# MOOC Zero-Energy Design

## Course Reader Module 1

TUDelft

This module provides additional information for the Massive Open Online Course (MOOC) Zero Energy Design.

Andy van den Dobbelsteen
Eric van den Ham
Tess Blom
Kees Leemeijer

Special thanks to BOOM (environmental research and design) for the use of the book Energie Vademecum and to BuildDesk / ROCKWOOL international A/S for translation of Energie vademecum.

# 1. Energy consumption

# 1 Energy consumption

(Derived from https://Klimapedia.nl/publicaties/energievademecum)

Energy consumption is growing strongly worldwide: In the last 45 years this total consumption tripled more than. Countries such as China, India and Brazil saw a much stronger increase in that period. Only in 2009 the total consumption decreased slightly as a result of the economic crisis that occurred in many countries. The general expectation is that the total world energy consumption will increase in the coming decades, as will the emission of $CO_2$ . What happens next is very dependent on energy policy in the short and longer term. Something else that also plays a role is the security of supply for energy: Energy sources have become the deployment of an international political game, leading to increasing tensions and uncertainties. In the following sections the  environmental effects of energy consumption are discussed and the development of energy demand at national and world level.

## 1.1 Societal aspects of energy consumption

The economies of the industrialized countries depend almost entirely on affordable and readily available energy. At the moment, this energy mainly comes from fossil fuels such as oil, natural gas and coal. The use of these fossil fuels has far-reaching consequences. Not only is the environmental pressure increasing (section 1.1.2), the supply of sufficient energy is also uncertain due to political relationships (section 1.1.1).

### 1.1.1 Security of supply

'Security of supply' means the degree of certainty that exists about the availability of sufficient energy sources now and in the future. To this end, we look at global energy stocks in relation to consumption and the geographical distribution of energy sources. On a global scale, in the shorter term it is not so much a scarcity of energy that is a problem but the availability of that energy. In addition, at least until 2030, fossil energy will provide more than 80% of global energy demand. Oil and gas wells are often located in areas with political and / or economic instability.

For the European Union (EU), the future of security of supply is not bright: The EU itself has limited oil and gas reserves and is currently already 50% dependent on OPEC countries and Russia. Around 2030, imports of oil and gas by the EU are expected to have risen to around 95% and 80% of total oil and gas consumption [1] (Figure 1.1). Only with a greatly reduced energy demand does security of supply only play a limited role, but that is not yet possible for the EU and the Netherlands [15]. The use of fossil fuel will certainly increase until 2030. Depending on the implementation of energy-saving measures and the use of sustainable energy, this use may flatten and eventually decrease.

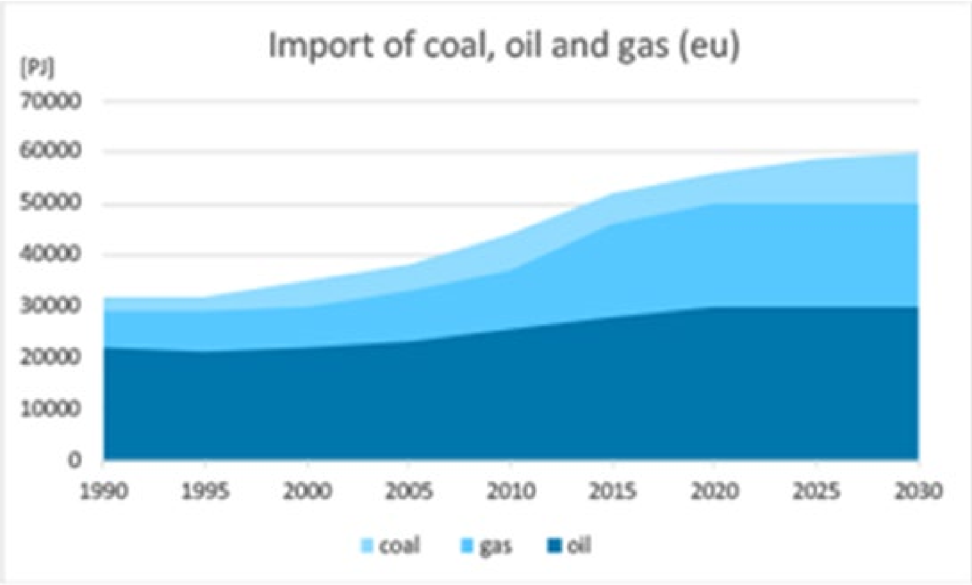


*Fig. 1.1 Dependence on import energy sources for the 'Baseline' scenario for the EU; (Source: European Commission, Commission staff working document EU energy policy data, SEC (2007) 12)*

### 1.1.2 Environmental pressure and energy consumption

The current use of fossil energy and nuclear energy has far-reaching environmental consequences: The degradation and pollution of landscapes are primarily local. The emission of greenhouse gasses and the imminent scarcity of energy sources have worldwide consequences.

#### Damage and pollution

The extraction and transport of fossil fuels cause various forms of degradation and pollution. For example, the extraction of natural gas causes subsidence in the north of our country and sometimes serious pollution occurs during the transport of oil by ship or pipeline. A lot of hot cooling water is released during the production of electricity and the issue of radioactive waste plays a role in nuclear energy. Nitrogen oxide ($NO_x$) and carbon dioxide ($CO_2$) are released during the combustion of coal, oil and natural gas. With coal and oil, sulfur dioxide ($SO_2$) and hydrocarbons are also released. $NO_x$ and $SO_2$ contribute to the acidification of the environment and $CO_2$ contributes strongly to the greenhouse effect.

#### Climate change

It has now been acknowledged that the increased emissions of 'greenhouse gasses' are causing serious problems with regard to global climate. The problems are exacerbated by the ongoing large-scale deforestation. Since 1990, global $CO_2$ emissions from fossil fuel use and cement production have increased by around 60% [6]. The Paris Climate Agreement (December 2015) agreed to do everything in our power to raise the temperature by no more than 2°C compared to the level before the industrial revolution. The aim is not to exceed 1.5°C. To achieve this temperature target, global greenhouse gas emissions must decrease, even more strongly than previously thought [2].

In the last 100 years there has been an average temperature increase of 1°C worldwide and of 1.7°C in the Netherlands [16]. A rise in the average temperature of 1 to 2°C can already have major consequences, such as an increased risk of flooding in coastal areas, high river discharges and hot dry summers [16]. Even with a significant reduction in greenhouse gas emissions, climate changes continue for a very long time due to the delayed reaction of the climate system.

### Exhaustion

Oil and gas reserves in particular are limited. The currently proven global reserves of oil and natural gas are enough for more than 50 years [3]. With coal that is still around 115 years. This is based on consumption in 2015. It is likely that there are even more recoverable stocks [2]. The reserves will increase due to new finds and improved extraction techniques. However, consumption will continue to rise in the coming decades (see section 1.1). The aforementioned periods must therefore be used with caution.

The same also applies to uranium, the fuel for nuclear power stations. Based on world consumption in 2011, there is still a stock for more than 100 years. However, if the use of nuclear energy increased globally, the supply would only be sufficient for an overall 20 years from the situation in 2007 [7].

## 1.2 Development of energy consumption

### 1.2.1 World energy consumption

World energy consumption has more than tripled in the last 45 years. North America, Europe and Asia are mainly responsible for this (Figures 1.2 and 1.3). Asia's energy consumption stands out because of the extreme increase since 2000 [3]. In Europe and North America, the demand for energy has remained fairly stable in recent years.

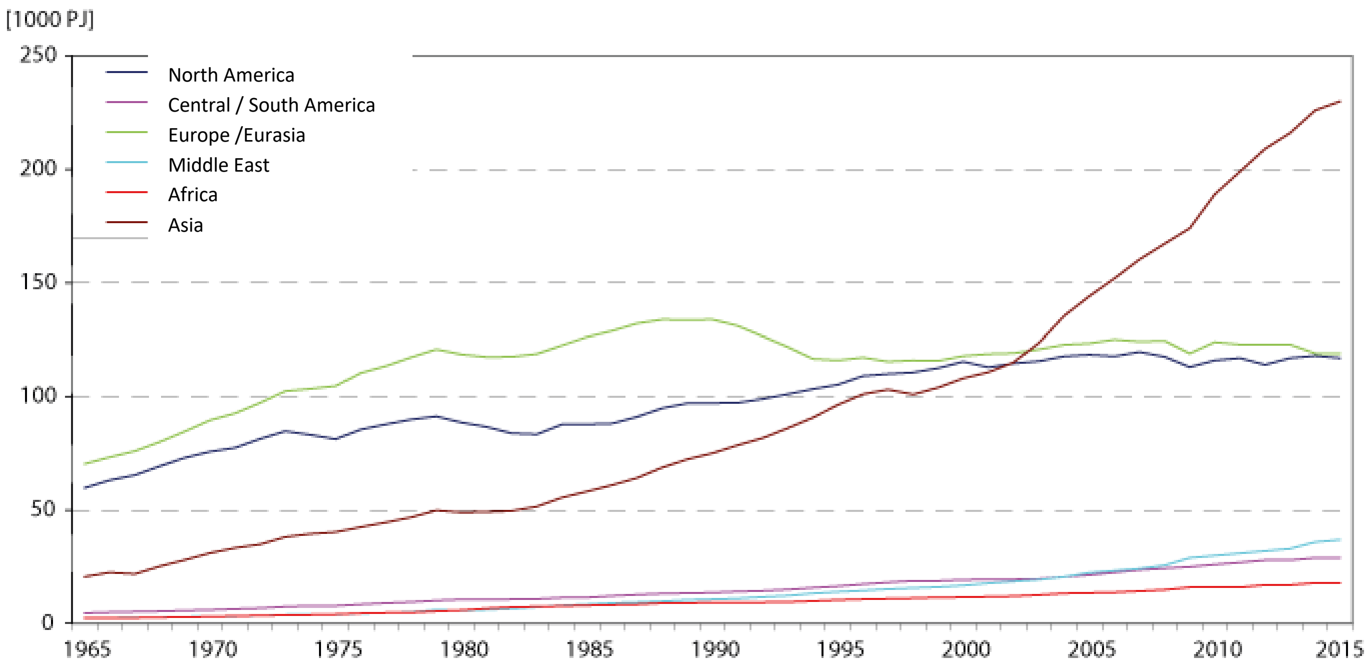


*Fig. 1.2 The world energy consumption (primary energy) per continent [3]*

Oil, gas and coal are the most important energy carriers in the world (Figure 1.3). The share of renewable energy is still very limited, but is increasing rapidly.

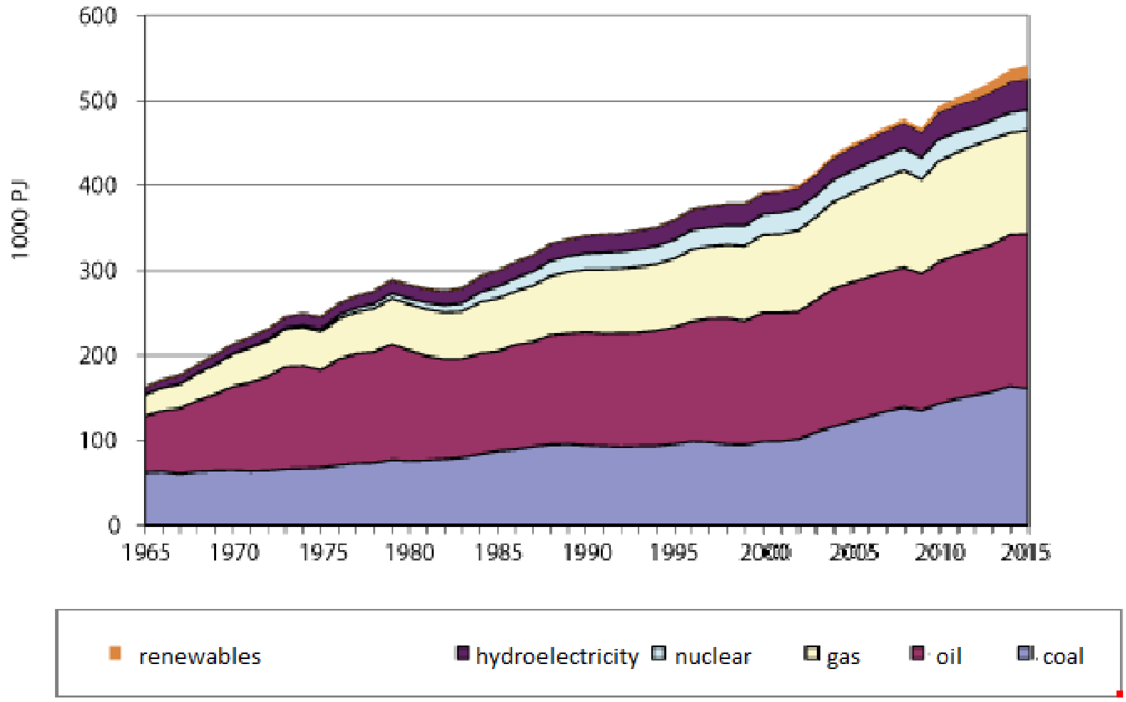


*Fig. 1.3 The primary world energy consumption per energy carrier [3]*

## Future consumption: scenarios

With the help of scenarios, insight can be gained into possible developments in energy consumption for the coming decades. There are various scenarios in circulation that contrast, for example, in the degree of international interdependence (globalization versus regionalization), in the choice between efficiency and solidarity or in the deployment of the various energy sources. Almost all scenarios have in common that the use of fossil fuel will certainly increase until 2030. Depending on the implementation of energy-saving measures and the use of sustainable energy, this use can then level off and eventually decrease.

For example, the IEA has compiled two scenarios of global energy demand, distributed across different energy sources (Figure 1.4). It can be seen that fossil fuels will long be the most important energy source. The Paris Climate Agreement (2015), however, requires a drastic reduction in the use of fossil energy, close to zero in 2050!

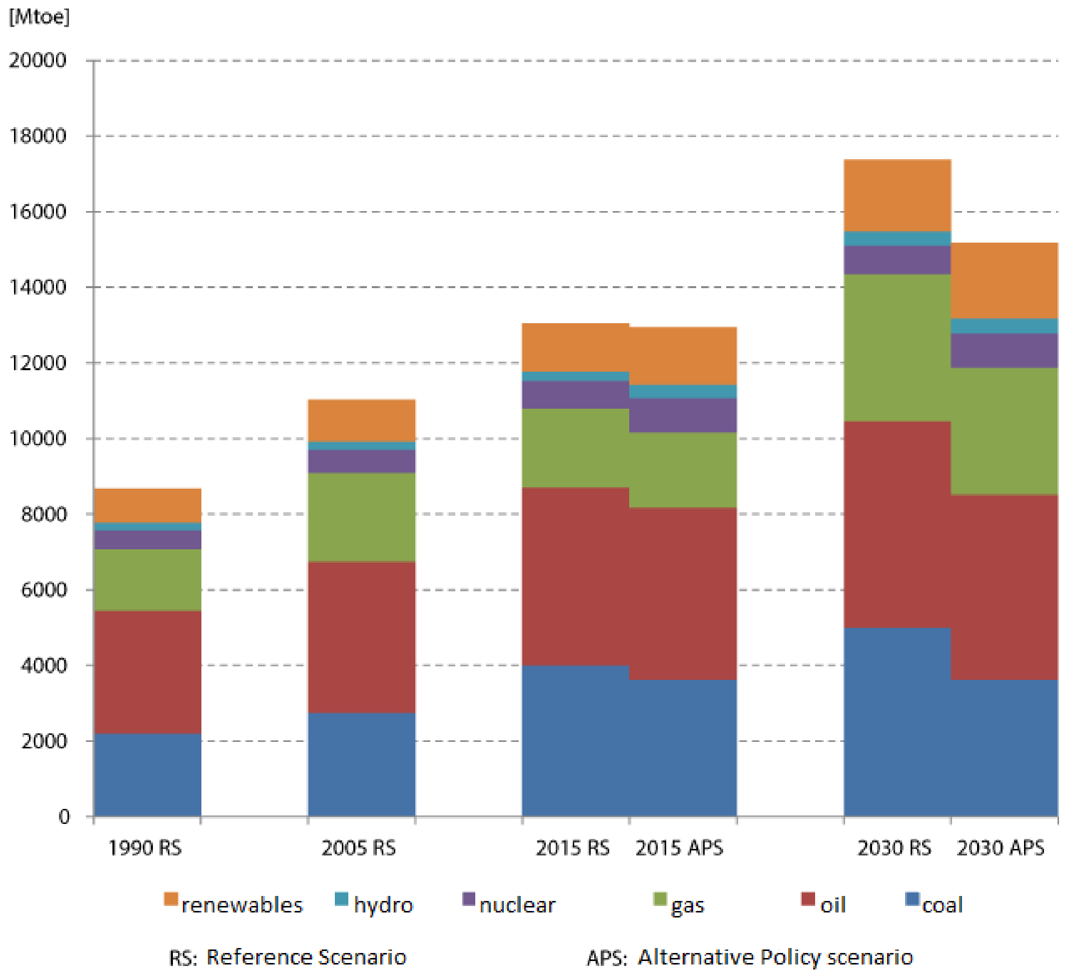


*Fig. 1.4 The (possible) development of world energy consumption from 1990 to 2030 according to 2 scenarios: the reference scenario (RS) according to current energy policy and an alternative scenario (AS) with far-reaching savings measures. 'Other sources' include the various sustainable sources such as biofuels, wind and sun. (Source: IEA [8])*
*Unit Mtoe = Megaton Oil Equivalent equals 41.9 PJ.*

## References

[1] Energierapport 2008; Ministerie van Economische Zaken, Den Haag, juni 2008; downloadable www.rijksoverheid.nl
[2] Energierapport 'Transitie naar duurzaam'; Ministerie van Economische Zaken, Den Haag, januari 2016 (www.rijksoverheid.nl)
[3] Bron: Statistical Review of World Energy - June 2014 en June 2016 voor gegevens van 2014 en 2015; te downloaden via http://www.bp.com/; BP Company, London, 2014/2016
[4] Effecten van klimaatverandering in Nederland 2012; Planbureau voor de Leefomgeving, Den Haag, 2012
[5] Dossier 'Klimaatverandering' via www.rijksoverheid.nl
[6] Mondiale emissie koolstofdioxide door gebruik fossiele brandstoffen en cementproductie per regio, 1990 - 2015, www.pbl.nl
[7] Earth's natural wealth: an audit; in: NewScientist, Magazine issue 2605, D. Cohen, 23 mei 2007 (www.newscientist.com)
[8] Key World Energy Statistics 2008; IEA (International Energy Agency), Parijs, 2008 (www.worldenergyoutlook.com)
[16] Dossier Klimaatverandering; Planbureau voor de Leefomgeving

# 2.

# Energy units & conversion factors

# 2 Energy units and conversion factors

## 2.1 Units for energy and power

The basic SI-unit for energy is joule, with the symbol J.
It is important to make the distinction between energy and power. Power is the amount of energy per unit of time. It has the unit joule per second (J/s) or watt (W). The amount of energy also equals the power times the time period: energy = power * time. (J = W.s)
Figure 2.1 shows the SI-units for energy and power and also some non-standard units of which kWh is the most commonly used unit for electrical energy.
A kWh means one kW or 1000 watts of power during 1 hour or 3600 seconds.
Thus 1 kWh equals 1000 W*3600s = 3.600.000 W.s = 3.6 MJ.

| **Units of energy** | | | **Units of power** | | |
|---|---|---|---|---|---|
| SI Units: | | | SI Units: | | |
| J | joules | 1 J | W | watt | 1 J/s |
| kJ | kilojoule | $10^3$ J | kW | kilowatt | $10^3$ W or J/s |
| MJ | megajoule | $10^6$ J | MW | megawatt | $10^6$ W or J/s |
| GJ | gigajoule | $10^9$ J | GW | gigawatt | $10^9$ W or J/s |
| TJ | terajoule | $10^{12}$ J | TW | terawatt | $10^{12}$ W or J/s |
| PJ | petajoule | $10^{15}$ J | PW | petawatt | $10^{15}$ W or J/s |
| EJ | exajoule | $10^{18}$ J | EW | exawatt | $10^{18}$ W |
| Non SI Units: | | | Non SI Units: | | |
| kWh | kilowatt hour | 3.6 MJ | hp | horsepower | 745.7 W |
| MWh | megawatthour | 3.6 GJ | | | |
| cal | calorie | 4.2 J | | | |
| kcal | kilocalorie | 4.2 kJ | | | |
| BTU | British Thermal Unit | 1055 J | | | |

*Fig 2.1 Energy units*

Some examples:

- The total amount of solar power that hits the earth's atmosphere is 1360 W/m$^2$, resulting in a total power of approximately 174 PW or 174 PJ per second. This equals 5.500.000 EJ.
- The total global energy consumption was estimated to be 567 EJ in 2012. With a population of 7 billion people the average energy consumption is around 80 GJ per person per year. This equals an average power of 2500 J/s or 2500 W per person.

## 2.2 Primary & secondary energy

### Primary energy

To understand the energy consumption, the difference between primary and secondary energy commodities needs to be understood. Primary energy consists of commodities that are captured directly from natural resources. So basically resources that exist in nature, examples are Coal, Oil, Gas, Nuclear, Geothermal, Solar, Hydroelectric, Biofuel, Wave and Tidal energy.

For primary energy resources distinction can be made between renewable and non-renewable.

| Renewables | Non renewables |
| --- | --- |
| Solar energy | Coal |
| Hydropower | Gas |
| Biofuel (short $CO_2$ - cycle) | Oil |
| Wind | Nuclear (no $CO_2$) |
| Waves | |
| Sea currents | |
| Tidal | |

*Fig. 2.2: renewable and non-renewable energy resources.*

If we want to prevent a depletion of resources a transition should be made to renewables, as they can last indefinitely whereby non-renewables consist of a limited supply which cannot easily be replaced. If we look at it from an $CO_2$ emission perspective, every kWh produced by sustainable primary energy resources reduces the emission of $CO_2$ by 0,62 kg compared to conventional means (CBS, 2013). Sustainable primary energy sources are based on solar radiation on the earth, natural dissipation of the earths rotational energy and the geothermal heat of the core of the earth. (fig 2.3.)

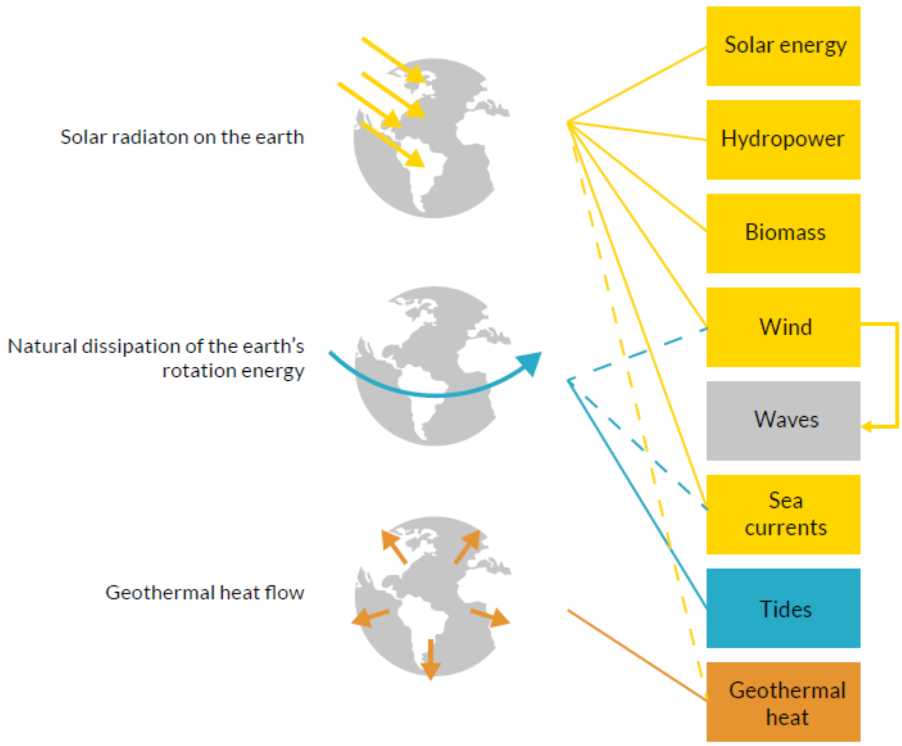


*Fig 2.3: Sustainable energy resources. Based on: Gommans, L.J.J.H.M. (2012). Gebiedsgerichte Energetische Systeemoptimalisatie, p39. Delft: TU Delft.*

## Secondary energy

Before we use the energy it needs to be transformed for the desired use. Secondary energy describes transformed energy when natural resources can not suffice. For example, crude oil cannot be used directly in cars or boilers, as it consists of an highly variable mixture of hydrocarbon molecules. We need a transformation to turn it into an useable product. In the building sector, secondary commodities are usually found in the form of electricity, An example is the electricity and heat produced by burning fossil fuels in power plants. The transformation and relation between primary and secondary energy for the building sector is explained in the diagram below. (fig 2.4.)

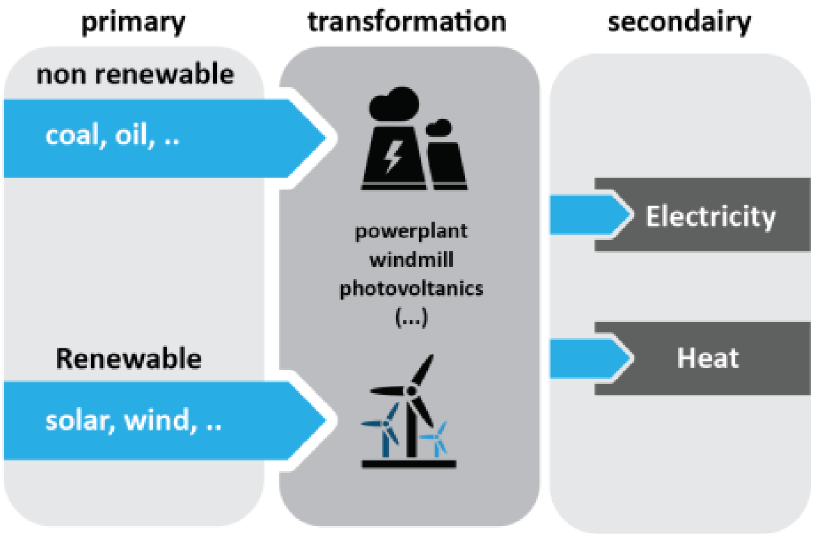


*Fig. 2.4 : Transformation of energy commodities. (for the building sector, secondary energy like oil products and synthetic fuels are omitted)*

The generation of electricity using, for example, natural gas, coal or oil (these are forms of so-called fossil energy or fossil fuels) takes place in a power plant with a relatively low efficiency between 40 and 60%, see fig 2.5.

| **Electricity transformation efficiency** | | |
|---|---|---|
| Gas turbine | Chemical to electrical | up to 40% |
| Gas turbine plus steam turbine(combined cycle) | Chemical/thermal to electrical | up to 60% |
| Water turbine | Gravitational to electrical | up to 90% (practically achieved) |
| Wind turbine | Kinetic to electrical | up to 59% (theoretical limit) |
| Solar cell | Radiative to electrical | 6–40% (technology-dependent) (Modern PV panels around 18%) |
| Fuel cell | Chemical to electrical | 40-60% up to 85% with CHP |

*Fig. 2.5 : Efficiency of power plants.*

Losses also occur during the transport of electricity from the plant to the user. In total the efficiency of the electricity production is somewhere between 30 and 50%, depending on the technologies used.
In the Netherlands the average efficiency is currently around 45%. So to produce 1 kWh of electricity 2.2 kWh or 8 MJ of primary energy is needed, see fig 2.6.

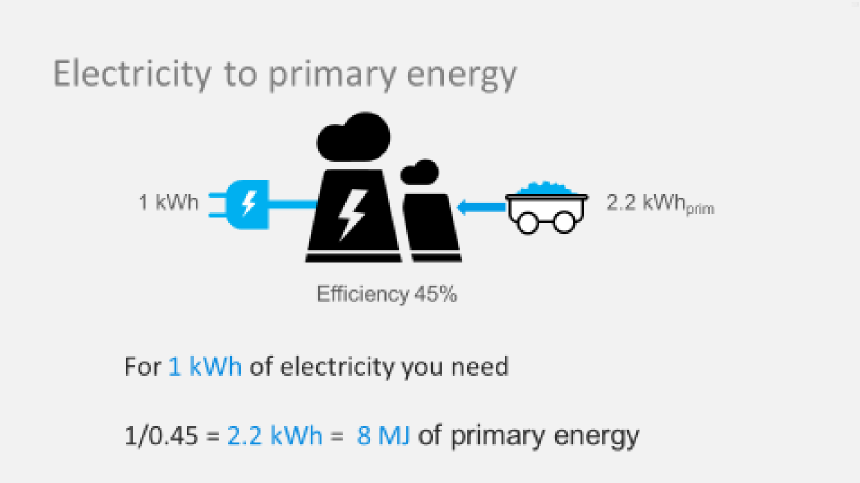

*Fig 2.6 Efficiency of electricity production*

## 2.3 Energy carriers and conversion factors

To calculate the total energy consumption for different energy carriers or commodities it has to be converted to standard units like MJ or kWh. Fig 2.7 gives conversion factors for several different fuels.

| Fuel | Volume/amount | Energy density |
|---|---|---|
| **Natural gas** | 1 $m^3$ | **35.2 MJ** 9.8 kWh |
| **Petrol** | 1 liter | **34.9 MJ** 9.7 kWh |
| **Diesel** | 1 liter | **38.2 MJ** 10.6 kWh |
| **Kerosine** | 1 kg | **43.5 MJ** 12.1 kWh |
| **Biomass** | 1 kg | **15.1 MJ** 4.2 kWh |
| **LPG /propane** | 1 kg | **49.6 MJ** 13.8 kWh |
| **Butane** | 1 kg | **49.1 MJ** 13.6 kWh |
| **Coal** | 1 kg | **28.6 MJ** 9.7 kWh |
| **Brown coal** | 1 kg | **20.5 MJ** 5.7 kWh |
| **Dry Wood** | 1 kg | **19.0 MJ** 5.3 kWh |

*Fig. 2.7 Energy density of fuels*

### Example calculation

A Dutch household uses 1.470 $m^3$ natural gas, and 3000 kWh electricity a year.
Assume an efficiency for the electricity production of 45%. (1 kWh elec = 8 MJ primary energy)

What is the yearly primary energy use of this household in MJ and in kWh?

1470 m3 natural gas equals 1470*35.2 MJ = 51744 MJ = 51.7 GJ primary energy = 14.4 $MWh_{prim}$
3000 kWh electricity equals 3000*8 MJ = 24000 MJ = 24 GJ primary energy = 6.7 $MWh_{prim}$
Total : 75.7 GJ = 21.0 $MWh_{prim}$

# 3.
# Strategies for sustainable building design

## 3. Strategies for sustainable building design

The Three-step strategy for energy or Trias Energetica is based on a step-by-step approach for energy-conscious design and consists of three consecutive steps:

1. Avoid unnecessary use of energy. (Examples: compact construction, insulation, airtight construction, 'natural' ventilation, heat recovery (ventilation air, shower water), natural cooling, hot water-saving measures);
2. Use renewable energy sources. (Examples: passive solar energy, solar water heater, ground heat for a heat pump, use of daylight);
3. Use the finite energy sources as efficiently as possible. (Examples: HR heating system, residual heat via combined heat and power, optimum control of pumps and direct current fans).

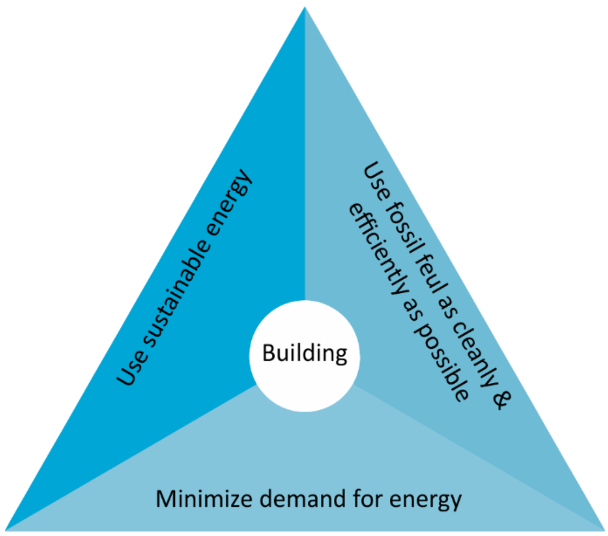


*Fig. 3.1: Trias energetica*

This strategy has successfully been used for decades, but has the disadvantage it still relies on the availability of fossil fuels. Therefore the Trias Energetica has been further developed into the “New Stepped Strategy”, fig 3.2.
This strategy puts greater emphasis on the reuse of residual flows, and can be used for Zero-Energy design.

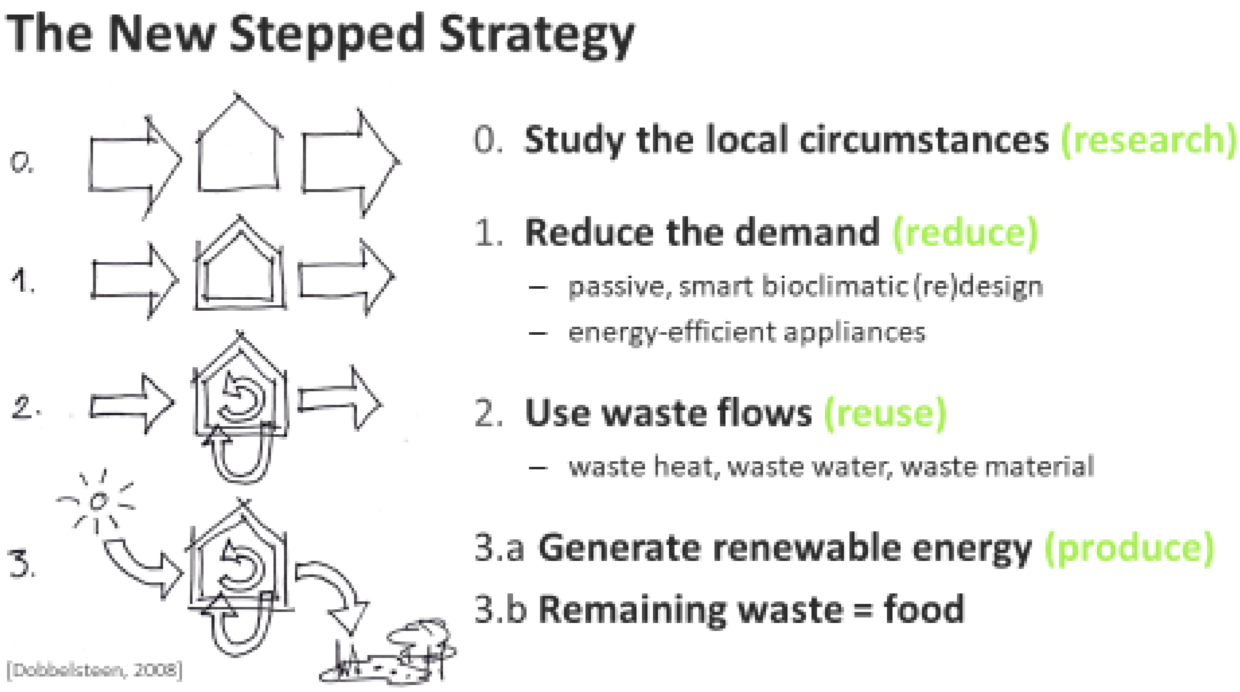


*Fig 3.2 New Stepped Strategy*

# 4.

# Heat balance of a building

# 4. The heat balance of a building

## 4.1 Definition

When talking about the energy need of a building for heating and cooling, a distinction must be made between the energy need of a building and the total energy use of technical equipment (radiators, boilers and fans) which delivers this energy.

The energy need for heating and cooling is based on the (mainly building physical) properties of a building, the climate in which the building is situated and the users (as they influence ventilation, comfort and internal heat loads). The European regulations (ISO 13790:2008) defines the energy need for heating and cooling as: "heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature".
From this definition we can clearly see that the extra energy need which is introduced by the technical equipment is not included in the determination of the energy need of a building. We define the energy need therefore as the energy need of the thermal zones of a building. This is different from the energy use, the amount of energy that is necessary to realise the heating and cooling of a building and in which the energy losses from the technical equipment are included.

## 4.2 The Energy Balance under steady state conditions

The energy balance is the starting point in determining the energy need of a building. The energy balance of a room consists of all the heat flows that enter or leave a room. The following types of heat flows play a part:

| **Flow** | **Description** |
|---|---|
| Transmission | Heat transfer through the building skin |
| Ventilation* | Air exchange of a room |
| Infiltration* | Airflow through cracks and crevices |
| Solar radiation | Radiation from the sun coming in through transparent surfaces |
| Internal heat load | Production of heat in a room by persons, equipment and lighting |

(*) Ventilation and infiltration can also be considered as mass flows, where a certain mass (amount) of air having an outside temperature enters the room and the same mass (amount) of air having an inside temperature exits the room.

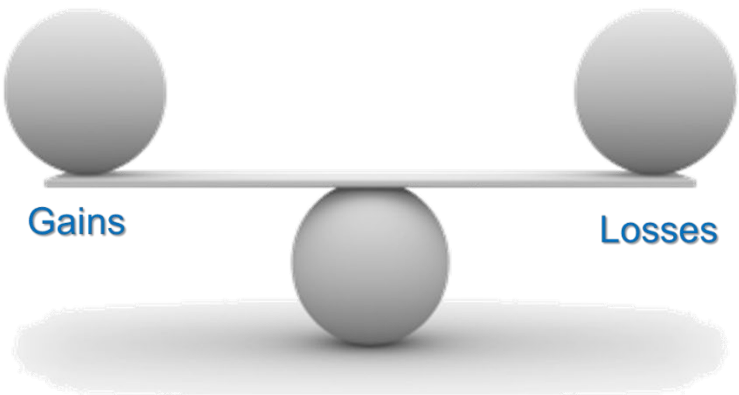


*Fig 4.1 The energy balance or heat balance*

Under stationary conditions – a condition in which the heat flows are constant (i.e. the same at 9.00 a.m. as at noon) - the following energy balance equation in J applies:

$$E_{in} = E_{out}$$

This balance equation can also be expressed in heating power [W= J/s]:

$$Q_{in} = Q_{out} \text{ or } Q_{in} - Q_{out} = 0$$

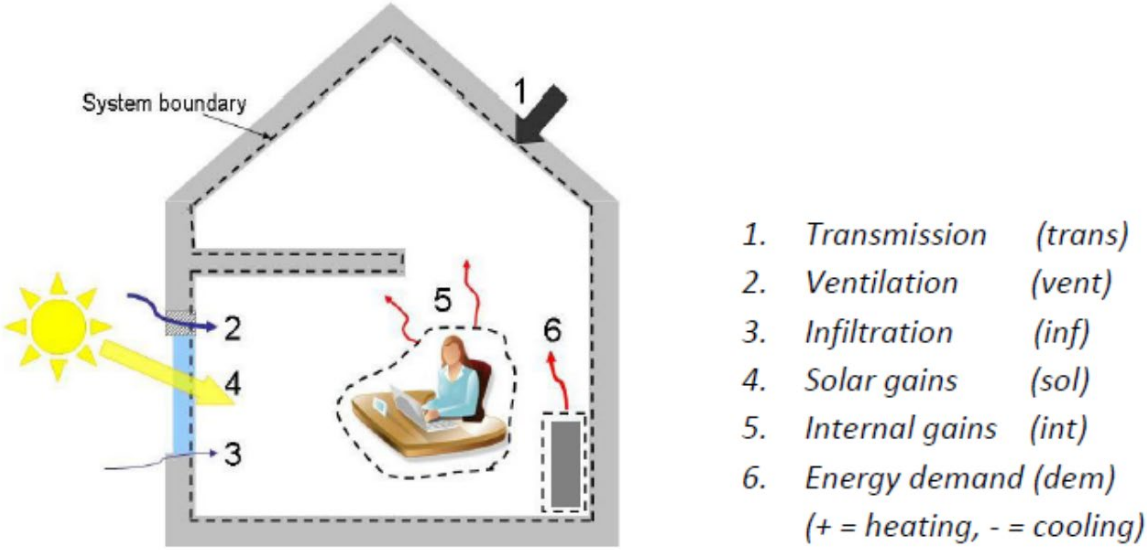


*Fig 4.2 Different components of the energy balance of a building*

The different components of the (energy) balance equation can be calculated as follows:

### 4.2.1 Transmission

Heat transfer through transmission ($Q_{transmission}$) is generally calculated using the following equation:

$$Q_{transmission} = U * A * (T_e - T_i)$$

With

| | | | |
|---|---|---|---|
| U | = | thermal transmittance of the wall | [W/(m²·K)] |
| A | = | area of the wall | [m²] |
| $T_e$ | = | outside temperature | [°C or K] |
| $T_i$ | = | inside temperature | [°C or K] |

When a wall consists of different faces, all the energy flows through transmission are added:

$$Q_{transmission} = \sum U * A * (T_e - T_i)$$

Depending on $T_e$ and $T_i$, the factor ($T_e$–$T_i$) is a negative or positive number. When $T_e$ is higher than $T_i$, which seldom occurs in the Netherlands, ($T_e$–$T_i$) > 0 and the transmission heat flow results in a heat gain in the room. When $T_e$ is lower than $T_i$, which is the main situation in the Netherlands, ($T_e$–$T_i$) < 0 and the transmission heat flow results in a heat loss in the room.

Remark: The transmission is often directly defined as the heat loss, i.e. as $U \cdot A \cdot (T_i - T_e)$. This is also a possibility, as long as you make sure that the plusses and minusses are consistently used when determining the total energy balance.

### 4.2.2 Ventilation and infiltration

The heat transfer by ventilation ($Q_{vent}$) and infiltration ($Q_{inf}$) can be calculated as follows:

$$Q_{vent} = \frac{V_{vent} * n * \rho * c_P * (T_e - T_i)}{3600}$$

$$Q_{inf} = \frac{V_{inf} * n * \rho * c_P * (T_e - T_i)}{3600}$$

With

| | | | |
|---|---|---|---|
| $V_{vent}$ | = | volume of the room | [$m^3$] |
| $V_{inf}$ | = | volume flow of infiltration | [$m^3$] |
| n | = | air change rate | [$h^{-1}$] |
| ρ | = | density or air (~ 1.2) | [$kg/m^3$] |
| $c_P$ | = | heat capacity of air (at constant pressure ) (~ 1000) | [J/(kg·K)] |
| $T_e$ | = | outside temperature | [°C or K] |
| $T_i$ | = | inside temperature | [°C or K] |

Another way of writing these formulas is:

$$Q_{vent} = \frac{q_{vent} * \rho * c_P * (T_e - T_i)}{3600}$$

$$Q_{\text{inf}} = \frac{q_{\text{inf}} * \rho * c_P * (T_e - T_i)}{3600}$$

With

| | | | |
|---|---|---|---|
| $q_{vent}$ | = | volume flow of infiltration | [$m^3/h$] |
| $q_{inf}$ | = | volume flow of infiltration | [$m^3/h$] |

Again the term ($T_e$-$T_i$) can be a positive or negative value depending on whether the outside or inside temperature is higher. For a higher outside temperature this results in a heat gain in the room and for a lower outside temperature this results in a heat loss from the room.

### 4.2.3 Solar load

The heat load by the sun ($Q_{sun}$) can be calculated as follows:

$$Q_{sun} = A_{glass} * q_{sun} * ZTA$$

With

$A_{glass}$ = area of the glass [$m^2$]

$q_{sun}$ = intensity of the solar load on the glass [$W/m^2$]

'ZTA' = solar factor (SF, Dutch: ZTA) or g-value according to EN 410 [-]

### 4.2.4 Internal Heat Load

The internal heat load ($Q_{int}$) can be calculated by adding up the heat production of all people, equipment, and lighting elements in a room.

$$Q_{\text{int}} = Q_{person} + Q_{equipment} + Q_{lichting}$$

## 4.3 The steady state heat balance

Under stationary conditions – a condition in which the heat flows are constant – the heat balance equation can be expressed in terms of all the different flows.

$$Q_{trans} + Q_{vent} + Q_{\text{inf}} + Q_{sun} + Q_{\text{int}} + Q_{need} = 0$$

In this balance the temperature different is in all cases defined as ($T_e - T_i$), which means that a positive value for ($T_e - T_i$) leads to a heat gain in the room and a negative value for ($T_e - T_i$) leads to a heat loss from the room.

A positive value for $Q_{need}$ is, likewise, a need for heating and a negative value for $Q_{need}$ signifies a need for cooling.

## 4.4 Ventilation and heat recovery

In many buildings heat recovery of the ventilation is being used. The fresh ventilation air will be guided along the filthy ventilation air, where temperature exchange is possible. Through this system the temperature of the ventilation air is not the same as the outside air temperature, but the temperature of the ventilation air is closer to the inside air temperature. In the Netherlands this applies mostly to the heating situation, where fresh ventilation air becomes warmer than the outside air. The heat losses by ventilation will be smaller than compared to the situation without heat recovery.

The efficiency of the heat recovery system is defined as follows:

$$\eta_{hr} = \frac{T_{as} - T_e}{T_i - T_e}$$

With:

$\eta_{hr}$ = efficiency of the heat recovery system [-]

$T_{as}$ = temperature air supply [°C or K]

$T_e$ = outside temperature [°C or K]

$T_i$ = inside temperature [°C or K]

A heat recovery system with an efficiency of 30% gives, while the outside air temperature equals 0°C and the inside air temperature equals 20°C, an air supply temperature of 6°C. (30=($T_{as}$-0)/(20-0)=>$T_{as}$=6)

In a heat balance the effect of the heat recovery can be taken into account by putting the efficiency in the calculation of the heat transfer by ventilation. The formula changes towards:

$$Q_{vent} = (1-\eta_{hr}) * \frac{q_{vent} * \rho * c_P * (T_e - T_i)}{3600}$$