

Energy Efficiency coefficients

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1. Introduction

Aim of the paper

When energy is converted or consumed for end-use, some of the potential energy content is lost due to friction, heat loss or other factors. The energy that is ultimately utilised is less than the energy supplied, and which we originally purchased. Knowledge about utilised energy and for which devices and energy commodities the energy losses are greatest constitute very useful information for many reasons. It could, for instance, explain how a switch from one energy commodity to another influences the trend in energy consumption. As an example, a switch from burning wood to using electric space heating implies that the energy supply requirement reduces, because electrical heaters are more efficient than wood stoves.

The degree of utilization of the individual energy commodity will also depend on the device and technology available where it is used, and the technology changes over time. For instance, new wood stoves are usually more efficient than old ones.

For energy planning and analytical purposes, information about losses and useful energy gives a broader perspective on energy consumption and its harmful consequences than figures for supplied energy consumption alone. Such a perspective might indicate if switching to more efficient fuels could be an appropriate way to save energy, or if investments in more efficient equipment are the way to go.

The aim of this paper is to describe how we can calculate utilised energy, and the advantages and challenges that these kinds of calculations present. In order to calculate utilised energy, we need to know which processes cause energy losses. This is described in section 3, while examples of a set of energy efficiency coefficients are included in section 7. Utilised energy is here defined as supplied energy minus energy losses, while energy efficiency coefficients give the ratio between utilised and supplied energy for different devices or user groups. User groups in this context means different categories of energy-users, such as households, industry, transport etc.

What are energy losses and efficiency?

According to the first law of thermodynamics, energy can neither be created nor destroyed. It can only change form. In any process, the total energy of the universe remains the same. For this reason, it is not scientifically precise to say that energy is “lost”. What we mean by losses in this paper is that the energy changes to a form that cannot be utilised for a specific energy purpose, usually as heat lost to the atmosphere. In addition, an efficiency coefficient will usually be defined as a measure of wanted effect, not total effect. However, there are some factors that complicate this rule. Some of the energy used in energy-driven equipment will always be “lost” as heat that can be utilised, even if the main purpose of the equipment is not to produce heat. For instance, an electric light bulb might have 5% efficiency at emitting light, while the remaining 95 per cent of the energy is heating the room. This means that the wanted effect is 5 per cent while the total effect is 100 per cent. Due to the way electricity is measured (in kWh), output equals input (1 kWh in = 1 kWh out), but there is a question here of whether the coefficient should be 5 or 100 per cent.

All energy-driven devices, such as ovens, computers, data servers etc. generate heat. It is debatable whether this heat generation should be regarded as a loss, because it often reduces the need for other space heating. One possibility is to distinguish between the efficiency of the equipment and that of the energy commodity, and say that the efficiency coefficient of a light bulb is 5 per cent, while electricity, as an energy commodity, is 100 per cent efficient. However, the latter would be only partly true, because we do not always benefit from heat that is generated by electrical devices. On warm summer days, it is not desirable to heat the house, and heat from equipment might actually increase the need for cooling.

Units and calorific value

Units: Calculation of utilised energy is only relevant when energy is presented in energy units, such as toe, joule or GWh. Physical units, such as tonnes, indicate the quantity of energy, but not the work it could do. In order to describe the work, or heat, from an energy commodity, it is necessary to multiply the physical quantity (such as a tonne of oil) with the theoretical energy content of the oil.

Gross and net calorific value: The theoretical energy contents of a fuel can be expressed either as gross or net calorific value (GCV or NCV). The GCV, or high heat value, measures the total amount of heat that will be produced by combustion. However, part of this heat will be locked up in the latent heat of evaporation of any water present in the fuel during combustion. The net calorific value (NCV), or low heat value, excludes this latent heat. NCV is that amount of heat which is actually available from the combustion process for capture and use; the higher the moisture content of a fuel, the greater the difference between GCV and NCV. NCV is the commonest measure and in this paper, the efficiency coefficients will refer to energy figures measured in NCV only. We will assume that the latent heat of evaporation is already excluded.

The structure of the paper.

- ✓ What is a thermal efficiency coefficient according to thermodynamic laws.
- ✓ Different kind of energy losses
- ✓ How the subject is treated in other manuals
- ✓ Calculation of prices of utilized energy
- ✓ Example of a set of efficiency coefficients and how to calculate useful energy
- ✓ Recommendations, and topics for discussion in the group

2. What is a thermal efficiency coefficient?

In thermodynamics, the thermal efficiency E_{th} is a performance measure of a thermal device such as an internal combustion engine, a boiler, or a furnace. The input Q_{in} to the device is heat, or the heat-content of a fuel that is consumed. The desired output is mechanical work W_{out} or heat, Q_{out} or possibly both. Because the input heat normally has a real financial cost, a memorable generic definition of thermal efficiency is

$$E_{th} = \frac{\text{What you get}}{\text{What you pay for}} \quad \text{or} \quad \frac{Q_{out}}{Q_{in}}$$

From the first law of thermodynamics, the output can't exceed what is input, so $0 \leq E_{th} < 1.0$

The second law of thermodynamics can also explain why energy availability diminishes when it is converted. This law is an expression of the fact that, over time, ignoring the effect of self-gravity, differences in temperature, pressure and density tend to even out in a physical system that is isolated from the outside world. This means that objects close to each other, but with different temperatures, over time will tend to have the same temperature.

3. Energy losses

Losses can arise through a variety of processes, and we will present a short overview of the different types of losses, in order to offer a better understanding of the topic. A useful exercise might be to estimate efficiency coefficients when all losses are taken into account, from extraction of the energy commodity through to its end-use. The percentage loss will typically then be rather large. However, efficiency coefficients usually refer to losses in one stage only, and losses are not accrued from stage to stage, because the origin and total cycle of energy commodities varies so much.

3.1 Gas flaring and capture / extraction of primary energy¹:

Oil and gas extraction involves a lot of gas flaring that obviously could be regarded as an energy loss, because the gas is burnt with no direct energy purpose, mainly for security reasons.

The extraction process itself might also involve “losses”. Not losses in the sense of that you lose something that has already been extracted, but rather the loss of potential due to inefficiencies in the extraction process. For instance, the techniques to extract crude oil and gas are not good enough to capture all the petroleum in a reservoir. A commonly used technique is to re-inject gas or inject water in order to extract more, but even so, the extraction ratio is often not higher than about 50 per cent. This means that, when the field is considered to be "empty", half of the petroleum reserves still remain underground.

3.2 Transformation to derived energy

While the extraction ratio of primary energy is dependant on the process of extraction, the production of derived energy² depends on the efficiency of the plants that transform the energy. The efficiency of energy plants is highly variable, but it is always below 100 per cent, due to the laws of physics, as described in section 2. The plants or conversion sectors include oil refineries, thermal power stations, coal-fired power plants, district heating plants and dual purpose power stations. Hydro-generated electricity can also be regarded as derived energy. The potential energy in waterfalls is always higher than the energy that is generated in the hydro power plant. How much higher depends on the efficiency of the plant. Losses in the conversion process usually appear in the countries' energy balances, as the difference between input and output in the transformation sector.

Often, but not always, the plants measure both input and output and it is then possible to collect these data for statistical purposes. However, the input data in particular can be of poor quality or non-existent. In order to compile complete and consistent energy balances, it may prove necessary to calculate the energy input from output, on basis of a set of average efficiency coefficients. It is useful to know the average efficiency coefficients, either in order to calculate the input, or to check the figures that are reported by the plants. Some coefficients for these types of plants are included in table 1, but the table is not complete.

3.3. Losses in distribution of energy

This is especially relevant for electricity, gaseous fuels and district heating. Transport of electricity through a grid network involves losses, due to friction and the transport process itself. The longer the grid, the higher the losses of electricity. Similarly, some of the produced district heating is lost to due to cooling and during distribution to end-users.

3.4 Losses in devices for end-use

When energy is used for end-purposes, e.g. in stoves, engines etc., some of the potential energy will be lost due to friction and inefficiencies in the equipment. The losses vary widely among different energy sources and devices. Reliable and exact calculations of useful end-use of energy require regular measurements of thermal efficiency coefficients for all devices. In addition, you need to know the exact energy consumption in the different devices. Such regular detailed measurements of consumption are seldom available. Most commonly, statistics for some broad user groups, such as households, some industries and transport will be available, while breakdowns by device or process are much rarer.

The level of detail in the statistics determines the precision and level of detail of the potential calculations of useful energy. The optimum solution is to have two sets of coefficients; one set that

¹ The production of primary energy bearers encompasses those that are produced without the input of other energy-bearing raw materials. The main primary energy bearers are coal, fuel wood, crude oil, naphtha, natural gas and hydro.

² The production of derived energy bearers includes the production of energy bearers in which other energy bearers are used as inputs, for example, petroleum products manufactured in an oil refinery from crude oil.

gives device-specific information and one that gives rough efficiency coefficients for the most common user group/ sectors, for instance, according to the classifications in the energy balances.

4. Useful energy balance (calculated as utilised consumption)

In the energy balance, the energy losses, as described in item 1-3 above, are specified in the upper part of the table, and thus excluded from the end consumption of energy that appears lower down in the table. In order to calculate utilised energy, it remains to adjust for the losses in end consumption (item 4). However, this is likely to be the most problematic calculation, because the utilised end-consumption of energy is seldom measured. The energy balance does not give information about consumption in different devices that would be necessary to provide a complete and more exact measurement of useful energy. (See example in table 3).

Due to the structure of the energy balance, the efficiency coefficients have to be applied to the different energy commodities and sectors, even if the losses are in fact due to inefficiency in the equipment which is used. As consumers and areas of use vary considerably within each consumer group in the energy balance, the thermal efficiency coefficients will be rough estimates for each consumer group in the energy balance (see table 2). The most homogenous sector in the energy balance is transport, because this is mainly consumption in vehicles. Often, the energy balances provide a breakdown by different types of transport (land, sea, air transport etc.) that could facilitate calculation of utilised energy for transport.

Another, more exact method, would be to breakdown the consumption figures in the energy balance by device, before calculating utilised energy, but this depends on having sufficient information to perform such a breakdown.

5. Description of how the issue is treated in other energy statistics manuals

Efficiencies of energy conversion devices are briefly mentioned in annex III, page 50-51 in the UN manual Energy statistics; Definitions, units of measure and conversion factors.

The annex stresses that, in order to measure useful energy, it is necessary to record

- a) The main types of appliances used by final energy consumers
- b) The amount of energy actually used by these various appliances
- c) The average efficiencies of these appliances when in normal use.

Employing these, the useful energy balance sheet is able to present a fifth category of energy losses - those at the final stage.

The manual mentions the various energy losses that are recorded, essentially those referred to in section 3. It also contains a table that shows average efficiencies of appliances at the final stage of consumption. However, the coefficients refer to a limited number of appliances, and not to the categories that usually exist in the energy balances. It doesn't give an explanation for how to calculate "useful energy balances".

The issue is not treated in the joint OECD/IEA/Eurostat energy statistics manual from 2005. Eurostat has compiled and published useful energy balance several years ago, but we have not been able to find this publication.

6. Prices of utilised energy

List prices of different energy commodities are usually not directly comparable, due to different efficiency coefficients in the devices or equipment where the energy commodities are used. For analytical purposes, it is very useful to compare prices of different energy commodities, adjusted for their efficiency, because it gives a picture of which commodity, in practise, it is most profitable to use.

The formula below gives a method to convert, for instance, the oil prices (based on a litre price) to price per kWh for one unit of utilised energy.

$$P_i = \frac{P \cdot B_e}{E \cdot E_h \cdot B \cdot K_{pi}}$$

where

- P is the price of the product, including taxes and duties (øre/litre)
- B_e is the fuel value of electricity (TJ/GWh)
- E is the product's specific gravity (kg/dm³)
- E_h is the product's fuel value (TJ/1 000 tonnes)
- B is the product's thermal efficiency coefficient
- K_{pi} is the consumer price index, 1980 = 100

7. Tables

Table 1. Energy efficiency coefficients in some applications*

Application	Energy efficiency
Combustion engine	20-30%
Electric motors	30-60% (small ones < 10 W); 50-90 (medium-sized ones between 10-200 W); 70-99.99% (above 200 W)
Household refrigerators	Low-end systems – 20%, high-end systems -40-50 %
Electric shower	90 – 95%
Incandescent light bulb	2 – 10%
Compact fluorescent lamp	About 7-9%
White light-emitting diode (LED)	About 4 – 10%
Electric kettle	More than 90% (little heat is lost during the few minutes a kettle takes to boil water)
Energy plants (efficiency in conversion)	
Coal-fuelled electrical generating plant (large)	About 46%
Combined cycle plant	Approaches 60%

*Measures of *wanted* effect. See discussion in introduction

Source: Wikipedia

Table 2. Thermal efficiency coefficients for calculation of useful energy balance

Estimated thermal efficiency coefficients of different energy sources and consumer groups^{1,2,3}

<i>Energy source</i>	<i>Industry, mining and quarrying</i>	<i>Transport</i>	<i>Others</i>
<i>Coal</i>	0.80 (0.75)	0.10	0.60
<i>Coke</i>	0.80 (0.75)	-	0.60 (0.70)
<i>Fuel wood</i>	0.65	-	0.65
<i>gas</i>	0.95	-	0.95
<i>Liquefied petroleum gas (LPG)</i>	0.95	-	0.95
<i>Motor gasoline</i>	0.20	0.20	0.20
<i>Kerosene</i>	0.80	0.30	0.75

<i>Diesel oil, gas oil, light heating oil</i>	0.80 (0.70)	0.30	0.70 (0.55)
<i>Heavy fuel oil</i>	0.90 (0.80)	0.30	0.75 (0.65)
<i>District heating</i>	1.00	-	1.00
<i>Electricity</i>	1.00	1.00 (0.95)	1.00

¹ The thermal efficiency coefficients are estimates. In some studies the coefficient estimates differ considerably from those given in the tables. ² The figures in brackets are the coefficients used prior to 1986

³ Heat that is lost through windows, walls etc. due to bad insulation is not accounted for in these coefficients.

Source: NOS Energy statistics 2000, Statistics Norway

Method of calculating useful energy balance

Calculation of utilised end consumption of energy on the basis of figures from the energy balance can be achieved by multiplying the figures for energy consumption for different user groups and energy commodities with the coefficients in table 2. Energy losses can be quantified by subtracting the utilised energy consumption from the supplied energy consumption. This is an approximate, but simple way to calculate it. A sample calculation for Norway is presented in table 3.

Table 3. Calculated useful energy balance and losses. Example for Norway

<i>Energy supply 2006 Petajoule</i>	Total	Coal	Coke	Fuel wood, wastes	Elec tri- city¹	Oil products	Gas	District heating
Net domestic consumption	801	16	24	44	388	291	28	9
Manufacturing industries	287	16	24	17	175	29	25	1
Mining and quarrying	4	0	0	0	2	2	0	0
Manufacture of paper and paper products	39	0	0	12	21	6	0	0
Electricity intensive industries	181	11	17	0	124	6	22	0
Other manufacturing industries	63	6	7	5	29	14	2	1
Transport	214	0	0	0	3	211	0	0
Fishing	18	0	0	0	1	18	0	0
Agriculture	14	0	0	0	7	7	1	0
Households	159	0	0	27	120	10	0	2
Other consumers	107	0	0	0	82	17	1	7
Useful energy, PJ								
Net domestic consumption	609	13	19	29	388	124	26	9
Manufacturing industries	269	13	19	11	175	25	24	1
Mining and quarrying	3	0	0	0	2	2	0	0
Manufacture of paper and paper products	34	0	0	8	21	5	0	0
Electricity intensive industries	174	9	13	0	124	6	21	0
Other manufacturing industries	57	4	6	3	29	12	2	1
Transport	62	0	0	0	3	59	0	0
Fishing	15	0	0	0	1	14	0	0
Agriculture	13	0	0	0	7	5	1	0
Households	147	0	0	17	120	8	0	2
Other consumers	104	0	0	0	82	14	1	7
Energy losses, PJ								
Net domestic consumption	192	3	5	15	0	166	2	0
Manufacturing industries	19	3	5	6	0	4	1	0
Mining and quarrying	0	0	0	0	0	0	0	0
Manufacture of paper and paper products	5	0	0	4	0	1	0	0
Electricity intensive industries	7	2	3	0	0	1	1	0
Other manufacturing industries	6	1	1	2	0	2	0	0
Transport	153	0	0	0	0	152	0	0
Fishing	4	0	0	0	0	4	0	0
Agriculture	1	0	0	0	0	1	0	0

Households	12	0	0	9	0	3	0	0
Other consumers	3	0	0	0	0	3	0	0

1. Assuming no losses of electricity. This is a simplified assumption according to the discussion in the introduction.

8. Recommendations

- 1) The efficiency of different types of equipment should be measured regularly, in order to follow the technical trends, and to be able to evaluate the extent to which more efficient equipment leads to energy savings.
- 2) On the basis of technical data about the efficiency of devices, and knowledge about the use of devices in different sectors, it should be possible to calculate average efficiency coefficients for the categories in the energy balances. - However, it exist a lot of appliances and devices, and the efficiency for even one single device can vary a lot, depending on model, type and age. How to capture this variety in one single coefficient has to be discussed. A working group, consisting of countries which have relevant experience, could be established in order to develop appropriate methods for this. Whether country-specific or standard coefficients should be used should also be discussed.
- 3) If 1 and 2 are done, the next step is to calculate useful energy balance (utilised energy consumption) in the countries, on basis of the coefficients. Once utilised energy consumption is calculated, several analyses are possible, in order to see the effects on changes in energy consumption from more efficient equipment, or structural changes. Structural changes, in favour of sectors that use energy more efficiently, are likely to influence energy consumption. Changes to more, or less, efficient energy sources, might also have an effect. The transport sector, for instance, is one of the less efficient, due to the large losses that occur in engines. Equally, transport is one of sectors with the highest increase in energy consumption.
- 4) Useful energy consumption could also be calculated on basis of other statistics than the energy balance, such as statistics for energy consumption by device, where available.

9. Some points for discussion in the Oslo group

- How to handle the difference between wanted and total effect, specially in electrical equipment, as discussed in the introduction
- Other countries' practices. How do other countries calculate useful energy, and which coefficients are used.
- How to measure efficiency coefficients for different devices, sectors/user groups or energy commodities and how often should the factors be updated. Is a small working group an appropriate forum for this?
- Energy efficiency coefficients may well vary between countries, due to different use and stocks of devices and heating equipment. Should country-specific coefficients be employed for different countries, or can it be assumed that these coefficients are approximately the same? In particular for the different user groups in the energy balance, it is likely that the average efficiency coefficients vary among countries.

References

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