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REVIEW ARTICLE

Revisiting energy efficiency fundamentals

**Luis Pérez-Lombard · José Ortiz ·
David Velázquez**

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Abstract Energy efficiency is a central target for energy policy and a keystone to mitigate climate change and to achieve a sustainable development. Although great efforts have been carried out during the last four decades to investigate the issue, focusing into measuring energy efficiency, understanding its trends and impacts on energy consumption and to design effective energy efficiency policies, many energy efficiency-related concepts, some methodological problems for the construction of energy efficiency indicators (EEI) and even some of the energy efficiency potential gains are often ignored or misunderstood, causing no little confusion and controversy not only for laymen but even for specialists. This paper aims to revisit, analyse and discuss some efficiency fundamental topics that could improve understanding and critical judgement of efficiency stakeholders and that could help in avoiding unfounded judgements and misleading statements. Firstly, we address the problem of measuring energy efficiency both in qualitative and quantitative terms. Secondly, main methodological problems standing in the way of the construction of EEI are discussed, and a sequence of actions is proposed to tackle them in an ordered fashion. Finally, two key topics are discussed in detail: the links between energy efficiency and energy savings, and the border between energy efficiency improvement and renewable sources promotion.

Keywords Energy efficiency · Energy efficiency indicators · Energy intensity · Energy savings

Introduction

Energy efficiency is on the focus of national energy policies and is considered as a keystone to mitigate climate change and for sustainable development. Energy efficiency defenders commonly quote a wide list of potential benefits that its improvement would bring, such as energy savings (reduction in energy consumption), environmental improvement (reduction in greenhouse gases and other pollutants), energy security (reduction in a country's reliance on imported energy sources), reduced energy costs (both for final users and for utilities), increased economy competitiveness and job creation (Schnapp 2012).

As a result of its interest, great efforts have been carried out during the last four decades to measure

L. Pérez-Lombard (✉) · D. Velázquez
Grupo de Termotecnia, Escuela Superior de Ingenieros,
Universidad de Sevilla,
Camino de los Descubrimientos s/n,
41092 Seville, Spain
e-mail: lpl@us.es

D. Velázquez
e-mail: dva@us.es

J. Ortiz
Building Research Establishment (BRE),
Garston, Watford WD25 9XX, UK
e-mail: ortizj@bre.co.uk

energy efficiency, to understand energy efficiency trends, to investigate the impact of energy efficiency on energy consumption and to design effective energy efficiency policies. The International Energy Agency (IEA) has played a leading role in the development of energy indicators to analyse how energy consumption is linked to human activities and to the efficiency in the use of energy. Energy efficiency policies have been implemented in most developed countries, and methodologies for the evaluation, measurement and verification of the impact of such policies have been developed worldwide (International Energy Agency 2009).

However, from our research work and professional experience within the field of building energy efficiency, we have learnt that many energy efficiency-related concepts, some methodological problems and even some of the energy efficiency potential gains are often misunderstood and a matter of ongoing debate, not only by laymen but even by specialists.

Consequently, this paper aims to revisit, analyse and discuss some efficiency fundamental topics that could improve understanding and critical judgement of efficiency stakeholders (policy makers, academics, technicians, final consumers, etc.) and could help in avoiding misunderstandings, confusions and unfounded judgements. Firstly, we address the problem of measuring energy efficiency both in qualitative and quantitative terms. Secondly, main methodological problems standing in the way of the construction of energy efficiency indicators (EEI) are discussed, and a sequence of actions is proposed to tackle them in an ordered fashion. Finally, two key topics are deeply discussed: the link between energy efficiency and energy savings, and the border between energy efficiency improvement and the promotion of the use of energy from renewable sources. Additionally, a glossary of key energy efficiency terms is annexed to improve the paper's readability.

Measuring energy efficiency

Efficiency concept

The term efficiency is widely used in different fields (engineering, economy, sociology, medicine, etc.) with different meanings, often as a qualitative attribute, and is semantically linked to other terms such as efficacy, effectiveness, savings and performance. It could be said it is a popular but vaguely used term, and thereby, it should be specified more precisely.

Efficacy is erroneously used as a synonym of efficiency. Efficacy is the capacity or power to produce a desired effect, whereas efficiency is the ability to achieve a desired result wasting minimum resources. Broadly speaking, being efficient means ‘doing more with less’ as described in the *Green Paper on energy efficiency* of the EU (European Commission 2005). In the engineering field, efficiency is generally defined as the ratio of the desired output (useful effect) to the required input (used resources) of any system. As an example of improper use of the word efficacy, we could mention its application to artificial light sources, usually evaluated in terms of lamp efficacy (California Energy Commission 2008) defined as the ratio of luminous flux (lumens) to input power (watts), which is indeed an efficiency ratio.

Effectiveness is either defined as the capability of producing a result, so being a synonym of efficacy, or as the degree to which something is successful in producing a result, much closer to the efficiency concept. Perhaps, the word effectiveness could stand between efficacy and efficiency if defined as the ratio of the actual result to the best theoretically achievable result (Cowan 1985), that is, a degree of proximity to the ‘ideal limit’ (how close the real output is from the ideal one). A proper use of the last meaning may be found within the thermal engineering field where the word effectiveness is used to indicate the ratio of actual heat transfer to the maximum ideal heat transfer rate[1] of heat exchanging devices.

On the other hand, it is frequent but inexact to identify savings with efficiency or vice versa. Savings indicate a reduction in the use of a given resource, so being an absolute amount of ‘not used’ resource, while efficiency is always a relative amount indicating the ratio of energy input to service output. However, the following message would be rather controversial if placed in the hall of a building: ‘Help us to be efficient, use the stairs instead of the lifts’. Those with a conservationist point of view would agree with this statement while others, more technically minded, would argue that the saving achieved would not increase the efficiency of the building. Consider another example, a dwelling where the boiler is improved and

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[1] The amount of heat that could be transferred in a heat exchanger of infinite area.

simultaneously the heating setpoint is increased, so that fuel consumption remains constant. The occupants receive a better quality of service (output) using the same amount of energy (input) as with the previous boiler. Could we say the house is more efficient? These examples highlight that the definition of efficiency involves both used resource and provided service. It seems obvious that efficiency improves if the same service is provided using fewer resources or if a better service is achieved with the same energy consumption. However, when both the service and the resource are modified, assessing the resulting efficiency requires deeper analysis, as later discussed in the paper.

Lastly, the word performance is also used within the efficiency field. It could be defined as the manner or quality of functioning (Amaratunga and Baldry 2002). Manner of functioning simply denotes operating in a particular way to accomplish a task or function (efficacy synonym), while quality introduces the nuance of the degree of excellence or success in the achievement of that task (efficiency synonym). Additional confusion has been introduced in Europe by the Energy Performance of Buildings Directive (EPBD) (Directive 2002/91/EC). The English word 'performance' has been translated as 'efficiency' in other European languages, while in the definitions section of the Directive, energy performance is defined as 'the amount of energy actually consumed or estimated…' which is indeed an energy use figure.

Indicators of energy use

Indicators are widely used in different fields (economy, medicine, etc.) as instruments which provide information to measure the change in a phenomenon or process. They are considered as a key instrument for evaluation since they may 'provide a simple and reliable means to measure achievement, to reflect changes or to help in assessment' (OECD 2002). In particular, energy indicators have been widely used in the last four decades with the aim of measuring, analysing and explaining the changes in energy used by humanity. They are useful to analyse how energy is linked to human and economic activity (International Energy Agency 1997a) and to better understand how economic, behavioural and technical driving factors shape energy use and related environmental impact (Schipper et al. 1992). The IEA has been pioneering in the development of energy indicators to study and analyse main factors behind changes in energy use and gas emissions. Energy indicators have become a keystone for the development of energy policies, since they help in summarizing energy information, analysing historical energy trends, drawing lessons from comparative analysis (benchmarking), monitoring target achievement of past and present energy policies, making effective policies for the future and focusing policy support. In short, energy indicators provide information to evaluate how energy consumption changes.

A deeper analysis of the reasons why energy is used must necessarily consider three additional concepts: *activity*, *structure* and *intensity*. The word 'activity' aims to explain the phenomena that generate or drive the demand of energy services, for instance, population is an indicator of how much activity is taking place in the residential sector. The term 'structure' is used to explain the relations between different activities, in particular the types of activities that are taking place and their impact on other activities belonging to the same sector. For example, the transport structure refers to the share of different transport modes within the transport sector. Finally, the word 'intensity' is used as a measure of the amount of energy input to deliver the unit of service, product or output, e.g., the energy needed to heat the unit of a floor area.

The IEA energy indicators approach aims to separate the effects of activity, structure and intensity on energy consumption by the use of factoral decomposition to achieve a disaggregated analysis of energy use (Schipper et al. 2001). Thus, changes in energy use are analysed through the so-called ASI equation:

$$E = \sum A_i \cdot S_{i,j} \cdot I_{i,j} \tag{1}$$

where E is energy use, A_i is a measure of the activity of sector i, $S_{i,j}$ represents the weight of subsector j within the structure of sector i, and $I_{i,j}$ represents the intensity of subsector j of sector i.

The decomposition of energy use can be extended to assess CO_2 emissions, if the effect of energy carriers ('fuels') is taken into account by a fuel factor (F) that embraces the share of a fuel within a subsector and the CO_2 emissions per energy unit of each fuel (carbon coefficient). Emissions (G) can then be assessed as:

$$G = \sum A_i \cdot S_{i,j} \cdot I_{i,j} \cdot F_{i,j,k} \tag{2}$$

where $F_{i,j,k}$ stands for the carbon content of fuel k used in subsector j of sector i.

Equations 1 and 2 are operative if energy consumption information is available for different sectors and subsectors, *activity indicators* are measured for each sector, the share of different subsectors in each sector (*structure indicators*) are known, *intensity indicators* measuring energy use per unit of service output are assessed and carbon factors are derived from fuel mix and carbon coefficients. A table summarizing the different sectors and subsectors covered by the IEA indicators approach and corresponding activity, structure and intensity indicators can be found in Unander (2005).

The product of A and S of Eq. 1 is sometimes referred to as 'energy service' and could be thought as a measure of the amount of service provided by an energy sector, subsector or end use. Services can be measured in physical units, such as floor surface (in square metre) or passenger-kilometre (pkm) or economical units, like gross domestic product (GDP) or value added.

Intensity indicators (I) measure the energy use per service unit, for instance, heating consumption per unit of floor area (in kilowatt hour per square metre) or car energy use per passenger-distance[2] (in kilowatt hour per passenger-kilometre). They are also referred to as efficiency indicators because they are related to the inverse of energy efficiency (a reduction in energy intensity may indicate an increase in energy efficiency). The product of I and F is often known as *carbon intensity* and denotes CO_2 emissions per service unit.

In short, the IEA approach aims to separate intensity and fuel factors from those related to the demand for energy services, since the reasons for their changes are so different. In the next paragraph, we focus on the definition of EEI that could be regarded as a subgroup of energy indicators, which aim to isolate efficiency changes from other activity, structural or behavioural factors that significantly affect the values of energy indicators.

Energy efficiency indicators

In the engineering field, the oldest EEI could be named energy conversion efficiency (η) or simply energy efficiency, measuring the ratio of useful energy output to energy input,

$$\eta = \frac{\text{Useful energy output}}{\text{Energy input}} \tag{3}$$

In this expression, both elements of the quotient are energy flows, and the ratio can be also referred to as a thermodynamic efficiency indicator.[3] Thermodynamics, as the science of energy processes, allows the quantification of energy flows from thermodynamic state variables. Energy can be expressed in terms of final energy, measurable at the point of use; primary energy, considering its impact on the energy resources; or other energy-related magnitudes such as gas emissions, energy costs or even the whole life cycle, so in principle, Eq. 3 can be assessed without difficulties.

A different approach, closely related to the IEA intensity concept, can be used to define other types of EEI. They relate used resource (input) and provided service (output) to measure the amount of energy needed to provide the unit of service. This type of indicators is commonly referred to as energy intensities (EI),

$$EI = \frac{\text{Energy input}}{\text{Service output}} \tag{4}$$

The former equation raises a key question: How should we measure energy input and service output? Energy is a physical magnitude, therefore measurable, but services involve very diverse activities (transportation, refrigeration, lighting, etc.) and a good deal of subjective elements (comfort levels, socio-cultural aspects, etc.) rather difficult to quantify.

With regard to the service output, it is worth distinguishing between quality and quantity. Evaluating the quality of service is generally difficult, especially when multiple services are provided by the system subject to analysis. For example, heating ventilation and air conditioning (HVAC) systems may supply space heating, space cooling, humidification, dehumidification and ventilation for an adequate indoor air quality. Quantifying the service output is done by measuring a suitable magnitude, demand indicator

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[2] Passenger-distance is determined by multiplying the number of passengers by the distance a vehicle travels, typically measured as passenger-kilometre (pkm).

[3] It is worth mentioning the nuances introduced by some Romance languages such as Spanish, French and Italian, using the words 'rendimiento', 'rendement' and 'rendimento', respectively, to refer to non-dimensional thermodynamic efficiency indicators in particular.

(Energy Information Administration 1995), which normalises the energy input facilitating comparative analysis. There are physical demand indicators such as passenger-distance for transport means or the conditioned area for HVAC systems and, economic demand indicators such as GDP of a country or the running costs of an installation.

Some sources (Asia Pacific Energy Research Center 2001) refer to physical and economic efficiency indicators when evaluating EI through physical or economical demand indicators. Physical efficiency indicators, directly relating energy to a physical measurement of system output, are also referred to as specific energy consumption (SEC). However, there are many different physical magnitudes to measure the amount of output (mass, surface, distance, volume, etc.), and perhaps SEC should be more precisely used to denote energy consumption per unit of mass of product in industrial processes (Phylipsen et al. 2002). Economical efficiency indicators[4] relating energy consumption and economic activity are commonly used for macro-policy analysis.

On the other hand, the expression 'energy performance' is also used in the field of EEI. The oldest energy performance ratio is coefficient of performance that measures the energy efficiency of a heat pump as the ratio of heat addition to the heat source (useful output) to energy input. Within the scope of building sector, European energy performance indicators (EPI) and American energy intensity indicators (also called energy use intensities) are equivalent since they are both ratios of energy use input to energy service output (Pérez-Lombard et al. 2009).

Great efforts to exhaustively review and comprehensively analyse the EEI of main energy end-use sectors (transportation, industrial, residential and commercial[5]) have been carried out by the IEA (International Energy Agency 1997b, 2008, 2004), the World Bank (Phylipsen 2010), the Energy Information Administration (1995) and the Lawerence Berkeley National Laboratory (Rue du Can et al. 2010). For the industrial sector, the handbook on energy efficiency by Phylipsen et al. (1998) and the survey for Asia Pacific countries (Asia Pacific Energy Research Center 2000) are of great interest.

Constructing energy efficiency indicators

As previously commented, measuring energy efficiency requires the definition, assessment and analysis of a set of EEI. The construction of these indices requires the consideration of some methodological problems: value judgement, energy quality, boundary definition, energy partitioning/aggregation and structural effects. This has been discussed in depth by Patterson (1996).

First, it must be accepted that valuations and value judgements are an integral part of the definition of EEI (*value judgement problem*). This is evident for the numerator of thermodynamic indicators because the energy output considered to be useful must be differentiated from that regarded as energy loss, but complex for the denominator of energy intensities, since the assessment of the amount and quality of service output for which energy input is required is always subject to valuations. For instance, within the HVAC field, the definition of the magnitude to measure the demand of comfort service by building occupants (floor area, conditioned area, thermal energy need, etc.) and the quality of service to be provided (indoor air quality requirements) are always a matter of discussion.

Secondly, the *energy quality problem* arises for those systems and processes involving energy sources and end uses of different energy quality. Some kind of adjustment is needed to make energy flows comparable and avoid unfair 'apple and oranges' comparison. A typical example is the necessary adjustment in the addition of electricity and fossil fuels because enthalpy does not take account of the second law of thermodynamics (exergy). Different attempts have been made to overcome the energy quality problem. Some authors have worked on the definition of 'second-law energy efficiency' by measuring energy in terms of Gibbs free energy, exergy or available work. Another approach is to define second-law energy efficiency relative to the 'ideal' minimum energy requirement. Patterson (1993) proposed the 'quality equivalent methodology' to measure energy quality in complex economic systems where there are many desired end uses of energy. However, none of them has been widely accepted, and first-law energy measurements based on enthalpy

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[4] Some sources improperly refer to this type of indicators simply as energy intensities.

[5] Note that in this classification, building sector is split into residential (household) and commercial (non-residential). Note also that the IEA usually splits transportation into travel and freight and includes commercial buildings within the services sector.

remain to be the standard in the evaluation of physical and economical EEI.

Third, the *boundary problem* deals with the adoption of boundary assumptions to clarify which energy flows or transformations are beyond the scope of the problem. For instance, sometimes, commercial energy inputs (delivered energy) are accounted for while other free energy flows, such as site-renewable energy sources, are neglected. In addition, one should consider how far back energy input should be traced (site energy, primary energy, embodied energy, etc.). For example, if two different space heating devices (electric heat pump and gas boiler) are compared in terms of provided heat per unit of energy input, the heat pump is far more energy efficient if energy input is measured at the 'site' (final energy) while their efficiencies turn out to be similar if measured at the 'source' (primary energy).

Fourthly, the *partitioning and aggregation problems* need to be addressed. The first deals with the difficulties in splitting the energy input of those systems and processes providing multiple services or outputs, while the second appears whenever one aims to sum up different physical outputs corresponding to the same energy input. Stated another way, problems arise both to split (disaggregate) the energy input into different outputs (e.g. how to allocate the energy input of a sheep farm to their wool and milk production) and to sum up (aggregate) different outputs corresponding to the same energy input (e.g. how to add kilograms of wool and litres of milk in a sheep farm). As for the partitioning problem, different conventions have been proposed to split energy input in proportion to different parameters (economic values, physical units, etc.). Other methods such as regression analysis have been used (Cleland et al. 1981), but none of them has gained widespread acceptance. Potential solutions to overcome the aggregation problem could be the 'basket approach', the Laspeyres physical index, the actual to reference ratio approach and the composite indicator approach (Nanduri et al. 2002). Thus, there is no common agreement on the subject, and assumptions for energy input allocation and energy output summation should be defined in each particular case.

A final problem could be referred as the *structural effects problem*. The challenge is constructing EEI capable to isolate *technical* or *net efficiency* from those underlying effects (activity, structural, behavioural, climatic, etc.) that could affect energy use and *gross* energy efficiency. For example, when using EI expressed as fuel consumption per kilometre to measure energy efficiency in car transportation, a shift in the market to off-road vehicle sales would increase EI, even if on average new vehicles were powered by more efficient engines.

Different approaches, methodologies and international joint projects have been developed to address the methodological problems standing in the way of constructing, measuring and evaluating EEI. Among the most widely known are the IEA approach (International Energy Agency 1997b), the ODYSSEE-MURE project (ADEME 2009) and the World Energy Council (WEC) energy efficiency project (World Energy Council 2008). However, these projects focus on the macro-level energy efficiency analysis basically for the upper levels (sector and subsector) of the efficiency pyramid for which energy data are available. Additional work has been carried out to provide methodologies for the decomposition of EEI, to develop top–down and bottom–up approaches to address energy efficiency trends and measure energy savings and to maintain international databases on EEI.

The IEA approach is accepted as a sort of standard for the definition of EEI for the upper aggregation levels (national, sectoral and subsectoral); however, for those energy systems placed at the intermediate levels of the efficiency pyramid, there is controversy on the construction of EEI. Moreover, some methodological problems such as energy quality and partitioning problems cause ongoing discussion, and unfortunately, none of the attempts to overcome their difficulties has gained widespread acceptance. For the above reasons, we believe that there is no common solution to the problems encountered in the construction of energy efficiency indicators for energy-using systems, and consequently, we propose a sequence of actions that could help to tackle main problems in an ordered and critical fashion: (1) setting service quality, (2) identifying aggregation levels, (3) defining energy use indicators and (4) choosing demand indicators (Fig. 1). In the following sections, the proposed sequence is explained in detail, and the case of HVAC systems is taken as a practical example of its application to a particular meso-level energy-using system. Further details on the construction of EEI for HVAC systems can be found in Pérez-Lombard et al. (2012).

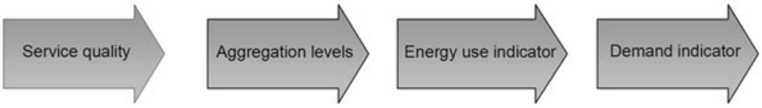

Fig. 1 Energy efficiency indicators construction process

Service quality

Firstly, the service provided by the system should be clearly defined and qualified. It is essential to agree service quality before attempting to quantify and compare different options, as it would only be fair to quantitatively compare alternatives providing a similar or agreed service quality. For instance, transportation's main purpose is moving people and goods to a certain distance, but other quality factors such as speed, security, comfort or ergonomics could be considered. For example, if energy efficiency of cars is compared in terms of EI expressed by fuel consumption per kilometre, small cars would probably be more efficient (lower EI) than large four-wheel-drive vehicles. However, one could argue that the latter are faster and more secure, or even that their engines could have higher conversion efficiency, and so the efficiency comparison would be controversial due to service quality factors. In short, the comparison of EEI for products or systems providing different services is difficult, and initial value judgements for the definition and qualification of service output become essential as a first step in the EEI construction process.

HVAC system application

Providing comfort to building occupants is the main output of HVAC systems, but defining and qualifying thermal comfort service is a complex problem. Firstly, the definition of thermal comfort is subject to personal value judgement.[6] Secondly, according to their ability to provide ventilation and to control temperature and humidity, HVAC service can be classified in different service levels (see table 1 in Pérez-Lombard et al. 2011) Additionally, different qualities could be defined for each HVAC subservice: ventilation, heating/cooling and humidification/dehumidification. As for ventilation, standard EN 13779 (2007) classifies indoor air quality in four IDA levels. As far as heating/cooling are concerned, service quality could be assessed simply by temperature set points, expressed in terms of space air or operative temperatures. Thus, it seems obvious that HVAC service quality depends on different parameters such as ventilation rates and indoor conditions. These parameters have influence on both energy input and service output, and consequently, a fair comparison of HVAC energy efficiency indicators would only be possible if service quality is agreed in energy calculations as recognised by the European standard EN 15251 (2007).

Aggregation levels

Secondly, aggregation levels for energy use should be identified and represented on the efficiency pyramid (International Energy Agency 1997b). Energy-consuming devices are placed on its base, followed up by new levels in sequence such as subsystem, service, system, plant, subsector and sector, and finally, on its vertex, aggregated national energy indicators. The higher in the pyramid level, the lower the number of potential efficiency indices and the higher the number of possible activity and structural effects. For instance, at the upper levels of the pyramid (macro-level), activity factors, such as population growth or increase in passenger-kilometres, and structural effects, such as changes in occupation rate or modal shifts in transport, may influence energy consumption of residential and travel sectors, respectively, thus hindering energy efficiency analysis and savings evaluation. At the lower pyramid levels (micro-level), structural effects may be neglected, and energy efficiency gains can be directly assessed by energy intensities. For instance, the transport system may be regarded to be more efficient if the ratio of energy consumption to pkm (travel energy intensity) decreases due to a modal shift from car use to public transport; however, at the micro-level, car, bus or train efficiency, measured by energy consumption per kilometre, could remain constant, with no efficiency gain achievement.

It is worth mentioning the benefits of defining specific efficiency pyramids for each energy system whenever possible. This way, additional levels of analysis can be addressed allowing the definition of new

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[6] ASHRAE 55 (ASHRAE Standard 55 2010) defines thermal comfort as the state of mind which expresses satisfaction with the surrounding environment.

disaggregated EEI that could be helpful in the efficiency analysis of such systems. In short, at this step, assumptions for allocating energy consumption to the different groupings defined at each aggregation level should be made to address the partitioning problem.

HVAC systems application

Global energy consumption of HVAC systems may be obtained by summing up of energy use of energy-consuming devices (boilers, chillers, fans, pumps, etc.). However, between global and equipment levels, two additional aggregation levels, subsystems (cool generation, heat generation, water transport and air transport) and services (cooling, heating and ventilation) can be distinguished and represented on the HVAC energy efficiency pyramid (see figures 2 and 4 in Pérez-Lombard et al. 2012). Allocating equipment energy use to subsystems is not a complex task; however, allocating equipment consumption to HVAC services is cumbersome.[7] The choice of aggregation levels and corresponding groupings plays a key role on the development of the energy efficiency analysis. Indeed, our research in the field of HVAC systems has proven that splitting energy use in subsystems has numerous advantages over a service partitioning.

Energy use indicator

Thirdly, a magnitude to measure energy use should be selected. At the micro-level, one faces stand-alone energy conversion devices where energy carriers (typically fuels and electricity) are converted into a useful form of energy such as motion, heat, cool or light. Commonly at this level, energy systems use one single energy carrier, e.g. electric motors, gas boilers, electric chillers or electric lamps, and thus, energy use may be measured in terms of final energy. However, for the comparison of systems using different energy carriers at the micro-level or for the addition of different energy carriers to obtain aggregated energy consumptions at the meso- and macro-levels, primary energy should be used to account for their effect on energy resources through the use of primary energy factors, also known as site-to-source conversion factors. An environmental approach leads to the assessment of energy use in terms of gas emissions or even to a life-cycle analysis. And if the economy is the focus, energy consumption should be measured by energy costs. Thus, in this step, any issue related to the boundary and energy quality problems needs to be addressed.

HVAC systems application

The complexity of the boundary problem for HVAC systems has been significantly increased with the introduction of some concepts from standard ISO 13600 (1997), such as delivered energy, exported energy, net delivered energy, cogenerated energy and self-generated energy, within the field of building energy analysis (see figure 9 in Pérez-Lombard et al. 2011). The amount of energy delivered to a building site by energy companies is referred to as delivered energy or site energy. For those buildings exporting self-generated (or cogenerated) energy, net delivered energy is defined as delivered minus exported energy. Almost every building is equipped with thermal energy generation for its own use, but rarely is part of this energy exported. Electricity generation and cogeneration of heat and power in buildings have become not uncommon, either for their own use or to be exported, especially since energy policies provide incentives or require feasibility studies for this kind of facilities. European Directives on energy end-use efficiency and energy services (ESD) (Directive 2006/32/EC), on the promotion of the use of energy from renewable sources (RED) (Directive 2009/28/EC) and on the energy performance of buildings (EPBD recast) (Directive 2010/31/EU) promote or require measures to increase on-site generation of thermal and/or electric energy from renewable sources. In particular, cogeneration, district heating and cooling and energy supply based on energy from renewable sources are regarded as high-efficiency alternative systems in the EPBD recast.

The use of renewable energy taken directly from the environment (site-renewable energy) is particularly controversial. Within the building sector, this energy flow can encompass: daylighting, natural ventilation, free-cooling, passive cooling and heating systems, heat pumps and self-generation of thermal or electric energy from renewable sources. The use of these free and inexhaustible energy sources reduces the need for importing energy and thereby net delivered energy and increases the share of renewable

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[7] See section 2.2 Pérez-Lombard et al. (2012) for details.

energy in building energy use, thus necessarily linking energy efficiency improvement and renewable energy promotion. This subject would be further discussed in 'Energy efficiency vs. renewable sources promotion'.

Demand indicator

Lastly, a magnitude to measure the quantity of service provided should be selected. Sometimes physical magnitudes are used, like the mass of product for an industry, the distance covered by a mean of transport or the floor area for a building. In other cases, economic variables such as the GDP of a country or the gross value added of the commercial sector are preferred.

The aggregation level has a significant influence on the complexity of defining and quantifying the amount of service, activity or achievement provided. At the micro-level, the useful effect or output of an energy conversion device can be rather easily defined. For instance, the output of a gas boiler is delivering thermal energy (in kilowatt hour) to a water flow rate, or the achievement of a lamp is providing a certain luminous flux (*lumen*). If the quality and quantity of the achievement are agreed, a reduction in energy consumption, keeping service output constant, reduces energy intensity, increases energy efficiency and saves energy. However, as previously discussed, even at the micro-level, quality factors may hinder efficiency analysis, such as the differences in supply water temperature of a boiler or the different 'lights' provided by incandescent and fluorescent lamps. At the meso-level, energy-using systems are composed of different energy conversion devices, e.g. HVAC systems consisting of boilers to heat water, chillers to cool water, fans to move air, etc. For this reason, defining the overall achievement of this type of systems is much more complex. Lastly, at the upper levels of the efficiency pyramid, it is not possible to clearly define the achievement or service provided, and so activity indicators are accepted as a 'basic agreement' for accounting for the activity of energy sectors. For instance, population is agreed to be a basic measure of the demand of energy of the residential sector, but it is evident that the definition of the service provided by houses is almost impossible.

HVAC systems application

Three demand indicators are mainly used to measure HVAC service output: floor area, thermal energy and delivered volume. Floor area is a typical normalisation parameter within the building sector. In the case of HVAC systems, conditioned area should be used rather than built area to neutralise the impact of unconditioned spaces on energy intensities. The second indicator is usually referred to as thermal demand or 'energy need' and assesses the amount of thermal energy required to provide space comfort. It may be calculated from a thermal balance of heat flows at space level and could be thought of as an indicator of the energy quality of architectural design. Lastly, when analysing energy efficiency of fluid transportation, the provided service is usually assessed by delivered volume and energy efficiency is measured by the specific consumption that represents the energy use to deliver the unit of fluid volume.

Discussion

In this section, the relations between energy efficiency improvement, energy savings and the promotion of the use of renewable sources are discussed in order to examine whether potential benefits of energy efficiency are really achieved.

Energy efficiency vs. energy savings

In this section, we aim to discuss in further detail the link between energy efficiency, a relative magnitude denoting the ratio of energy input to service output, and energy savings, an absolute amount measuring a reduction in energy use. Broadly speaking, energy consumption (E) may be expressed as:

$$E = \text{service demand} \cdot \text{energy intensity} = \frac{\text{service demand}}{\text{energy efficiency}} \tag{5}$$

Obviously, energy consumption does not only depend on energy efficiency (or intensity) but also on the demand of energy services (the product of A and S in the ASIF equation).

Energy efficiency concept and EEI have been addressed in 'Measuring energy efficiency'; however, energy savings should be further analysed before discussing their link with energy efficiency. In a broad sense, energy savings may be defined (see Appendix) as a reduction in the use of energy, and thus, they could be achieved by lower service demand, higher energy efficiency (lower energy intensity) or both. In this approach, 'actual savings' may be directly measured as the difference between real consumptions at different times, so they are also referred to as 'change in energy use' or 'mutation of consumption' (Boonekamp 2011). The main advantage is that 'actual savings', being equivalent to a reduction in real energy consumption, are easily explained, shown and understood, while its main disadvantage lies in the difficulties to decompose the impact on energy savings of activity, structural, behavioural and efficiency factors.

Another approach to the energy savings concept is considering that energy is saved only when the same activities are performed or the same outputs are provided with less energy consumption. In this approach, service demand remains constant, and an improvement of energy efficiency necessarily lowers energy consumption and saves energy, so that 'efficiency always leads to savings'. This type of 'hypothetical savings' is to be assessed by the difference between a 'baseline consumption' (the one that would be in the absence of energy efficiency improvement assuming no changes in the demand of energy services) and 'real consumption' after efficiency improvement. In this case, savings represent the absence of energy use due to efficiency improvements and aim to isolate the effect of efficiency factors on energy consumption, assuming that the rest of the effects remain unchanged. This approach to the savings concept is commonly used for the evaluation, measurement and verification of those energy savings that are subject to energy contracts, typically between energy consumers and energy services companies, and for the measurement and verification of national energy savings targets, which are a keystone of energy policy in many developed countries. Details on the methods to measure energy savings through this approach are beyond this paper's scope and may be found in Boonekamp (2006), Lawrence Berkeley National Laboratory (2011), Efficiency Valuation Organisation (2010), Boonekamp and Thomas (2009) and Bosseboeuf et al. (2005). However, it should be highlighted that 'hypothetical savings' are commonly misunderstood by final consumers; indeed, sending 'savings and efficiency messages' when energy consumption is increasing could be seen by someone, at least, as misleading. For instance, Spanish consumers have difficulties to understand that 'Savings and Energy Efficiency Strategy for the building sector in Spain during the period 2004–2012' aims to save 6.81 Mtoe, while building energy consumption in the same period is expected to grow at an average annual rate of 3.5 %.

In the discussion that follows, we use the words energy savings in its broad sense ('actual savings'), denoting a reduction in energy input irrespective of the reason that causes it. Let us use Table 1 to orderly raise some efficiency versus savings questions. At first sight, the table shows that energy efficiency and energy savings are not equivalent; in other words, an increase in energy efficiency does not assure energy savings, and a reduction in energy use does not always imply an energy efficiency improvement.

Firstly, let us discuss those situations where energy efficiency clearly grows. Keeping service output constant while reducing energy input (row 1) is only one of the ways to improve energy efficiency; however, many sources reduce the energy efficiency concept to this particular case: reducing energy use without affecting the quality of the provided services. If the

Table 1 Energy efficiency vs. energy savings

Energy input	Service output	Energy savings	Energy efficiency	Particular term
↓	Constant	Yes	↑	Technical energy efficiency
Constant	↑	0	↑	Energy productivity
↓	↑	Yes	↑↑	Efficiency optimization
↓	↓	Yes	?	Energy conservation
↑	↑	No	?	Rebound effect (if efficiency increases)
↑	Constant	No	↓	Inefficiency due to higher consumption
Constant	↓	0	↓	Inefficiency due to lower service
↑	↓	No	↓↓	High inefficiency

same energy is used to deliver more service output (row 2), energy is not saved, but efficiency is improved; however, we prefer to use the words ‘energy productivity’ to denote this particular case. In the case that better services would be provided using fewer resources (row 3), energy efficiency would rapidly grow, and energy savings would be achieved. This ‘optimal’ case could be referred to as ‘efficiency optimization’.

Let us discuss now those situations in which energy use and service output are both reduced or increased simultaneously. In the case that energy input and service output decrease (row 4), it is obvious that energy savings are achieved, but the assessment of energy efficiency requires a comparison of the decreasing rates of energy input and service output. As previously said, energy may be measured, but in the evaluation of the service output, there is plenty of subjectivity that might easily undermine any attempt to assess whether energy efficiency grows or decreases. The words ‘energy conservation’ are precisely used to indicate that a reduction in energy consumption corresponds with a reduction in the amount or quality of service provided. There are three different types of energy conservation measures: (1) those that save energy without changing energy efficiency, because energy input and services output decrease at the same rate; (2) those where energy consumption decreases at a higher rate than the drop in service output, thus not only is energy conserved but efficiency is improved and (3) those where energy input decreases at a lower rate than the drop in the demand of energy services, and so, energy efficiency drops, while conserving energy. This is the reason for the question mark in row 4. Examples of energy conservation measures include using occupancy sensors to turn off the lights, using the car less or bringing winter and summer space temperatures lower and higher, respectively, in HVAC systems.

In short, energy conservation is better associated with activity, structural and behavioural effects, while energy efficiency is commonly used to indicate technological improvements aiming to reduce energy intensity. The optimal option to save energy would be blending energy conservation and technical efficiency.

Those situations where energy use and service output increase simultaneously (fifth row in Table 1) are also a matter of debate. Energy efficiency can increase, even with higher energy consumption, if this grows at a lower rate than the service output. This sort of ‘efficiency paradox’ is unfortunately common due to two key reasons. First, improvements in the quality of life come usually with the demand for more and better energy services that usually increase energy consumption. Good examples of these are the emerging economies with rapidly growing energy consumption figures in recent years despite significant improvements in energy efficiency (Energy Information Administration 2009). For instance, from 2002 to 2007, total primary energy consumption in India grew at an average annual rate of 5 %, while energy intensity, in terms of primary consumption per dollar of GDP, had an average annual decrease of 4 %. On the other hand, energy efficiency causes a ‘rebound effect’ in consumption that has been analysed by several authors (Greening et al. 2000; Brännlund et al. 2007; Holm and Englund 2009; Sorrel 2009). Improvements in energy efficiency lead to a more cost-effective use of energy services, increasing the potential to satisfy bigger demands and thereby increasing energy consumption. An excellent discussion of the rebound effect including suitable examples taken from the European energy policy can be found in Lebot et al. (2004).

The background question at this point could be: Is the goal saving energy or being more efficient? We believe that the final goal would be saving energy. Energy policies should exploit the opportunities in every stage of the ‘energy chain’ (Cullen and Allwood 2010) to achieve this goal. Thus, efforts should be made to reduce the amount and quality of energy services demanded (energy conservation) and to reduce the energy input to provide the unit of service (technical efficiency), so that the need for energy carriers (delivered energy) could be reduced, including their subsequent impact on energy resources (higher primary efficiency) and on CO_2 emissions (lower carbon intensity). Unfortunately, up to now, energy policy has focused primarily on the supply side and on technical efficiency and has devoted less attention to energy conservation. It should be desirable that energy efficiency would be enough, but unfortunately, energy consumption is continuously growing despite efficiency policy efforts, even in developed countries. It seems that we have taken efficiency gains to demand higher amounts and levels of energy services, rather than to reduce consumption. Conservation measures and policies are essential (Herring 2000) to achieve a rational use of energy mainly through behavioural changes that involve ethical and cultural issues. A change from consumerism to conservationism (Herring 2006), a sort of 'energy use revolution' should be on top of our priorities if a successful outcome is to be achieved. Key insights to improve this discussion may be found in the following outstanding papers: Lebot et al. (2004), Moezzi (1998) and Bertoldi et al. (2009, 2010).

Energy efficiency vs. renewable sources promotion

It is commonly agreed that promoting energy efficiency improvement and the use of renewable energy sources are strategic instruments in order to alleviate the world energy and environmental crisis. However, their goals are different: energy efficiency pursues reducing the energy used by systems to provide energy services, while renewable sources aim at replacing exhaustible resources and reducing their environmental impact. For a better discussion of the border between efficiency improvement and renewables promotion, we will separately analyse on-site and off-site renewables.

Energy systems may take renewable energy directly from the environment and use it to reduce their need to import energy from the supply side. For instance, solar panels on a building's roof may collect solar energy to heat water, reducing delivered energy consumption of water heating. The use of this type of renewable energy flows is usually referred to as 'site renewables' use or 'renewable behind the meter' (RBM) technologies (Boonekamp and Thomas 2009) to denote that they are 'collected on-site' and not accounted for by delivered energy meters. RBM technologies have become common within the building sector, since they reduce net delivered energy consumption, so they are being regarded as an energy efficiency improvement (the same service is provided with lower energy input from the supply side). So, at this point, a first link between renewables and efficiency is evident: site-renewable technologies can be considered as energy efficiency measures. Indeed, they are listed as efficiency measures in annex IV of the Energy Services Directive (ESD). However, there is ongoing controversy on the subject. For example, in the WEC review on energy efficiency policies (World Energy Council 2008), one may read: 'It is not clear why measures to promote solar hot water heaters were chosen as a case study, as this is not an energy efficiency measure, but a renewable energy measure'.

So, it is clear that site-renewable technologies can improve energy efficiency, but are they accounted for in the calculation of the renewable share of total energy consumption? To answer to this question, one should examine the details of the calculation of the overall share of energy from renewables sources. If site renewables are included both in the numerator and denominator, thus avoiding an unfair assessment of renewable ratio, a policy target for the renewable share, such as that established by the Renewable Energy Directive (RED), could simultaneously promote energy efficiency and renewable energy use. This could be thought as a second link between renewables and efficiency policies.

In the discussion above, we have assumed that site renewables are treated all the same, but unfortunately, this is not the case. Those technologies allowing on-site thermal or electric generation (or co-generation of heat and power) from solar, wind or water energy are referred to as active, and they are usually favoured, since they are accounted for by the renewable share, they are covered by energy efficiency policies and, additionally, they often receive special economic incentives. The rest of the technologies (daylighting, passive cooling, etc.) are referred to as passive and are simply treated as energy efficiency measures. We believe that site renewables should be considered all the same since they all save net delivered energy and increase the renewable share. Consequently, energy policies should avoid unfair approaches that promote the use of active renewable sources, in comparison to passive ones. Fortunately, this unfair treatment is being reduced as the list of site renewables covered by policies for the promotion of renewables is extended, as clearly shown by the inclusion of heat pumps in the RED.

The situation is quite different for those energy carriers generated from renewable energy sources ('green electricity', biofuels, biomass, etc.). Systems importing these off-site renewables do not reduce their energy use, nor do they improve their energy efficiency, despite replacing an exhaustible resource and reducing its environmental impact. Moreover, using some off-site renewables may increase delivered energy consumption (negative energy savings), if energy efficiency of the device that uses the renewable source is lower than that of an equivalent device using an exhaustible carrier. A typical example may be the promotion of the use of biomass boilers with energy efficiencies far lower than those of gas-fired boilers.

Finally, let us remark that the difference between energy and carbon intensities (clearly stated by Eq. 2) should not be disregarded during the design of energy efficiency policies. Unfortunately, this nuance is many times neglected, and carbon intensities are improperly used as a substitute of energy efficiency indicators. For example, most European energy certification schemes aimed at improving energy efficiency in buildings are based on carbon intensity expressed in terms of CO_2 mass emissions per unit of floor area and year. As a result of this approach, some certifiers tend to promote the use of off-site renewables to improve the energy label, before paying attention to the efficiency of building services. We do not believe that a building becomes more energy efficient because of the use of biofuels for heat generation or by installing a biomass boiler. In the former case, the building would be less carbon intensive or more ‘environmentally friendly’, but the underlying building efficiency would remain constant.

Conclusions

The efficiency concept relates desired results and required resources. In an energy context, the result is the provision of an energy service, and the resource is the energy input to the system. Thus, the quantification of energy efficiency should be addressed by means of EEI relating energy input and service output.

Main problems for measuring energy efficiency both in qualitative and quantitative terms have been discussed. Efficiency-related concepts, such as efficacy, effectiveness, intensity, performance, savings and conservation, are often improperly used, even by specialists, thus hindering energy efficiency analysis. This paper attempts to make those concepts precise and has chosen the best available definitions to provide a consistent terminology, summarized in the Appendix.

The quantitative assessment of energy efficiency is necessarily based on the construction and measurement of a set of EEI. The paper revises the main methodological problems for their construction and proposes a sequence of actions to tackle these problems in an ordered fashion: (1) setting the service quality, (2) identifying aggregation levels on the efficiency pyramid, (3) defining a magnitude for consumption measurement and (4) choosing a suitable magnitude to quantify the service provided. A brief summary of the application of this sequence to the construction of EEI for HVAC systems is included to illustrate this procedure.

Finally, two key but controversial topics have been discussed: the link between energy efficiency and energy savings, and the border between energy efficiency improvement and renewable sources promotion.

Energy savings and energy efficiency concepts have been compared, and some specific related terms such as technical efficiency, energy productivity, energy conservation, rebound effect, etc. have been clarified. Unfortunately, promoting energy efficiency without achieving energy savings would not address global energy challenges. Therefore, efforts should be made to reduce the amount and quality of energy services demanded (energy conservation) and to reduce the energy input to provide them (technical efficiency), so that the energy imported by energy systems could be reduced, including their subsequent impact on energy resources and on the environment. In short, energy efficiency policies are not enough, and their combination with conservation policies is essential to achieve a rational use of energy mainly through behavioural changes: citizens being aware of their responsibility in energy consumption and environmental crisis.

The use of site-renewable technologies reduces net delivered energy and can be considered, therefore, as an energy efficiency measure. Additionally, if site renewables are fairly accounted for in the calculation of the renewable share, they simultaneously promote the use of renewable sources. We believe that site renewables should be considered all the same, being all addressed by efficiency and renewables policies. The case of off-site renewables is different, since they do not reduce system energy use, nor do they improve energy efficiency, despite replacing an exhaustible resource and reducing its environmental impact.

It is expected that the growing trend of energy consumption will continue during the coming years, as long as resource exhaustion or economic crisis allows it. A profound ‘energy revolution’, combining conservation, efficiency and renewable policies with higher social awareness of rational energy use, is urgent and essential to achieve a sustainable energy future.

Appendix

Definitions of key energy efficiency terms

Efficiency concept	
Efficiency	Ability to achieve a desired effect, result or output wasting minimum resources
Effectiveness	Ratio of the actual outcome to the theoretically possible or ideal outcome
Efficacy	Capacity or power to produce a desired effect, result or output
Performance	Manner or quality of functioning
Savings	Reduction in the use of resources
Energy efficiency concept	
Energy efficiency	The ratio between service output or result and the energy input required to provide it
Energy savings	A reduction in the use of energy
Energy intensity	The amount of energy needed to provide the unit of service or activity
Energy performance	The quality of functioning of a system regarding its energy use
Energy conservation	A reduction in the use of energy that corresponds with a reduction in the amount or quality of provided service; also referred to as energy sufficiency
Energy productivity	More service is provided by the use of the same amount of energy
Service output	The output, effect, result, good, product, activity or achievement provided by an energy-using system
Structure (*S*)	The shares of sectoral activity accounted for by each subsector.
Activity (*A*)	The output of an energy system, typically at sectoral level.
Energy services	Final actual services for which energy is used.
Energy efficiency indicators	
Energy indicators	Ratios measuring energy consumption and the underlying factors driving that consumption. They are useful to analyse how energy is linked to human and economic activity
Energy efficiency indicators (EEI)	Ratios aiming to measure the relation between a delivered service, output or result and the energy input required to provide it; also known as energy efficiency ratios
Energy conversion efficiency	Ratio of useful energy output to energy input; also known as thermodynamic energy efficiency or simply energy efficiency
Energy intensity (EI or I)	The amount of energy needed to provide the unit of service or activity; a ratio of energy input to service output; the ratio between energy consumption and a demand indicator
Unit consumptions (UC)	Energy consumption per energy-using unit; also known as unitary energy consumption
Specific energy consumption (SEC)	Energy consumption per unit of physical output; the ratio of energy consumption to a physical demand indicator; also known as physical-based indicators
Energy performance indicators (EPI)	A ratio aiming to measure the quality of functioning of an energy system. Typically, EPI are energy intensities
Demand indicators	A measure of the amount of service, activity or achievement provided for which energy inputs are required.
Structural indicators	Magnitudes to measure the shares of sectoral activity accounted for by each subsector
Activity indicator	A basic measure of accounting for the activity of an energy sector; a demand indicator at the sectoral level

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