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# Measuring energy efficiency: Is energy intensity a good evidence base?

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## HIGHLIGHTS

- Energy intensity measure reflects consumption, not energy efficiency.
- Thermodynamic indicators should describe energy efficiency at all levels.
- These indicators should have no reference to economic or financial parameters.
- A set of energy efficiency indicators should satisfy several basic principles.
- There are trade-offs between energy efficiency, power and costs.

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## ABSTRACT

There is a widespread assumption in energy statistics and econometrics that energy intensity and energy efficiency are equivalent measures of energy performance of economies. The paper points to the discrepancy between the engineering concept of energy efficiency and the energy intensity as it is understood in macroeconomic statistics. This double discrepancy concerns definitions (while engineering concept of energy efficiency is based on the thermodynamic definition, energy intensity includes economic measures) and use. With regard to the latter, the authors conclude that energy intensity can only provide indirect and delayed evidence of technological and engineering energy efficiency of energy conversion processes, which entails shortcomings for management and policymaking. Therefore, we suggest to stop considering subsectoral, sectoral and other levels of energy intensities as aggregates of lower-level energy efficiency. It is suggested that the insufficiency of energy intensity indicators can be compensated with the introduction of thermodynamic indicators describing energy efficiency at the physical, technological, enterprise, sub-sector, sectoral and national levels without references to any economic or financial parameters. Structured statistical data on thermodynamic efficiency is offered as a better option for identifying break-through technologies and technological bottle-necks that constrain efficiency advancements. It is also suggested that macro-level thermodynamic indicators should be based on the thermodynamic first law efficiency and the energy quality problem may be left to enterprise-level thermoeconomic optimization.



## 1. Introduction

In this paper we present an analysis of the existing energy efficiency indicators (EEI), which testifies to a discrepancy between the engineering concept of energy efficiency and the energy efficiency as it is understood in macroeconomic statistics (and later used for policy-making). We also demonstrate the nature of an important shortcoming – implicit merging of energy efficiency and energy consumption data at different levels. The validity of this phenomenon has not been analyzed yet. Eliminating this shortcoming will increase the methodological consistency in energy efficiency statistics. It is also the first attempt to draw a line between energy efficiency and energy consumption (intensity) indicators and establish the link between them based on engineering thermodynamics and economic understanding of associated trade-offs for energy efficiency at corporate (micro) and national (macro) levels. Finally, we formulate recommendations about the basic principles and criteria for establishing a more straightforward set of energy efficiency indicators based on the first thermodynamic law efficiency.

Energy efficiency is and will continue to be a competitive advantage for both countries and companies. Its improvements

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have considerably slowed down the energy consumption growth in OECD countries over the last 30 years. Moreover, it is expected that the economic growth in OECD countries will be supported by enhanced energy efficiency, not by an increase of primary energy consumption [1]. National and regional energy sectors are usually subject to regulation, which should stimulate companies to be more environment-friendly. Obviously, evidence-based energy efficiency policy has to be informed by reliable indicators which reflect the situation at the national/international level and, at the same time, correspond to the sum of efforts undertaken at the facility/company and appliances/processes levels.

Energy efficiency is largely influenced by the processes taking place at engineering, physical and technological levels. The statistical data in this sphere at macro level is expected to reflect those effects in an integrated form. However, the discrepancy between the actual efficiency at micro-level and various economic measures added to the energy efficiency formula may hinder proper (informative) aggregation, and, furthermore, it may form energy efficiency trends, which are not substantiated by actual changes at lower levels, but instead, caused by economic factors. In this paper it is suggested to avoid this obstacle through the introduction of aggregated (macro-level) engineering thermodynamic indicators which give a more precise picture of energy efficiency as compared with traditionally used energy intensity indicators. Thus, we suggest an additional multilevel set of energy efficiency indicators based on thermodynamic efficiency and recommend aggregating energy efficiency and energy consumption data separately, even though it can be used together to put the energy issues in a broader perspective.

## 2. Methods

Our study contributes to the development of energy efficiency indicators used by national and international organizations. Some deficiencies of energy efficiency measurement that have previously been identified by researchers are discussed in Sections 3 and 4.1. However none of the studies have explicitly linked engineering thermodynamic indicators and economic measures of energy efficiency based on energy intensity. At present thermodynamic indicators are mostly used for micro level solutions. In our study we attempt to fill in this gap by examining the relation between energy efficiency and energy intensity. Thus, the study may be deemed useful by company managers and policy-makers who are willing to use a direct measure of energy efficiency.

We realize that public and corporate energy policy relies not only on technological progress, but also on the changing behavior of people aimed at saving energy [2]. In our analysis, however, we only concentrate on the former, underlining the physical basis of energy efficiency with a view to bring more clarity to energy efficiency measurements and to motivate the development of a consistent set of energy efficiency indicators to aggregate lower-level energy efficiency data at a national level.

We begin with a review of existing definitions of 'energy efficiency' and 'energy efficiency indicators' and analyze their relation with the concept of energy (Section 3). In presenting energy efficiency definitions suggested by the researchers we highlight the *pros* and *cons* of energy efficiency measures based on macroeconomic and engineering approaches. After that we analyze the use of energy intensity data, which is predominantly used at macro level (i.e. at national level) to estimate energy efficiency, and discuss its direct link with energy consumption. This analysis leads to identification of several criteria for building a set of energy efficiency indicators independent from energy intensity to address the demonstrated methodological difficulties in linking energy efficiency and energy intensity measures (Section 4.1). Finally, we analyze the possibility to widen the use of thermodynamic efficiencies to compensate the drawbacks of energy intensity as the measure of efficiency (Sections 4.2 and 4.3). The advantages and disadvantages of the statistical indicators based on the first and the second laws of thermodynamics are analyzed with particular attention to the difficulties and limitations outlined by Patterson [3].

## 3. Theory

A structured framework is still required to measure energy efficiency more precisely by taking into account complex industrial sites and energy flows, multiple products and fuels, and the influence of production rate on energy efficiency [4]. Brookes asserts that there is a "problem of the lack of any reliable indicator of progress in energy efficiency at the macroeconomic level" [5: 358]. Jollands and Patterson [6] note that "the need for indicators (particularly national level indicators) to be relevant to management and policy is a common theme throughout the indicators' literature" [6: 252]. Appropriate measurement frameworks should rely on a precise definition of 'energy efficiency'. However, despite the seeming clarity of the term, its meaning differs considerably across publications. Energy efficiency is often used as a generic term which refers to using less energy to produce the same amount of services or useful output [3].

The most well-known source of statistical information about the energy sector, the International Energy Agency (IEA), defines energy efficiency as "a way of managing and restraining the growth in energy consumption. Some company is called more energy efficient if it delivers more services for the same energy input or the same services for less energy input" [7]. Despite its brevity, this definition combines several rather indirectly connected measures. This definition starts with the reference to energy consumption. Moreover, it involves 'restraining the growth in energy consumption' which is a dynamic characteristic mathematically equivalent to the time derivative of energy consumption. The later notion of services is also problematic since it uses the economic term having no direct connection to energy. Some researchers [8] point to the methodological problems with the interpretation of existing energy efficiency indicators including the IEA energy indicators: value judgment problem (what exactly is considered to be the energy output and the quality of service?), the energy quality problem (in the sense of the second law of thermodynamics), the boundary problem (what part of energy is taken into account and what energy flows are left out?), partitioning and aggregation problems (for multiple services and outputs), the problem of structural effects (how to separate the influence of technical efficiency from the effects of behavioral, climatic and other factors?).

Since energy efficiency is an engineering concept at the most fundamental level, one could expect a more precise mathematical definition that would make up an energy efficiency indicator. Patterson [3] made a thorough review of energy efficiency indicators that can be used for policy-making. In general, the energy efficiency indicators are of the form 'energy input of a process/useful output of a process'. Patterson looked into 'physical–thermodynamic indicators', 'economic–thermodynamic indicators' and 'pure economic indicators' of energy efficiency, such as the widely used 'energy/GDP' or 'energy cost/GDP'. He points that "little attention has been given to precisely defining the term" [3: 377].

Following the Patterson's [3] macro-approach, Ang [9] revisited the classical energy efficiency indicators applied in national and international studies to offer a composite national index based on a bottom-up approach. The researcher states that there is no single definition of energy efficiency because the use of the energy efficiency concepts in engineering, environmental, economic and other studies may involve different methods and purposes.