# Energy Efficiency: What it is, Why it is Important, and How to Assess it

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# ENERGY EFFICIENCY: WHAT IT IS, WHY IT IS IMPORTANT, AND HOW TO ASSESS IT

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# Contents

# Chapter 1

# Preface

The topic of this book is the energy efficiency in industry, *i.e.* the potential reduction of the energy dissipated along a chain of processes from the natural resources extracted by humans, or primary energy, to the useful forms of energy such as electricity, transport fuels, mechanical energy, heat or even ammonia. It also deals with the energy required to produce consumer goods like phones and capital items like tractors, or to provide services like freight shipments, and information and communication technologies.

The search on better energy efficiency of processes started even before the very notion of energy, or the equivalence of heat and work, was established. Indeed the first improvements on the steam engine to reduce its coal requirement at identical work took place before the foundation of the thermodynamic theory.

The present study does not cover new developments in the field of energy conversion, as was the fundamental understanding of work production from heat in the steam engine (which was at the origin of the thermodynamic theory). Instead, it gathers and analyzes critically established knowledge and data in both fundamental and engineering sciences to determine the efficiency of any industrial system (from coal exploitation to phone manufacturing), and to compare between possible designs for potential gains.

The book aims equally to bridge a growing gap between this specialized and complex information about processes, and questions about energy efficiency at the economy or society level. Consequently it intends to address a large audience from physicists and engineers to economists, executives and teachers, i.e. anyone with an interest in energy.

### What is Energy Efficiency?

The chapter of the book following the introduction shows that, even for a well-defined system and its materials and energy flows, the assessment of energy efficiency is not as simple as it may appear at first.

Within the book the efficiency/inefficiency of the system is defined by the energy required per unit of its resource input or its production output. However, the rate changes with the choice for the denominator and with what are considered energy requirements. Is the energy consumed to manufacture the equipments and materials, or to produce the electricity and fuels used by the system, included in the requirements? Must we count all the energy consumed or only that dissipated in the processes? Are the requirements limited to external primary energy?

Moreover, a practical rate like the energy consumed per unit of joule J of ethanol produced can give a value higher than one. It does not mean that there is any violation of the energy conservation, or the system dissipates more energy than it extracts. A more fundamental rate can be established based on the thermodynamic laws. It leads to the notion of the self-reliant energy system, which uses only the energy resource it extracts and processes to meet all its requirements, both fuel and feedstock. By its mere existence our whole energy system, from petroleum industry to hydroelectric production, is self-reliant. But not each of its components is necessarily self-reliant. The notion is important not only in terms of the fundamental significance of the efficiency of a system, but also for the viability of entire societies and their thriving economies, as the example of an ancient coal exploitation demonstrates.

### Why is Energy Efficiency Important?

Because of the importance of the energy - and subsequently of energy efficiency in terms of energy savings - for the activities of our own society and for our personal life, the book in the third chapter also deals with these connections between industrial efficiencies and the economy or the human well-being.

The energy efficiency issue has gained renewed importance with the recent rise of hydrocarbon prices. France, the author's country, imported roughly 85 G$ - billion dollars - worth of crude oil, refined petroleum products and gas in 2012. At the end of 90s the annual trade bill amounted to a mere 20 G$ (in constant $ value). This rise represents 2 to 3% of the annual France Gross Domestic Product GDP, small as a percentage but with a staggering impact on economic growth and national debt levels. Further improvements in efficiency in the transport sector or in the thermal insulation of buildings could significantly alleviate this financial burden.

The objective of the third chapter is equally to distinguish among the various energy related notions in economic and social themes those that are not relevant to the energy efficiency in its strict definition.

Thus an economic system is judged efficient if it generates a large added value. The latter represents the sales of the system outputs less the cost of its inputs. The added value is distributed in salaries, taxes and surplus capital. In the long run, especially for basic industries such as electricity generation and ammonia industry, the value benefited from the improvements of the manufacturing processes and the lowering of their energy and material consumption rates. Along with rising productivities in labor and capital investments, these gains in the basic industries permitted to decrease the unit price of their products, on which the whole economic activity has drawn to thrive. The price reached such a low level that it reduced the weight of the economic value of these industries in the GDP, less than 10 percent in developed countries.

However, the unit price can equally be driven by the balance, or imbalance, between demand and supply, or, in the short term, by government ill-defined regulations or by speculative markets, as observed in the case of the industry and market of the photovoltaic modules since 2000. Mechanisms of price fixing add another layer of complexity, which may well hide fundamental trends in the efficiency of processes and so in the long-term cost of products.

Thermodynamic theory, which has explained and guided the 250 fold efficiency gains of the steam engine since its inception, also determines the limit to these gains, as seen in the last chapter of the book. For the last decades the extraction and transformation of each barrel of crude oil have required increasing amounts of physical resources - energy, equipment...-, despite evident progress in the specific efficiencies of the processes involved. Because of the oil high demand - except during crises - due to its essential function in running nearly all economic activities, its prices have definitely followed the physical trend. Only the thorough technical study of extraction processes and their improvements as well as that of the characteristics of the deposits to be developed to maintain production can reveal future developments. In summary, not only "it's the economy, stupid", but also "it's thermodynamics and engineering, stupid".

At the consumer level energy saving can also be obtained by the decision to drive less, to buy a smaller car, or to reduce the heating temperature in his/her house$\cdots$, which is in fact independent of efficiency. It is more often than not motivated by the final price of the useful energies like electricity and transport fuel, as the behavior of the typical American drivers proves. They are essential consumer costs which governments try to control to deflect the social pressure.

Moreover, the price paid by the consumer for other goods and services such as cars and insurances has little relationship to the energy costs to produce them. As a result of productivity and efficiency gains of basic industries the energy cost component is generally similar to the one in the country GDP. At the personal level incentives for saving energy are thus reduced.

At first glance the abundance of the energy resources on Earth surface, or close to it, is independent of the efficiency of the processes employed to extract and make them useful. The resource base is actually huge compared with the human demand, either in terms of energy of flows, like solar radiation, or energy stores such as fossil organic carbon in the crust of Earth. However, only a very tiny fraction of this energy resource is amendable to exploitation. Its characteristics - concentration, accessibility, state... - do allow the use of efficient process. Other portions of the resource can require more energy to extract and transform them than they actually contain, making their extraction physically non-viable.

**How to Assess Energy Efficiency?**

The fourth chapter describes a methodology to assess the rate of energy consumption of a complex system and the dependence of this indicator on a variety of physical and technical quantities.

The methodology rests on the decomposition of the system on its much simpler parts for which a local consumption rate - *a priori* independent of the system one - is defined and calculated from available and accurate information (flow data and established relationships at process level). Thus is isolated the mechanized operations at the farm in an agro-ethanol industry. Its efficiency is expressed with the volume of diesel required per unit of cultivated surface. From the local rate of the operation is determined the operation contribution to the global rate of consumption. The relation between both rates provides some of the variables of the system efficiency. The conversion from the consumption of diesel per ha of crop acreage to the consumption per joule of ethanol requires the yield of crops per hectare, the mass of sugar or starch in the harvest and the fraction of sugar converted into ethanol. The physical analyses of these variables and others from different operations define possible future gains or limitations on the final efficiency of the agro-ethanol industry.

The fifth and last chapter dwells on the self-sufficiency of energy systems, or in other words, whether systems can only rely on the resource they extract for their operations. Coal extraction from underground mines necessitated efficient steam engines to lift the coal and pump the excess water. These engines had to consume only a fraction of the coal lifted at the surface for coal exploitation to be viable and self-reliant.

Agro-ethanol industry is a more complex energy system as it requires the outputs of other energy systems - diesel, electricity, ammoniac... -, and consequently depends on their efficiency. From the industry actual direct consumptions (electricity, fuels...) and by replacing existing processes to produce internally these requirements, the system can be made self-reliant, consuming its own production and/or resource. Hence its real efficiency can be determined. It may well be possible that the industry does not produce enough energy to fuel its own processes.

**And More**

The reader is invited to learn more about the agro-ethanol industry and its efficiency throughout the book. Other examples like steam engines, the ammonia industry, phone manufacture... are also used to illustrate and support the various arguments developed in this book about energy efficiency.

Feedbacks on this study are welcome. Oversights on such a complex matter cannot be ruled out.

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He is also grateful to P. Brocorens, P. Alba and B. Durand for their thorough review. P. Brocorens is a young researcher on advanced chemistry at the University of Mons working on the properties of new materials like conjugated polymers and composites. P. Alba is a retired engineer of Elf Aquitaine where among various positions he had been in charge of the economic studies of the company. B. Durand is an expert of petroleum geochemistry and had been responsible of the geology-geochemistry department at Institut Français du Pétrole (IFP). He had been also director of Ecole Nationale Supérieure de Géologie in Nancy.

This book also benefited from the review of J. Heissner, promoter of a novel project of a self-sustainable village in New-Zealand. I wish him success in his project.

X. Chavanne

Physicist (PhD, member of Société Française de Physique) and research engineer. He worked on various topics in academic and applied areas: study of the turbulent natural convection both experimentally and theoretically, modeling of the convection in glass furnaces at St Gobain company (with physical models and theory), development of soil moisture sensors for both fundamental and industrial objectives (use of a dielectric principle). Since 2004 study of the efficiencies of different industrial systems in areas from the telecommunications to basic industries and to transport.

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# Chapter 2

# Introduction

## 1. First Mentions of Energy Efficiency

The first evocations of the efficiency of an industrial system in modern terms can be associated with the improvements of the steam engine by J. Watt, and with the work of S. Carnot to establish a theory of fire machines at the turn of the nineteenth century. Both J. Watt and S. Carnot used as an indicator of efficiency the quantity of coal burnt, or its calories, per unit of the product of mass of water lifted by the height. Indeed, the notion of energy itself was introduced later by the experiments of J. Joule and the establishment of the thermodynamic theory by R. Clausius and W. Thomson.

The steam engine was first developed successfully in Great Britain in 1712 by T. Newcomen to access water filled coal mines [1, 2]. Because of the wood disappearance and the easy access at the surface or shallow depths of peat and coal in some regions of Europe (Holland, Great Britain, Wallonie region in Belgium, the basin of la Loire in France...), the fossil resources were exploited as early as the thirteenth century. Due to a rising demand the production had to be increased.

The Newcomen machine had a very low yield in terms of conversion of coal heat into work (less than 0.3% as established later; see the details in the chapter **??**). Successors of T. Newcomen managed to increase this efficiency, most notably J. Watt after 1769 (separate condenser among various modifications). One of Watt's sale pitches was that his new machine was able to save 75% of coal by comparison with the previous design [3]. The efficiency was all the more important as J. Watt's improvements and modifications allow the use of the steam engine in other industries (textile, iron...) to provide mechanical energy. Thanks to Watt and other inventors the steam engine became more efficient - still less than 5% in 1824 - while more available and reliable to produce energy than other means such as muscular work, windmill or even water mill. After 1830 with the locomotive the steam engine was used in the transportation of freight and people.

Around 1820 the aim of the physicist S. Carnot was to determine the ideal transformations along a cycle in a "fire" machine (not only a steam engine) to produce a maximum of work from a fixed amount of heat [4]. It was equivalent to solving an efficiency problem with the deduction of the fundamental factors, chiefly the temperature difference between the hot and cold sources rather than the level of gas pressure as believed at that time, to be most important (at least for an ideal cycle). His study founded the theory of thermodynamics with notions like thermodynamic cycles, reversible transformations, adiabatic and isothermal compressions or dilatations of a perfect gas... Thanks to his work large and fast improvements were made possible with the existing machines (the steam engine benefited of the theory as shown in the chapter **??**), and new machines were conceived (internal combustion engine, gas turbine). Some modern steam engines in power plants can reach a yield of 45% and gas fired plants can surpass 55% owing to two combined cycles.

## 2. Structure of the Present Book

In the early industrial revolution energy efficiency of processes was one of the major preoccupations of engineers to save expensive coal or to increase the outputs of an industry with the same amount of coal. Energy efficiency has always been a priority when the supply of energy is restricted resulting in high prices, as observed in the beginning of 19th century for coal and nowadays for crude oil. Obviously, as it was also the case in the nineteenth century, energy efficiency is not the only factor to consider when developing a process or a system at the industrial scale. They must also fulfill economic or environmental constraints such as labor and equipment productivity, which can further impact the energy consumptions.

The purpose of the book is not to present new developments on energy conversion, as was the understanding of work production from heat in the steam engine. But rather it will show how to gather and analyze critically already established knowledge and data of both fundamental and engineering sciences to determine the efficiency of a large range of industrial systems.

It also deals with the role of the energy efficiency in the economy and human societies.

The book in the second chapter establishes first a definition of the efficiency for any system. It is expressed with an indicator based on the rate of consumption of the system, *i.e.* its energy consumed per unit of its output. It turns out that different indicators for a system and its flows are possible. A practical rate is estimated from the direct inputs and outputs of the industry, like coal and lift work in the case of the steam engine. Its scope can be enlarged to include indirect consumptions like those to extract and clean the coal used by the steam engine. However, in the case of energy systems like steam engine or coal exploitation, the application of the energy conservation suggests a different and more fundamental rate based in the energy dissipated.

The third chapter shows how the efficiency gains and its limitations still play an important role in our societies, its economy, human well-being and comfort, and our extraction of natural resources although it is not as apparent as it was in the times of Watt and Carnot due to the very progresses of efficiency since then. Other factors have also to be considered like the cost of production in monetary value, the prices of energies and products, energy conservation by end consumers, as well as the abundance and characteristics of the energy resources.

The fourth chapter is dedicated to a methodology and its mathematical tools to derive a rate for the system under study and the dependences of this rate. Energy efficiency can be studied for quite simple systems like the steam engine as well as for more complex ones such as the production of ethanol from agriculture - agro-ethanol - or the phone manufacture. The main principles of the analysis are the decomposition of the system towards simpler operations of few processes or even just one, and the determination of the natural rates of consumption of these operations. These local rates, deduced only from data at operation level, are much less variable than the rate of the whole system. A reverse process allows to derive from the local rates the latter rate. As a result of the process, the physical and technical variables on which the system rate depends are identified. In the process, and thanks to different sources and/or established knowledge in sciences and technologies, large errors on data and on assumptions are tracked. The suggested methodology also provides tools to propagate the remaining uncertainties from the raw data to the system rate. This allows to quantify the compromise between the accuracy on the rates and the time required for data gathering and analysis.

The last chapter deals more specifically with the energy systems. Among them are examined self-reliant systems. The resource they use must provide both the fuel consumed in their processes and their feedstock. Historic industries such as the exploitation of a coal basin offer examples of autonomy due to the necessity themselves to use local resources for production. Significantly, in industrial times only fossils fuels show their ability to approach self-sufficiency. If they are to be substituted for conventional and dominant systems, alternatives systems like the agro-ethanol production must also demonstrate this capability. This can be achieved thanks to modifications of present systems with existing processes. However, the resulting rate of dissipation expressed as the energy dissipated per unit of total input of the system must be lower than one in order for the self-reliant system to produce a surplus output.

**Note about Unit Symbols** Due to the difficulty to define an equivalence between the different forms of energy such as between final and primary energies, the unit of each form of energy is accompanied by a subscript informing about the form.

Thus the subscript **LHV** in $\mathrm{J_{LHV}}$ stands for the low heat value of a fuel, **HHV** in $\mathrm{J_{HHV}}$ for its high heat value, **e** in $\mathrm{J_e}$ for electricity, **m** in $\mathrm{J_m}$ for the mechanical energy, **th** in $\mathrm{J_{th}}$ for the thermal energy, **ph** in $\mathrm{J_{ph}}$ for the energy of photons, **EF** in $\mathrm{J_{EF}}$ for the final energy - part of the direct requirements $E_D$ - consumed by the system under study, **EP** in $\mathrm{J_{EP}}$ for the overall primary energy $E_{EP}$ used to produce $E_D$ by the system *aux*...

The subscripts of units are also used for other quantities if necessary. For instance the volume of water lifted over a fixed height is measured by $\mathrm{m_w^3.m_h}$.

The use of subscripts for the symbol of units is not recommended by the Comité International des Poids et Mesures (CIPM) in charge of defining the Système international d'unités (SI) [52]. All energies have a unique (derived) SI unit, joule, based on their equivalence in terms of heat value. But, as we have seen, the different forms are not equivalent in terms of usefulness for the consumer. Otherwise the notion of efficiency itself can be questioned.

Notations like J of electricity or J of primary energy could be used. But for concision we prefer to use the convention introduced above. We follow the rest of the norms enacted by the CIPM.

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