approaches.

The rest of the paper is structured as follows: The next section provides a theoretical background on energy efficiency in production engineering, then goes on to describe derived gaps and industry needs, and answers how we address these issues. Then, we present the research methodology which incorporates empirical and axiomatic approaches to support validity of results. The following section describes the e-KPI method, while the subsequent sections explain the inclusion in the corporate decision-making process. Finally, we end the paper by highlighting important findings and research limitations, and conclude by providing an outlook for future research.

## 2. Literature review

Performance indicators play a significant role in evaluating the efficiency and effectiveness of manufacturing systems for a target performance area (e.g. cost, sustainability, energy efficiency). In the last decade, efforts in the academia and industry shifted toward achieving energy efficiency in manufacturing. In this context, many scholars discussed energy efficiency measures, standards, labeling regulations, metrics and performance measurement on national and policy level (e.g. [21,6,7,22–27]). On a more disaggregated level, studies focused on modeling energy consumption (e.g. [28,29]), and a varied set of approaches have been developed for improving energy efficiency performances in production from machine tool to plant (i.e. an array of machine tools and processes) level. For instance, Hu et al. [30], He et al. [31] and Devoldere et al. [32] focused on improving energy efficiency on machine tool level.

There is a similar situation for manufacturing at production system and factory level where several heterogeneous solutions have been offered regarding energy consumption and efficiency (e.g. [33,17,34–36]). Other recent studies proposed techniques and tools for energy management (e.g. [37–40]). Monitoring and control approaches as a part of energy management were addressed in several articles (e.g. [41]), aiming at the development of appropriate methods for improving energy performances in manufacturing.

The US Environmental Protection Agency introduced the ENERGY STAR industry program, promoting indicators as an effective lever to measure energy-based performances [42]. Later, Boyd et al. [43] described the importance of these indicators for benchmarking plant energy consumption. Feng and Joung [44] proposed a sustainable manufacturing measurement infrastructure and Tanaka [45] explored different ways to measure energy efficiency performance. Additionally, Aguirre et al. [46] proposed metrics called 'energy-production signatures' for diagnosis of energy inefficiencies and benchmarking of energy-related performances of manufacturing plants. Later, Zhou et al. [47] developed an approach for monitoring energy efficiency trends over time in a country and for comparing the economy-wide energy efficiency performance among countries.

Based on an analysis of relevant literature and industry, Bunse et al. [48] highlighted the importance of energy-related production performance indicators as a key need of the manufacturing industry for identifying inefficiencies within a plant's energy consumption, particularly placing emphasis on the improvement potential at the machine tool level. In this context, Vikhorev et al. [49] provided a decision support framework for the monitoring and management of energy consumption in a factory, focusing on the energy used by productive resources. However, that particular paper by Vikhorev et al. [49] focused solely on the energy aspects and thus lacked a consideration of synergies and trade-offs with other production performance indicators. In another recent study, Aramcharoen and Mativenga [50] identified critical energy states for machining components to support energy consumption analysis of machines and work pieces.

The review of the pertinent literature reveals that both academia and industry still lack approaches and tools to better understand the energy consumption behavior and inefficiencies of machine tools, particularly with a focus on synergies and trade-offs with other production management decisions (e.g. quality, maintenance, production planning, etc.).

This study is built upon the research gaps derived in May et al. [20] which carried out a comprehensive review of the literature on energy-related key performance indicators and May et al. [51] which analyzed the industrial needs toward energy efficient manufacturing. Thus, based on insights from the aforementioned two previous studies of the authors, Table 1 highlights the research gaps and industrial needs addressed in this study. The table also explains how these gaps are addressed in the research work, thus presenting progress beyond the published literature on KPIs for energy efficiency.

## 3. Research methodology

The development of methodologies and approaches which are specifically designed to support decision-making processes can suffer from a mutual relationship of academic and practical stringency: (i) the approach is scientifically rigid, but difficult to apply in practice (the practice gap) or (ii) the approach is applicable in practice but scientifically not underpinned (the research gap). To