TÉCNICO LISBOA

Lecture Notes

Energy Management

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FORWARD

The objective of these lecture notes is to summarize the main contents of the course Energy Management at Instituto Superior Técnico. The objective is not to replace any fundamental text book on Energy Management, but solely to highlight the main points that are scattered around many textbooks, reports and other important documents on Energy Management.

They result mostly from the development of the MOOCs Energy Services (esX) and Economic and Legal Aspects of Energy in Buildings (elbX), from the MOOCS@IST, and from many other indirect contributions of many colleagues that have lectured this course with me over the years: Paulo Ferrão, Tânia Sousa, André Pina, Patrícia Baptista, Diana Neves, Cláudia Sousa Monteiro, Samuel Niza, Francisco Capucha. A particular word of appreciation to Diana Fernandes, that helped me to develop the Economic and Legal Aspects of Energy Services MOOC during 2017 and 2018, and compiled many of the information presented in this lecture notes, including formulas and figures. More recently, to João Araujo, a student from the class of 2019-2020, which gave a detailed feedback to all chapters, which highly improved the text.

A final word to Fernanda Margarido, who co-authored chapters 10 and 11, and did a fantastic review of the whole document.

Now, I pass the ball to the many students that every year participate enthusiastically in classes to provide feedback, by finding mistakes, inconsistencies, and suggesting ways to improve these notes.

Lisbon, September 21sh, 2020

Carlos Santos Silva

CONTENTS

I. DEFINITIONS

1 INTRODUCTION TO ENERGY MANAGEMENT

1.1 Energy management definition

Energy management is the body of knowledge (set of concepts and activities) that deals with the use of the energy resources of a system in the most efficient way.

This includes designing, implementing and operating the energy generation and energy consumption units within an organization. The main objectives are, by decreasing order of importance:

1. Provide the adequate level of energy services to develop the activities of the organization
2. Minimize energy demand
3. Minimize energy costs
4. Promote local use of energy resources
5. Promote adequate energy use behaviour from the users

1.2 The energy manager

The Energy manager is the agent in an organization/company who is responsible for the implementation of energy management.

To do this, the list of tasks that need to be performed by the energy manager include:

- Setting targets for energy management
- Undertake energy audits across an organization
- Monitoring energy usage across the organisation
- Prepare reports summarising energy usage
- Create and deliver training activities for organization collaborators regarding energy consumption
- Keep up to date with changes in energy regulation
- Keep up to date with industry standard best practice

To develop all these tasks, the Energy Manager must develop a large set of skills, including:

- Solid background on energy management
- Numerical and analytical capacity to develop calculations, estimations, algorithms
- Knowledge and experience in Project Management
- Knowledge on general IT tools, but also in specialized software
- Comfortable in communication, presentation, and coaching activities

1.3 Energy management certification

There are several certification organizations for Energy Managers:

- Energy Manager Certification, by the Institute of Energy in UK, which provides a two level certification: Level 1 (Certificate in Energy Management Essentials) and Level 2 (Energy Management Professional, which requires 2 years of previous experience and 200 hours of training);
- Energy Manager Professional, by the Energy Management Association in US

- Certified Practitioners in Energy Management Systems (CP EnMS), by the Institute for Energy Management Professionals in US, which is recognized by the DOE in US
- Professional Energy Manager, by Schneider
- Professional Energy Manager, by the Institute of Energy Professionals

In general, all these certification processes require:

- **Fundamental knowledge** in energy core knowledge (thermodynamics, heat transfer, fuels, and combustion), but also in project management and finance
- **Energy applications and technologies**, like heating and ventilation, air conditioning and refrigeration, building physics and thermal comfort, lighting, compressed air, steam and process heating, and motors and drives
- **General context knowledge of energy**, like energy industry and energy costs, measurement and verification, data testing and analysis, energy and the environment, energy management systems and standards (including ISO 50001), and energy conversion and transport
- **Other topics**, like on-site electricity generation, building management systems, and carbon management

1.4 Fundamental bibliography for energy managers

There are many and very good textbooks for energy managers. From those, these are three examples of the most used books:

- Energy Management Handbook, 8th Edition, by Steve Doty, Wayne C. Turner
- Energy Management Principles, Applications, Benefits, Savings, 2nd Edition, Craig B. Smith, Kelly E. Parmenter, Elsevier
- Guide to Energy Management, 8th Edition, Barnley L. et al

2 ENERGY SYSTEMS

2.1 Definitions

2.1.1 Energy

Energy is the capacity that a physical system has to change its states or the states of other physical systems, like changing their velocity or their temperature. The mass of the system is a measure of its energy content.

All changes that occur in nature are caused by some form of energy exchange. Energy is always a transference between systems and cannot be created or destroyed. This describes the first law of thermodynamics, also known as the energy conservation principle.

There are many forms of energy, but they can all be categorized in two groups:

Potential energy, which describes the forms in which energy is stored in a system, like nuclear, chemical, gravitational, or thermal

Kinetic energy, which describes the forms in which energy is transferred between systems, like work (mechanical or electrical) or heat

Energy is a scalar unit and in the International System of Units (SI), it is measured in Joule (J). 1 joule is the energy exchanged, for example, while:

- applying a force of 1 Newton (N) to move a body for 1 meter (m)
- passing a current of 1 Ampere (A) in a resistance of 1 Ohm (Ω) for 1 second (s)

The first measurements of energy were done while measuring heat using a Calorimeter. The name "calorie" was given to the amount of energy required to increase by 1ºC the temperature of 1g of water at 14.5°C. 1 calorie (1 cal) corresponds to 4.184 J.

When talking about energy, the use of the SI unit (J) is not the standard. In fact, the unit that is used depends very much on the context.

For example, when talking about electricity, the kilowatt-hour (kWh) is the most used unit; when talking about climatization, the British Thermal Unit (BTU) is very common; when talking about the energy consumption of a country, the Tonne of Oil Equivalent (toe) is the prevailing unit. Table 1 presents the conversion factors for the most common energy units to the SI unit Joule.

Table 1 - Most common energy units and its conversion factor to the SI unit (J)

UNIT	CONVERSION TO JOULE (J)
KWH	3 600 000
BTU	1055
TOE	$41{,}87 \times 10^9$

2.1.2 Power

Power is the rate at which energy is transferred from or to a system. Its unit is the Watt (W), which corresponds to 1 Joule per second.

Energy and power are related in the following way

$$E = P \times \Delta t \tag{1}$$

where:

E is the energy

P is the Power (W)

Δt is the time period elapsed (measured in seconds or hours)

2.1.3 Energy System

An energy system is a well-defined system in which energy flows enter the system to perform certain activities.

The energy can be converted into multiple forms (energy output). According to the second law of thermodynamics, a fraction of it is always lost in the conversion process. An energy system may represent, for example, a car engine, a house, a machine or the country's energy system.

2.1.4 Conversion efficiency

In any energy system, we have some energy conversion process, which is the process of changing one form of energy to another. The metric that measures the energy conversion efficiency is called the system efficiency and is usually represented by η.

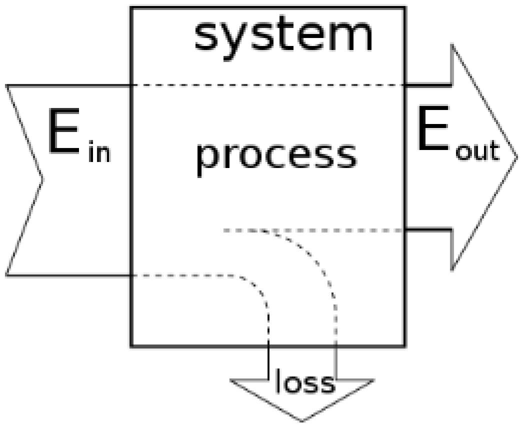


Figure 1 - Energy system conversion

The energy efficiency (or the first law efficiency) is the ratio between the energy output over the energy input, regardless of its form (work or heat).

$$\eta = \frac{E_{output}}{E_{input}} \tag{2}$$

Remember that this value may be smaller than one (e.g. in thermal engines), but it can be greater than one (e.g. in heat pump systems).

2.1.5 Energy conversion levels

We introduce now four new concepts: the primary energy, final energy, useful energy, and energy service. The breakdown of primary to energy service is very relevant, because in each conversion step some energy is always lost.

2.1.5.1 Primary energy

Primary energy is the energy embodied in natural resources which need to be extracted (e.g. oil and coal, but also wind and solar). Therefore, primary energy refers to energy sources as they are found in the nature.

2.1.5.2 Final energy

Final energy is the energy available at the consumer level. It results from the transformation of primary energy sources into energy commodities, and in general involve some transformation and/or transportation process (e.g. electricity, gasoline, or LPG).

2.1.5.3 Useful energy

Useful energy is the energy that is actually used by the users. It corresponds to the portion of the final energy that is available after the conversion at the end-use technologies. It is, for example, depending on the technology conversion, what electricity becomes (e.g. light, mechanical energy, or heat).

2.1.5.4 Energy service

Energy services refer to the activities that the users can perform with the useful energy. For example, light (useful energy), is actually used to read or cook – that is the service. However, this light may be generated by a light bulb using electricity (final energy), or directly by solar radiation (both primary and final).

What is really important for the users is the service, and not how it is supplied. Therefore, it is not measured in energy units like Joule (J), but in a certain level of service and the time that it is required. For example, regarding light, in an office we need at least 300 Lux during the period we are working. That is, the required service is 300Lux for 8 hours/day. Other examples include "we need 40 liters of water at 40°C per day for hygiene purposes" and "we need 20°C 24 hours/day inside a building".

2.1.6 Other definitions

2.1.6.1 Energy supply

The energy supply is the energy that is extracted from nature. It includes all the activities that allow the extraction, transportation, and storage of fuels. Usually energy supply refers to primary energy vectors.

2.1.6.2 Energy demand (Energy consumption)

The energy demand is the energy that is consumed by a particular system or economic sector. It is the energy required to provide the products and services, and usually refers to final energy vectors. The energy demand may be described by technology (in the case of a building energy system, it could be the energy for HVAC systems, or the energy for lighting) or by economic activity (in the case of a country's energy system, it could be energy in the industry or the residential sector).

2.1.6.3 Energy conversion

Energy conversion describes the conversion process from primary to final (e.g. energy conversion in a power plant or a refinery) or from final to useful (energy conversion in a boiler or a light bulb).

2.1.6.4 Energy Losses

Energy losses refer to the part of the energy flow that is lost in the conversion process, for example as heat.

2.2 Representation

2.2.1 Reference energy system

The reference energy system (RES) is a representation of all the technical activities required to supply various forms of energy to end-use activities. This framework helps to describe an energy system by describing the energy flows, the energy conversion technologies, and the energy outputs.

In practice, it is a diagram that represents activities, the technologies, and the energy flows from primary energy supply to final energy use, and eventually (though not as common) useful energy flows and energy services.

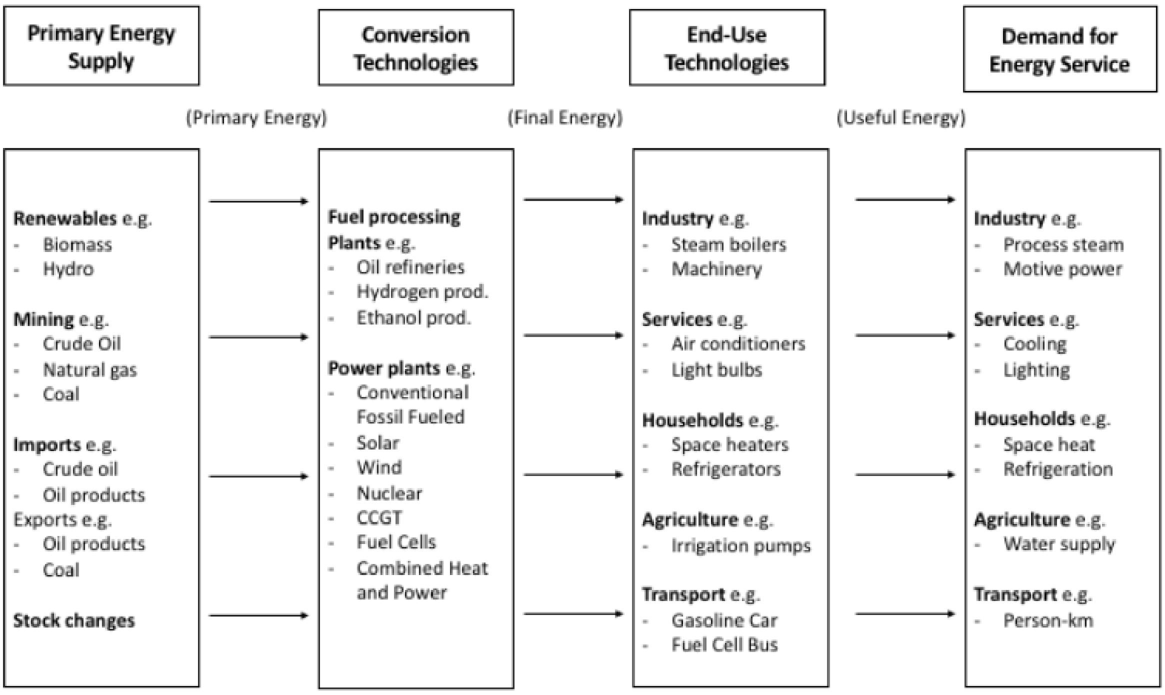


Figure 2 - Reference energy system representation

In the reference energy system in Figure 2, we can observe that on the left side we have the technologies and activities that enable us to collect primary energy (the primary energy supply area), such as oil extraction, coal mining, biomass collection, etc. Then, the second area refers to conversion technologies from primary to final energy supply and its transportation, like electricity generation on power plants or oil refining. In some cases, like biomass or natural gas, the primary energy is consumed directly as a commodity (final energy) and there is no conversion process.

We have a second level of technologies which are the end-use technologies, which allow us to change the final energy into a form of useful energy to perform different activities, like heating, mechanical movement, or light. These activities, which are not energy nor technologies, are the energy services.

2.2.2 Energy Balance

The energy balance is a tabular representation of the energy system that presents in an aggregated way the amounts of energy used in given activities. In a way, as shown in Figure 3, it looks like the reference energy system rotated 90°, with numerical values.

Energy balances can be used to describe the use of energy in a country or a building. The thorough analysis of the energy balance can provide us with several pieces of information about how the energy system is designed and how it operates.

The energy balance is a table where in the columns we have the energy vectors or products (primary, final, or eventually useful) and in the rows we have the activities on the supply or the demand (or eventually the services). Then, in each cell, we place the amount of energy (primary or final) that was used in each activity (supply, conversion or energy end use).

Energy balances are usually used to represent the consumption of countries in a given year. As the aggregated energy values are very high and oil is still the reference energy vector in international markets, energy balances are usually represented in Tonnes-of-oil-equivalent (toe), which is a very large energy unit that represents the amount of energy contained in one tonne of oil.

The energy balance allows us to see the relative importance of the different fuels in their contribution to the economy. The energy balance is also the starting point for the construction of various indicators, as well as analyses of energy efficiency.

SUPPLY AND CONSUMPTION [unit]	Coal	Crude oil	Oil products	Natural Gas	Nuclear	Hydro	Geotherm. solar etc.	Biofuels & Waste	Electricity	Heat	Total
Production	7371	660	-					806	-		
Imports	945	2660	1285					1	763		
Exports	-57	-1	-237					-4	-757		
Intl. marine bunkers	-	-	-					-	-		
Intl. aviation bunkers	-	-	-48					-	-		
Stock changes	-136	-71	-21					1	-	-	-227
TPES	8122	3248	979					804	6	-	16032
Transfers	-	51	-47	-	-	-	-	-	-	-	4
Statistical differences	303	59	-48	-	-	-	-	-	5	10	329
Electricity plants	-6785	-	-17	-17	-	-823	-	-	3127	-	-4515
CHP plants	-	-	-33	-99	-	-	-	-	36	39	-58
Heat plants	-104	-	-349					-1	-	778	-106
Blast furnaces	-247	-	-					-	-	-	-247
Gas works	-		-					-	-	-	-
Coke/pat.fuel/BKB/PB plants	-99	-	-					-	-	-	-99
Oil refineries	-	-3457	3160					-	-	-	-297
Petrochemical plants	-	99	-103					-	-	-	-4
Liquefaction plants	-	-	-					-	-	-	-
Other transformation	-	-	-					-	-	-	-
Energy industry own use	-	-	-					-	-322	-20	-387
Losses	-76	-	-					-	-508	-81	-696
TFC	1115	-	3541					804	2344	727	9956
INDUSTRY	582	-	498					22	608	296	3007
TRANSPORT	1	-	2178	4	-	-	-	-	23	-	2206
OTHER	511	-	176	281	-	-	6	781	1714	431	3901
NON-ENERGY USE	21	-	689	132	-	-	-	-	-	-	842

TPES
Total primary energy supply

Supply
Refined products and electricity are secondary energy; production equals zero to avoid double counting.

Transformation
Negative value represents an input, positive value represents an output.

Transformation **losses** appear in the **Total** column as negative figures.

Figure 3 - Typical representation of an energy balance of a country (Source: EIA Global Headline Energy Data, 2017 edition)

2.2.3 Energy Sankey Diagram

The Sankey diagram is a graphical representation of the flows in a system, in which the width of the arrows is proportional to the flow quantity. We can think about them as a mixture of the reference energy system and the energy balance. In Figure 4 and Figure 5 we can see two examples: one for Portugal 2016, and another one for the world in 2005, which includes energy services.

2.2.3.1 Portugal 2016

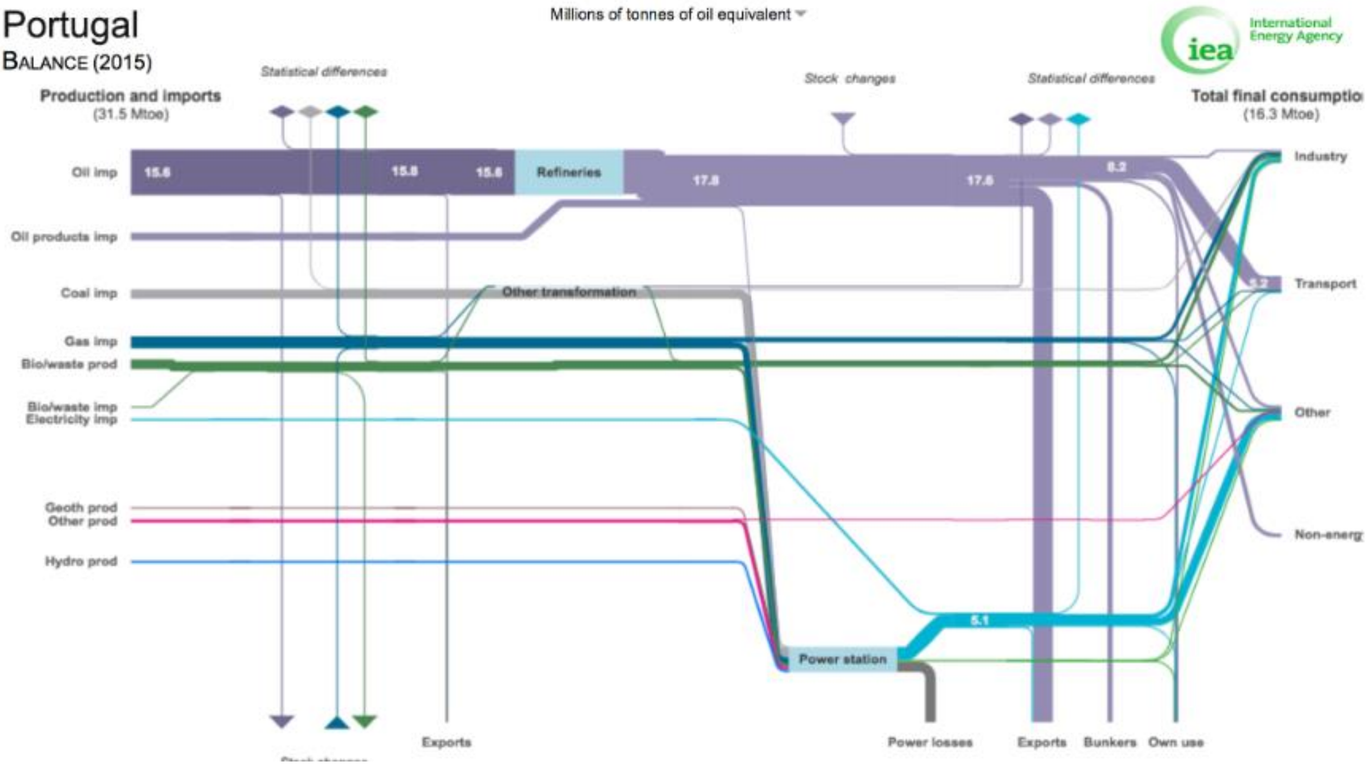


Figure 4 - Portugal Energy Balance in 2015 (Source: IEA)

In this case, we can observe that the consumption of oil in Portugal is exclusively used to refine oil products, which are mostly either used for the transportation sector or exported.

We can also see that power generation is very diversified, with the use of renewables, coal, natural gas, and imports. The generated electricity is mostly used in "Other" (commercial, services and residential sectors) and in "Industry".

2.2.3.2 World (2006 and 2016)

In this Sankey Diagram, we can see that in 2005, oil and coal were the most important energy resources used around the world, followed by gas and biomass (ahead of nuclear and renewables). We can also see that electricity is mostly produced by coal, followed by gas and nuclear, and that in 2005 renewables accounted more than oil for power generation.

What is particularly interesting in this energy diagram is that, in terms of energy services, we can see that most of the energy was used to provide services inside buildings: thermal comfort, hygiene, sustenance (preparing food), illumination, and communications. In terms of the Transport service, we see that half of the energy consumed is used to move people, and the other half is used to move cargo.

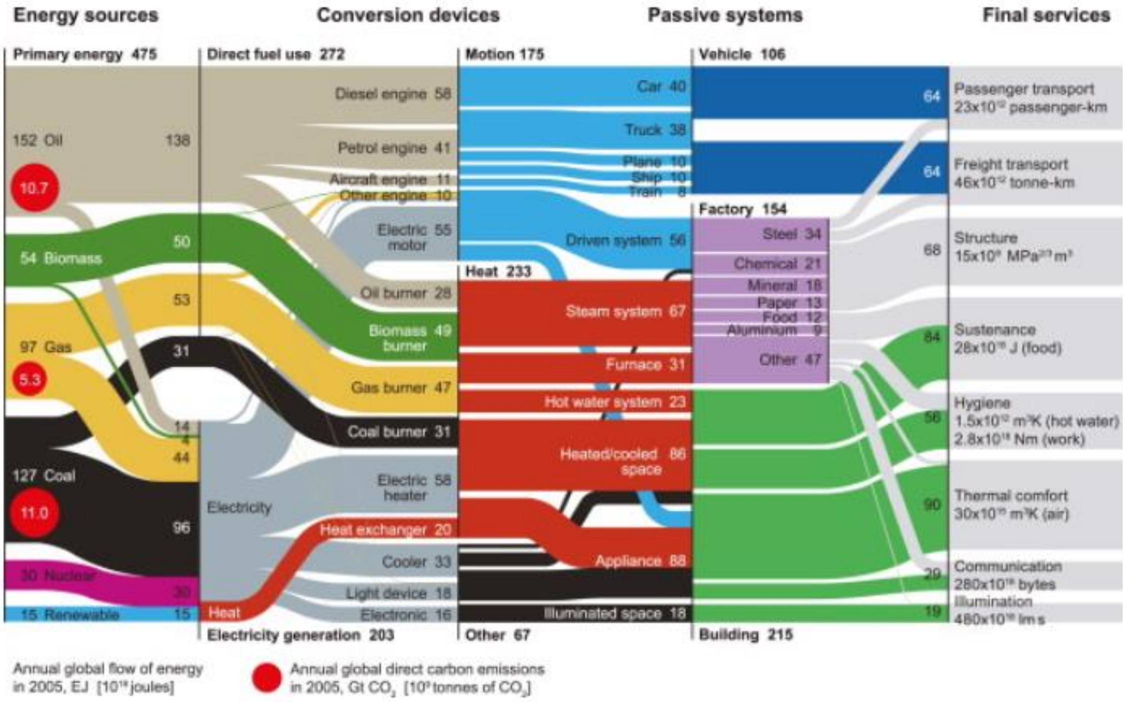


Figure 5 - World Sankey diagram (2006), including energy services (Source: Jonathan M. Cullen, Engineering Fundamentals of Energy Efficiency, PhD Thesis, Cam, Figure 3.2 Tracing the global flow of energy from fuel to service, p. 58)

II. CONTEXT

3 ENERGY AROUND THE WORLD

This chapter presents an overview of the energy use around the world.

3.1 The word Sankey diagram

The world Sankey Diagram of Figure 6 clearly describes the world energy system in 2016.

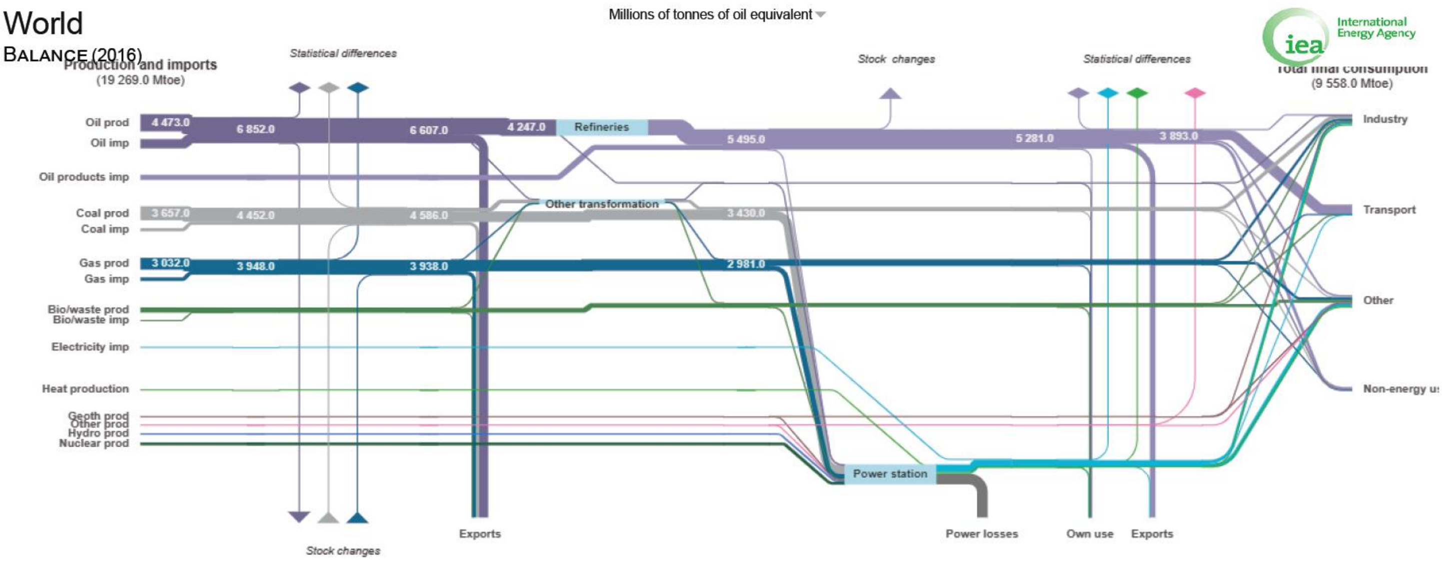


Figure 6 - World energy Sankey diagram in 2016 (Source: IEA, https://www.iea.org/Sankey/#?c=World&s=Balance)

Comparing it with the Sankey diagram presented in Figure 5, we see that over the last decade there were no significant changes in the world energy system. On the demand side, the world energy demand is more or less divided equally into three parts: Transports, Industry and Other uses (this sector refers to Residential, Commercial and Public Services, Agriculture and Forestry, Fishing, and Non-Specified Uses).

In the power generation sector, coal and natural gas are still the dominant energy resources. The main difference to 2005 (see Figure 5) is that the use of oil for power generation in 2016 is residual, and renewables, including hydro, surpass the generation of electricity by nuclear.

It is also clear that almost the entire transportation sector uses oil products and its derivatives, while Industry has a more diverse energy mix (as it uses coal, gas and electricity). The “Others” use Electricity, Gas and Biomass (especially in developing countries for food preparation).

Considering that Residential, Commercial, and Public Services are all developed inside buildings, we can see that most of the “Others” sector is basically describing the energy demand in the Buildings sector.

A special note related to Agriculture, Forestry, and Fishing. The energy consumption in these sectors is usually considered very small, in general it has to do with the accounting system used in these economic sectors. The Agriculture activity per se may involve some direct consumption of fuel in machines, but the production of fertilizers is a significant part of the Industry demand. This would not happen if energy statistics were based on energy services, where one of the services would be the Production of Food, and which would include the consumption of energy for fertilizers, plus the consumption of the machines. That is why we can see that in Figure 5 that the service “Sustenance” is partially supplied by the food industry.

3.2 Total Primary Energy Supply

In Figure 7, we can see that oil and coal are the main energy products and that, over the last decades, their relative weight to the total energy mix has been similar. Coal consumption has increased more than oil consumption, but the only relevant change is the consumption of renewable resources, which, although it still represents a small fraction of the total consumption, has increased significantly.

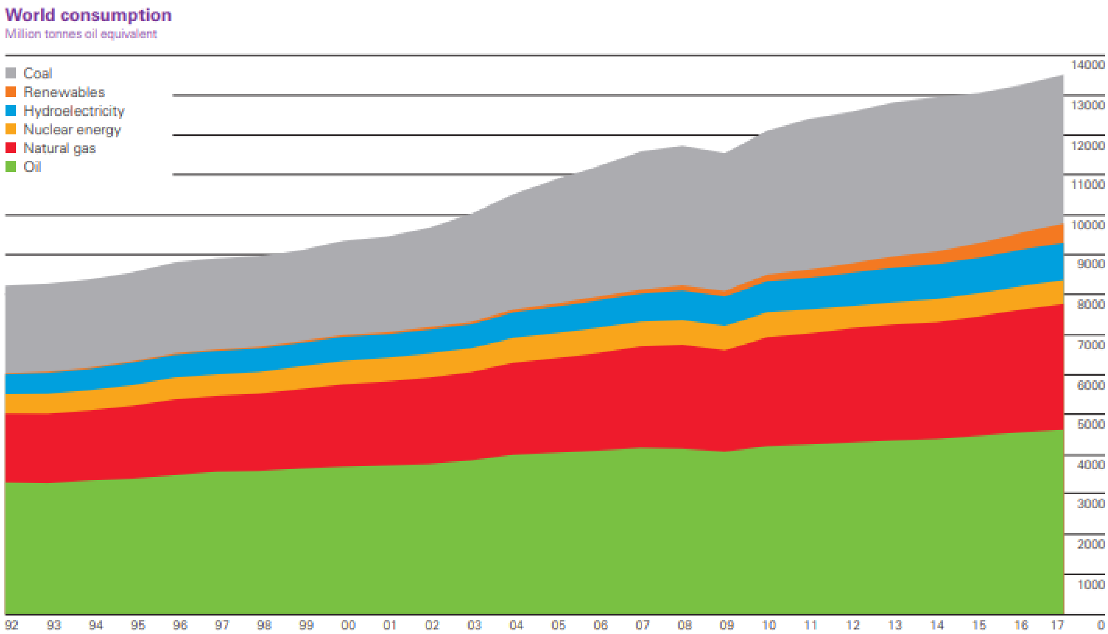


Figure 7 - World primary energy supply evolution (source: BP Statistical review 2017)

In 2017, the growth of primary energy consumption averaged 2.2%, compared to 1.2 % in 2016. This was the largest increase to date since 2013, and compares with the 10-year average of 1.7% per year.

By fuel type, natural gas accounted for the largest increment in energy consumption, followed by renewables, and then oil.

Energy consumption rose by 3.1% in China. China was the market with the largest growth of energy demand, for the 17th consecutive year.

3.3 Final energy demand

In Figure 8, the evolution of the final energy demand in the world is presented. The figure shows that oil products are the largest type of final energy consumed in the world, followed by electricity, ahead of gas, coal, and biofuels and waste. Electricity is the type of final energy with whose consumption has experience the largest growth over the last decades, as it grew from less than 10% of the total final energy, to the current eighteen percent.

The growth of final energy consumption is smaller than the growth in primary energy, which indicates that the overall efficiency of conversion of the system “world” has actually decreased.

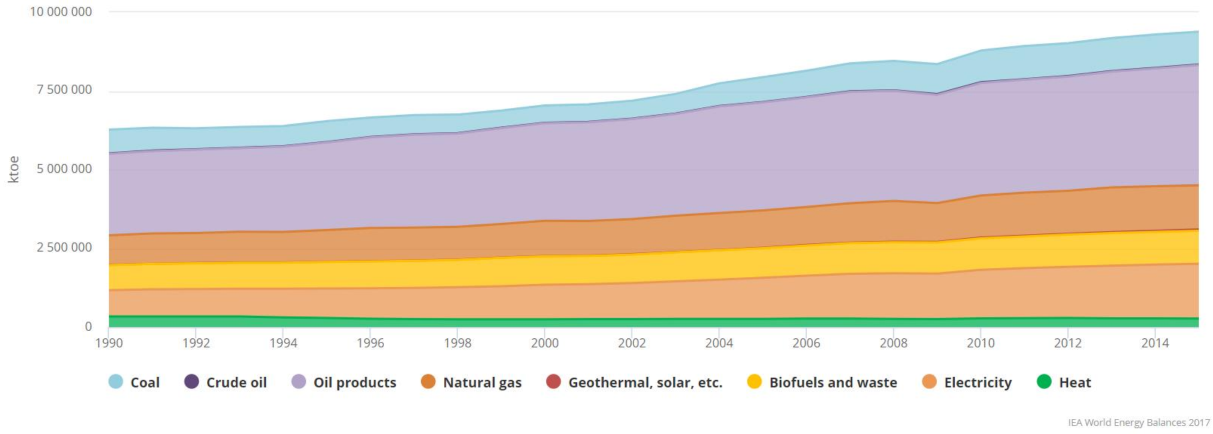


Figure 8 - World final energy demand in the world (Source: IEA World Energy Balance 2017)

In Figure 9, it can be seen that the energy used is more or less divided in three sectors:

- Transport, representing 35%, out of which transportation by car represents 21% of the total (almost two thirds of the transportation sector)
- Buildings (which combine services and residential), representing 34%, with residential space heating representing 10% of the total final energy demand in the world;
- Industry, representing 31%, where the extraction (mining) and the transformation of basic metals (e.g. to produce steel) represent 10%.

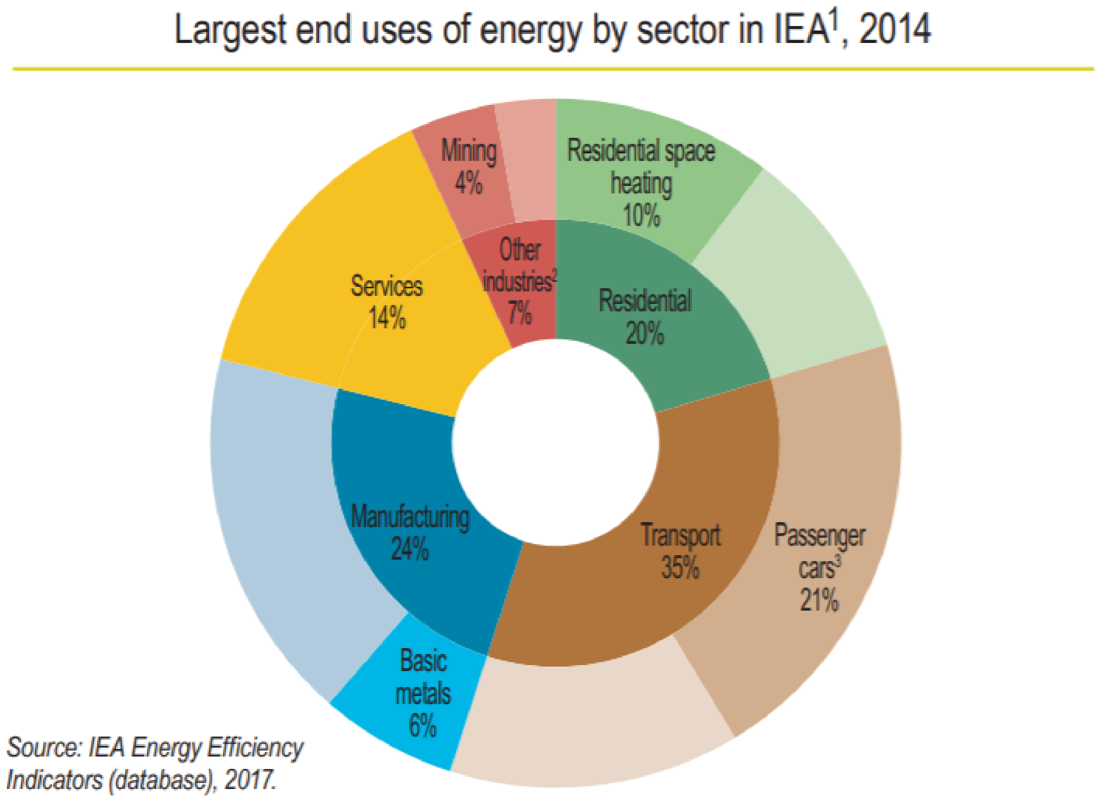


Figure 9 - World final energy demand by sectors and end uses (Source: IEA Energy Efficiency 2017)

3.4 Electricity generation

Figure 10 shows how electricity was generated around the world in 2017. It can be seen that Europe is the region with the more diverse generation mix, in the sense that Hydroelectric, Nuclear, Coal, Natural Gas, and Renewables contribute to the generation with more or less the same amount. In North America, the use of Natural Gas is higher than Coal and Renewables is increasing, but it still represents less than Nuclear. In South and Central, Hydroelectric is the dominant energy resource, while in Africa the most used fuel sources are Natural Gas, Coal, and Hydroelectric. In Middle East, Natural Gas consumption is also ahead of Oil, and in Asia Coal is by far the dominant resource, followed by Hydroelectric and Natural Gas. The generation by Oil represents only 1 TWh per year, mostly in the Middle East, Asia, and South and Central America. If we join Hydroelectric with the other Renewables, the generation of electricity using Renewable resources already surpasses Natural Gas generation.

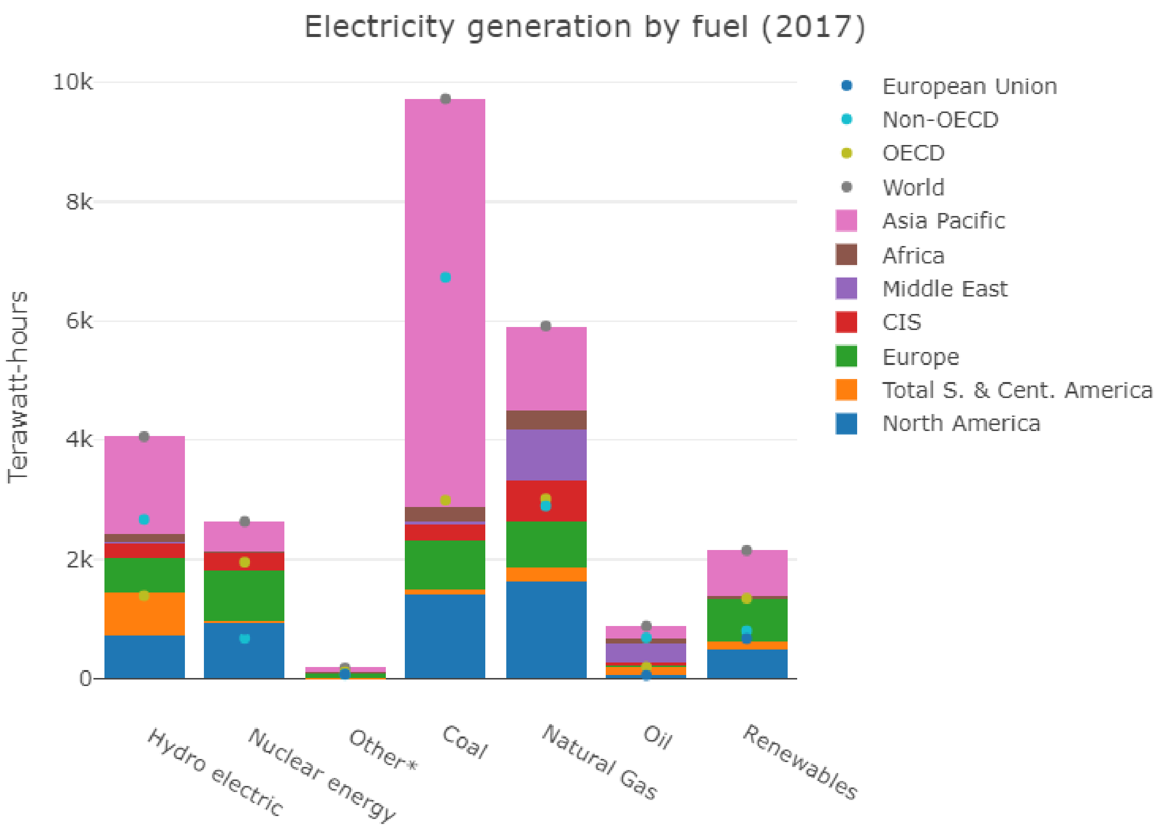


Figure 10 - Electricity generation by fuel in the world in 2017

4 ENERGY MARKETS AND PRICES

In this chapter, we introduce how the different energy supply chains work and the types of markets stemming from these supply chains, in order to understand their influence on the energy prices.

4.1 Energy Supply Chains

4.1.1 Oil and Gas

The oil and natural gas supply chains, and the players involved, are very similar (and are often the same). In general, we can divide the supply chain in three blocks, as shown in Figure 11:

- Upstream (Exploration & Production)
- Midstream (Transportation & Storage)
- Downstream (Refining, Petrochemical, & Marketing)

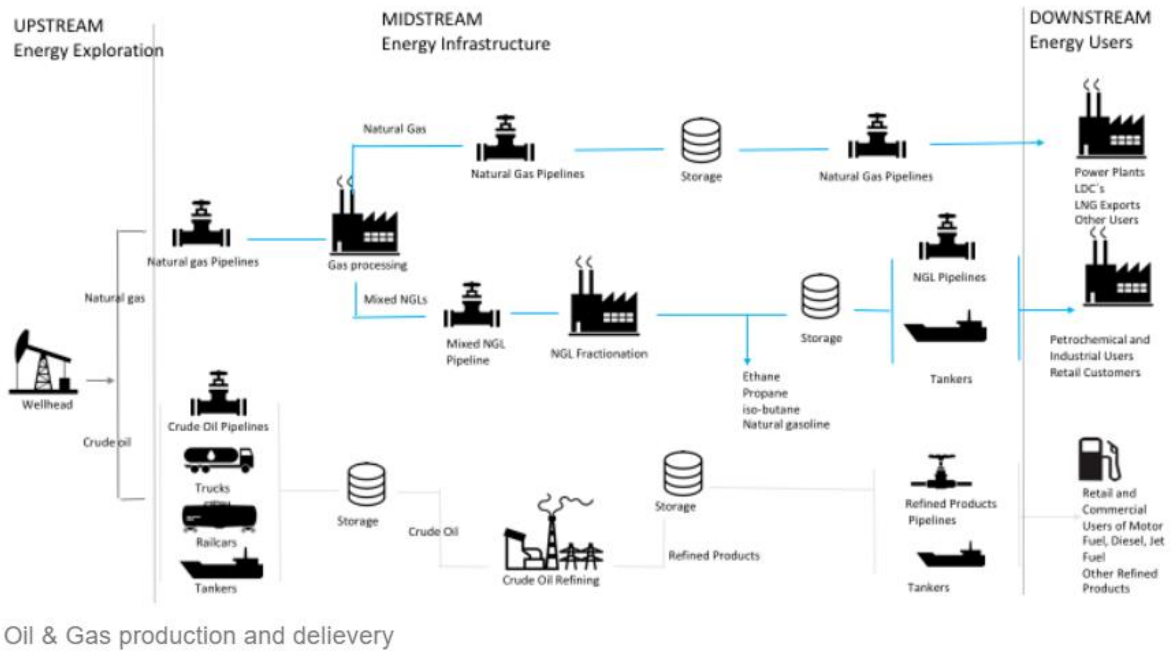


Figure 11 - Oil and gas supply chains

The main difference between both supply chains is that oil requires a transformation step (the refining of oil products), while gas can be used as it is extracted.

In the oil supply chain, the oil is transported in its raw state (crude oil) through different transportation means (pipelines, tankers, trucks and railcars, in many cases all of those) into the core infrastructure, which is the refinery. At the refinery, the crude oil is transformed into oil products (diesel, gasoline, liquefied petroleum gas), and is then transported and distributed by the retailers. It often happens that the refineries are not only located far away from the extraction sites, but also from the consumption sites (for example, some countries that extract oil do not have enough refining capacity, so they export crude oil and import oil products).

The natural gas extracted at the well is transported through ships and pipelines. Several compression stations are placed along the pipelines. In case the gas needs to be transported by ship, a transformation step must be included, because gas is transported in the liquid state. Liquefaction stations at the ship departure point and gasification stations at the arrival point are responsible for this transformation. Finally, the gas arrives at the final users, which can be, for example, power plants for electricity or heat production.

In both supply chains, it is easy to store both crude oil, oil products, or gas in different points of the supply chain, and so it is easy to match the demand and the supply.

Therefore, the costs associated with these fuels be divided as follows:

- The cost of the energy raw material (oil, gas, coal)
- The costs of conversion (oil refining) and transportation (logistic costs)
- The retail margins
- Taxes

4.1.2 Electricity

In the case of electricity, the suppliers operate the power plants. Then, the electricity is transported through transmission lines at a very high voltage (in order to decrease the losses) by the Transmission System Operator (TSO), and then through distribution lines (at high, medium or low voltage) to the final users (homes, offices and factories) by the Distribution System Operator (DSO). Between power plants, transmission, distribution, and final users, we have substations that are responsible for converting the voltage and connecting the different layers, acting therefore as infrastructures that provide safety and security to the operation of the grid. Finally, the electricity is sold to the customers by retailers (Figure 12).

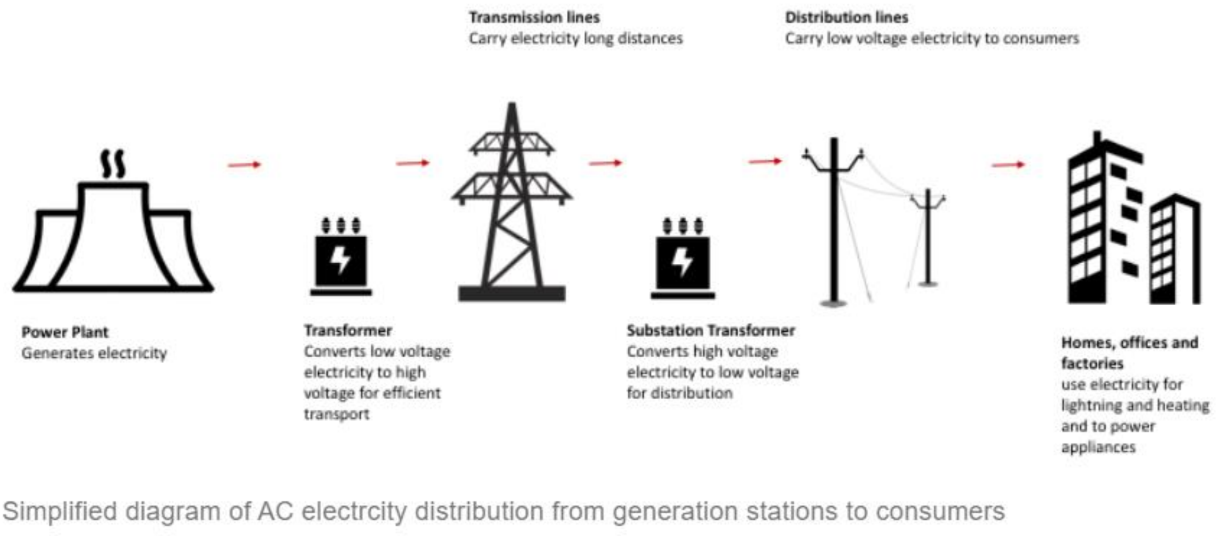


Figure 12 - Electricity supply chain (centralized)

There are two main differences between the electricity supply chain and the oil and gas supply chain:

- As it is much more difficult to store electricity efficiently (from the technical and economic point of view), the supply and the demand in electricity grids must be matched in real time
- The transportation and distribution of electricity must be made in such a way that the voltage variation and frequency variations are very small. Otherwise, the system will get unbalanced, and the supply and demand must be decoupled, originating supply disruptions

These characteristics explain why the supply chain in most countries/regions was managed by only one company, and why the systems were centralized.

Therefore, the costs associated with electricity can be divided as follows:

- The cost of electricity generation (including the raw materials such as oil, gas, and coal, and the power plant operation costs)
- The transportation and distribution costs (the use of the TSO and DSO grids, the regulation costs)
- The retail margins
- Taxes;

4.2 Types of energy markets

The market design is a representation of the principles that describe how the market operates. In energy, the two common market designs are (Figure 13):

- **Monopoly**: describes a market where only one company is responsible for the supply chain from the supply to the demand
- **Liberalized** or competitive market: describes a market where there are multiple companies at the different stages of the supply chain (extraction, generation, retail)

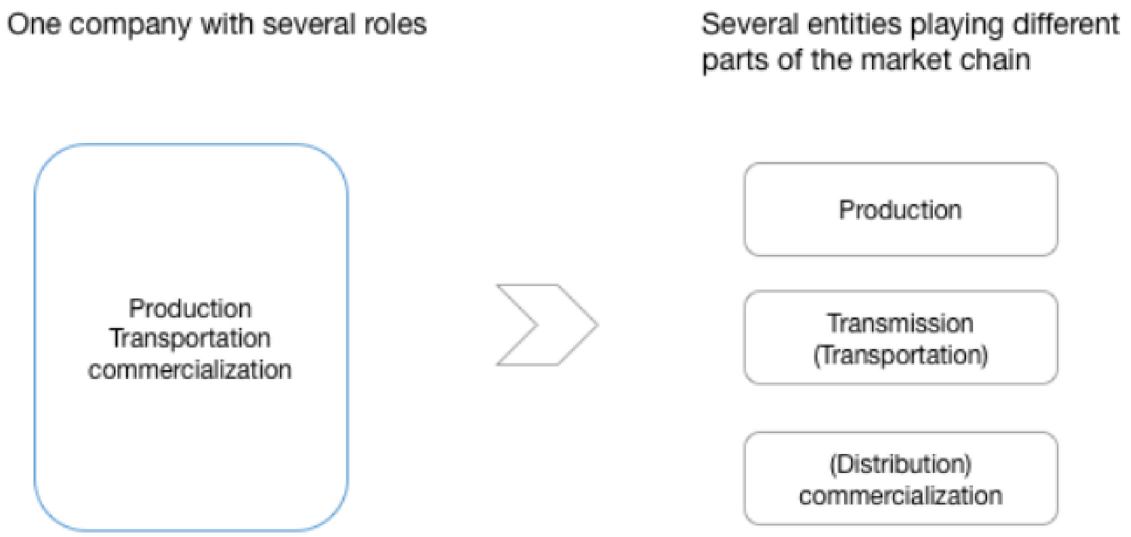


Figure 13 - Difference between monopoly and liberalized market designs

Some energy markets, like coal, have been liberalized for many years, as there are multiple companies in all steps of the supply chain. Other markets, like the oil and gas market, were an oligopoly (when few companies operate as a monopoly) when they were started, but today can be considered as liberalized markets.

The electricity market started out as a monopoly, but currently many countries are shifting to liberalized markets.

In Europe, until the XXI century, most *utilities*[1] operated under a monopoly, as they were in general state-owned companies that performed the generation, transmission, distribution, and retail. In order to get to a fully liberalised market, Europe has chosen an unbundling model. Generation and retail markets were fully liberalized. Transmission and Distribution markets, where the companies which operate in them are responsible for the core infrastructure of the system (the power lines and substations), operate under a regulation authority through concessions (companies compete to become the only responsible for the infrastructure during an extended number of years).

The split of generation, transportation (and grid operations & management) and commercialisation, is reshaping the energy sector. The consolidation and integration of the EU Energy Market presents a great opportunity for several stakeholders and a challenge to consolidated utility companies.

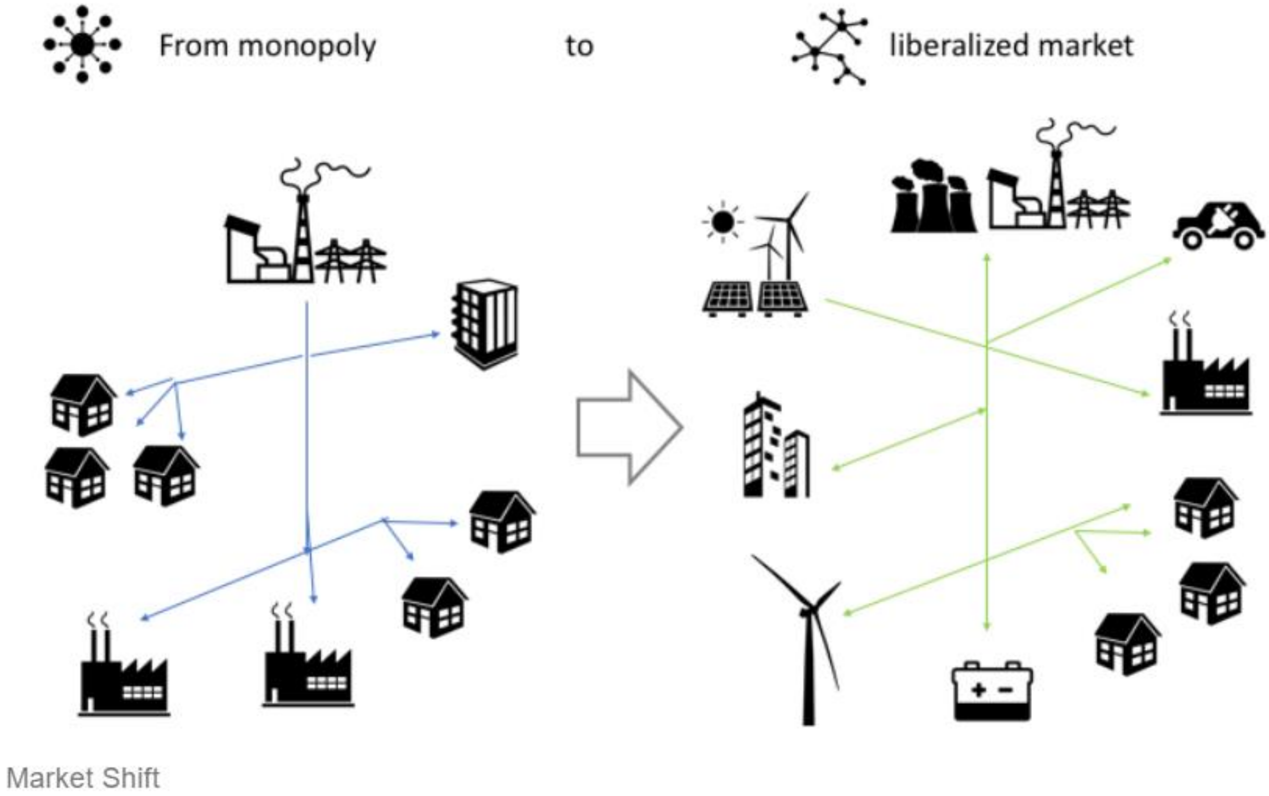


Figure 14 - Electricity market shift from monopoly to liberalized market

Currently, we are going through a transition of how energy markets operate, from a centralised monopoly model to a distributed and liberalised market, as shown in Figure 14. This market transition has been occurring in parallel with an energy systems transition, from centralised generation models to distributed generation models.

In centralised generation systems, energy is generated in large power plants that are typically located away from final users. Now, with the increasing use of different technologies (namely renewables,

[1] Utilities are companies that supply utilities (gas, water, electricity, etc.)

like wind and solar), it is possible to generate electricity closer to final users in smaller power plants. Ultimately, users can themselves generate electricity for self-consumption (or to inject in the grid).

The growth of distributed generation, namely RES (such as Wind farms or Rooftop PV), the new storage technologies, and the appearance of electrical vehicles (EV), to name a few reasons, have been contributing to make the grid management task increasingly more complex. The grid management had to change from a model where only one company was responsible for all activities, and where all the flows had one direction (from generation to demand), to a model where many companies can operate both at the generation and commercialisation, and where the customers themselves can generate energy. Therefore, grid management is becoming more complex due to the existence of multiple players, and because energy flows can have two directions. At the end, for the system to work, all partners have to cooperate to make sure that when they are connected, the voltage and frequency are the same, and that the supply is enough to supply the demand. This is even more difficult, as many renewable resources are characterised by their intermittency.

Both of these transitions, which cannot be decoupled since one contributed to the other, introduced many challenges, and are reshaping the energy sector, both technologically and economically.

4.3 Market players

The main players in energy markets are:

- The Governments, which are responsible for planning, and have the ultimate responsibility to oversee that all players develop their activity within the rules
- The suppliers, which are responsible for supplying the energy to the energy system (power plants, refineries, etc.)
- Retailers, which are responsible for selling the energy to the final clients
- Transmission System Operator (TSOs) and Distribution System Operator (DSOs), which are the companies responsible for managing the physical infrastructures (overhead electricity lines, pipelines, substations, etc.) – the transmission refers to the infrastructure on which the bulk energy between the power plants and cities, or between countries, is transported. Meanwhile, the distribution refers to the infrastructure on which energy is transported between the transmission infrastructure and the final users
- National Regulatory Authorities (NRAs): which are responsible for monitoring and supervising the activities of all agents. They are required since in all these supply chains different players share the same infrastructure

4.4 Energy Prices

To understand how the final energy price is determined, we can start by decomposing it into three components: energy, network, and taxes and levies (Figure 15).

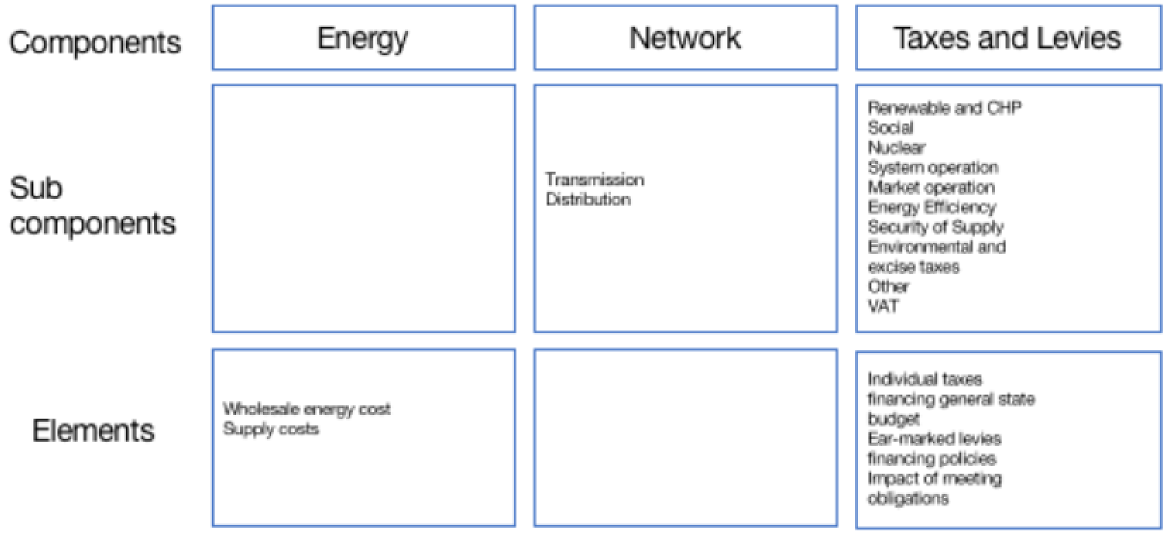


Figure 15 - Energy costs decomposition

The energy component includes the costs of extracting the energy, converting it, and commercialising it. In general, they are charged by kWh (or litre, or m^3) of consumed energy.

The network costs correspond to the costs of transporting the energy through the infrastructure (transmission and distribution), and generally include a part that depends on the energy consumption (kWh). However, it can also depend on the power drawn from the grid (kW), in the case of electricity or gas. It also includes a fixed cost corresponding to the availability of supply.

The Taxes and Levies costs correspond to the taxes associated with the consumption of any good (like VAT), but also to levies, which correspond to special payments to the government related to a very specific end. Examples of levies are levies associated with the system operation, such as those associated with specific energy resources (renewables, nuclear, CHP).

4.4.1 Oil and natural gas prices

For oil and natural gas prices, the prices vary mostly according to the price of the raw resource, and then the taxes and levies that the governments decide to charge.

Regarding the raw materials price, we can see in Figure 16 that the oil price (Brent) varied a lot throughout the represented period. These variations were due to geopolitical events (wars, embargos), and sometimes due to extreme weather events (like hurricanes in the gulf of Mexico), that disrupt the supply. A very interesting fact is that the average price has not evolved (the consumption of oil throughout the world has been stable over the last decades).

In terms of gas (Russian gas and NBP), we can see that since 2010 there has been a decoupling between crude oil and natural gas prices (which were historically highly correlated). This has been mostly caused by the exploration of shale gas in US, which has led to an increase in gas availability, but also because gas and oil are not being used anymore for the same uses, and therefore are no longer substitute products. Oil is mostly used for transportation, and gas for heating and electricity generation. Furthermore, gas prices have been slightly decreasing over the last years.

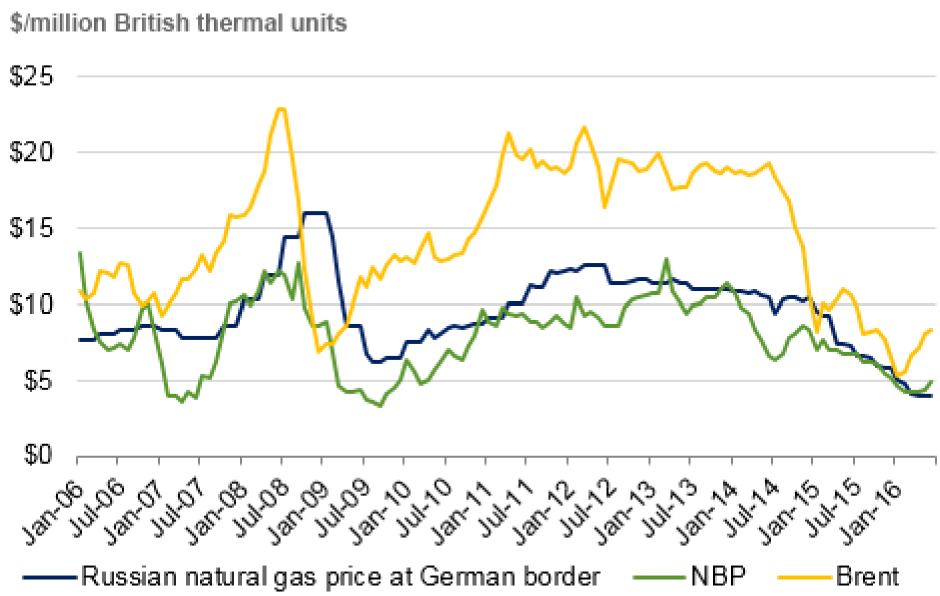


Figure 16 - Oil and gas prices evolution in Europe between 2006 and 2016 (Source: IEA)

Regarding the impact of taxes on prices, Figure 17 shows the diesel and gasoline prices in Europe, in 2016, for the different countries. It is possible to see that not only the price of the product is very similar between diesel and gasoline, but also between the different countries, with small variations (depending mostly on the refining capacity). However, the final price is very different, owing to the taxes and levies imposed by the governments (which impose final variations of 50% between the different countries). It is also interesting to see that in Europe diesel is less taxed than gasoline. The reason for this is that previously diesel was mostly used by freight transportation and collective transportation. Therefore, this was a way to penalize the use of individual transportation.

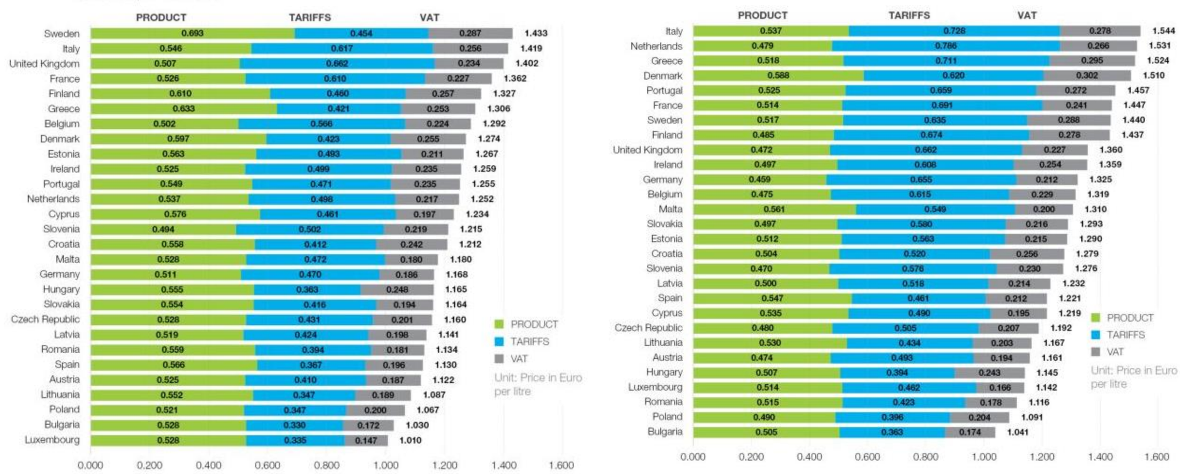


Figure 17 - Diesel (left) and gasoline (right) prices in different EU countries in March 2018.

4.4.2 Electricity prices

In Figure 18, the evolution of the cost of electricity and the weight of the different parts in the costs are represented. From 2008 to 2015, you can see a significant increase of the RES & CHP levies of electricity prices, whose purpose was to support the feed-in-tariff support mechanism of renewable technologies.

In a feed-in-tariff scheme, the renewable energy generation agents did not have to participate in the liberalised market since they got a fixed tariff for renewable generation, usually above market prices. This reduced the financial risk of the investors in this project, and it allowed the EU to be the leading region in the world in terms of renewable use in electricity. However, this achievement has been supported by the final users in the form of levies.

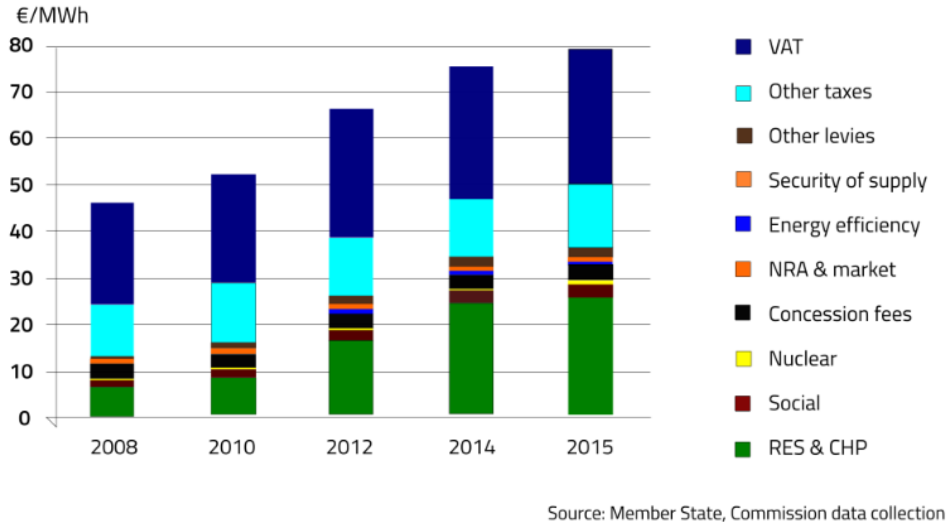


Figure 18 - Evolution of electricity costs in EU

Another example is Levies in Energy Efficiency, which were residual in 2008, but have been gaining importance in the overall taxes and levies of electricity prices.

Figure 19 shows the electricity cost for household consumers in the different European Countries in 2015. Here you can see that not only the base energy price is different (depending on how you generate the electricity), but also that the taxes and levies relative weight varies significantly, as well as the VAT.

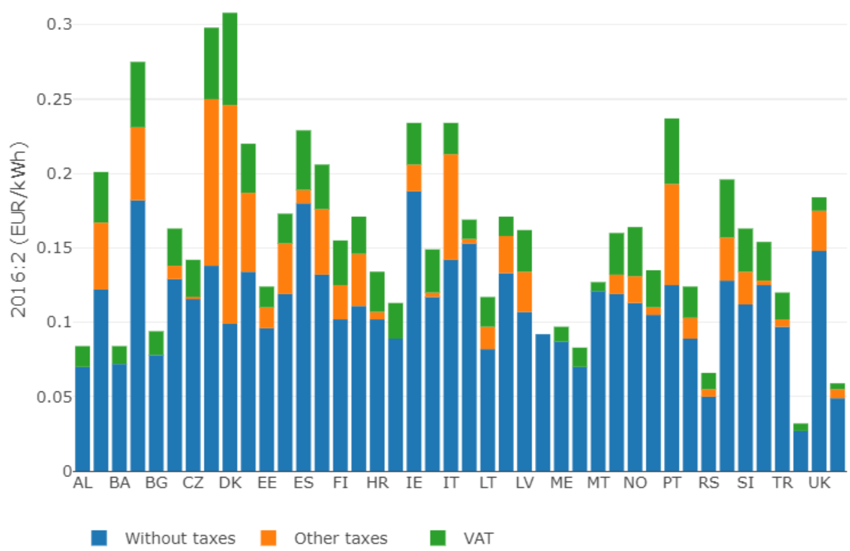


Figure 19 - Electricity prices for households in EU (2016)

Figure 20 shows the electricity price for industrial users. We can see that, in general, industrial users have access to cheaper electricity. This is because the quantities purchased are larger. Furthermore, the taxation levels are also very different from the residential sector.

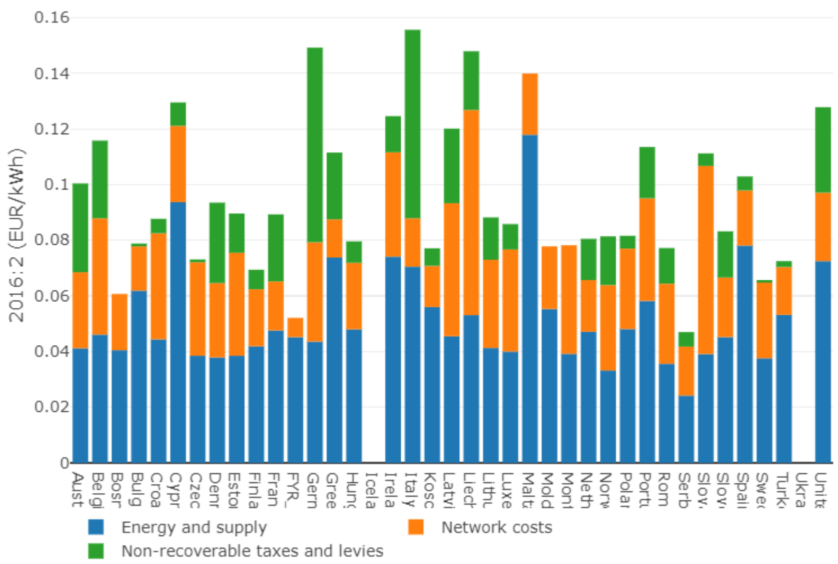


Figure 20 - Electricity prices for industrial consumers EU (2016)

These taxes and levies reflect each country resources, policies, and its targets. In general, in countries that want to push for renewables, they may either impose taxes on fossil fuels, subsidise RES, or a combination of both. A country may also charge fossil fuels to penalise their negative externalities (like CO_2 emissions).

Therefore, when analysing the components among the different countries, you will see the impact of such policies and choices on the energy prices.

4.5 Drivers for energy prices

As a conclusion, three main drivers influence energy prices:

- The primary energy resource costs
- The energy mix
- The context (weather, geopolitical conditions, economy)

4.5.1 Primary energy costs

The cost of the primary energy resources influences the cost of energy directly.

In general, the specific cost of fuel per unit of energy is lower for coal than for natural gas or oil. This is explained by the fact that coal is a resource that is more available in nature, and requires simpler technology to extract and to transport. Oil is becoming more expensive to extract, because the extraction is moving from onshore well to offshore deep wells.

For the same reason, renewable resources are in general the energy resources with the lowest price (except for biomass, whose collection may present a significant cost).

The cost of primary energy resources is also affected by the existence of this resource in the country or not. If it is not available, then it becomes necessary to import the fuel, with its associated costs (purchase, taxes, and transportation).

Regarding the conversion, the cost depends on the investment required to install a power plant or a refinery, the operation, and maintenance costs. Nonetheless, the final price is still largely dependent on the cost of the fuel.

In the case of electricity, natural gas power plants are more efficient than coal power plants, and require lower initial investments. However, the cost of electricity produced by natural gas power plants is, at the end, still more expensive than coal, because the price of natural gas per unit of energy is higher.

Finally, the commercialisation costs may be affected by different taxes and levies, also depending on the origin.

4.5.2 Energy system mix

A second factor that influences the final prices of energy is the energy mix. The energy mix is the group of different primary energy sources from which a final energy vector is produced. In the case of electricity, the energy mix represents the relative contribution of each primary energy resource (coal, gas, renewables, nuclear, and others).

If the contribution to the energy mix is mostly made by primary resources, whose cost is expensive, it will influence negatively the energy price. For example, countries where the electricity generation is based on coal generally have lower energy prices than countries that use more natural gas. Countries that have a significant share of renewables have in principle a higher cost, not directly because of the primary resource cost or the operation and maintenance costs, but mostly due to the taxes and levies collected to support the operation of the system.

4.5.3 Other factors

Other factors that may influence the energy prices significantly are the costs associated with the context, which include weather, geopolitical conditions, and the economy.

4.5.3.1 Weather

Weather may be the context factor that mostly affects the prices, in many ways. In general, cold winters will require the use of much more heating fuels, like coal or gas. As the demand will increase, so will the prices. Conversely, if the winter is mild, the consumption of fuels for heating will drop, and the prices will tend to decrease, as there will be a surplus of supply. However, weather also affects significantly renewable resources. For example, in countries that depend on hydropower plants, dry years will require the use of other technologies, like gas, and therefore the prices will increase. In wet years, the hydropower plants production will be significant, the use of other technologies will be smaller, and therefore the prices will go down.

4.5.3.2 Other factors

Geopolitical conditions also affect the prices of resources. For examples, wars usually affect negatively the prices of primary energy resources, as in general the extraction is affected.

Economic conditions also affect the prices. In general, when the economy is growing, the competition for energy resources is higher, and so the costs will increase. When we have an economic crisis and the industrial activities decrease, there is less demand for energy resources, and the prices tend to go down.

Therefore, the costs of energy depend on many different factors, and that is why, in general, an energy system, such as a country, or a building, is more robust to energy price variations if the energy mix is more diverse and flexible.

4.6 Dynamic pricing and Intervention in Price Setting Mechanisms

The prices of energy may not be fixed, in order to reflect the fact that the production costs vary throughout different periods. This is particularly true for electricity. This is known as dynamic pricing, and can be implemented using different strategies:

- Time-of-Use (ToU)
- Critical peak pricing
- Real Time pricing

4.6.1 Time-of-Use (ToU)

Time-of-Use (ToU) is a dynamic pricing application in which fixed time bands are set and the price for each time band reflects the average wholesale price in the time band. Although less common, a high granularity-low dynamics application is possible, where hourly consumption is priced at monthly average prices.

4.6.2 Critical peak pricing

Critical peak pricing is a dynamic pricing application in which a higher price is charged in limited periods when the consumption peak at the system level occurs, in an attempt to incentivize users to avoid consuming energy at peak time.

4.6.3 Real time pricing

Real-time pricing is a dynamic pricing application in which the price is posted and communicated to the consumer in real time, reflecting the cost of the market in real time.

5 REGULATIONS AND STANDARDS

In this chapter we introduce the concept of regulation and standards, and describe how policy and legal frameworks in the area of energy management have evolved until today, particularly in Europe.

5.1 Definitions

5.1.1 Regulation

Regulation (or regulatory framework) is the set of official documents (laws) developed by a governmental agency that defines a set of rules, usually compulsory, that need to be implemented.

Examples of regulation are European directives and the national laws that stem from those in each member state.

5.1.2 Standards

Standards are a set of guidelines developed by recognized agencies/organizations that define a set of best practices that should be followed (and therefore are not compulsory).

Examples of standards are the ISO50001, which sets the best practices to implement energy management systems in organizations.

5.2 European and National Legal Frameworks

The aims set out in the EU treaties are achieved by several types of legal act. While some are binding, others are not. Some apply to all EU countries, others to just a few.

The legal basis for the enactment of directives is Article 288 of the Treaty on the Functioning of the European Union (formerly Article 249 TEC), under section 1: “THE LEGAL ACTS OF THE UNION”

According to Article 288, “To exercise the Union’s competences, the institutions shall adopt regulations, directives, decisions, recommendations, and opinions”.

There are different types of EU legal acts:

- A **regulation** shall have general application. It shall be binding in its entirety and directly applicable in all Member States
- A **directive** shall be binding, as to the result to be achieved, upon each Member State to which it is addressed, but shall leave to the national authorities the choice of form and methods
- A **decision** shall be binding in its entirety. A decision which specifies those to whom it is addressed shall be binding only on them
- **Recommendations** and **opinions** shall have no binding force

We will look now in particular to the process of how directives are implemented in the different member states through national regulation, as described in Figure 21.

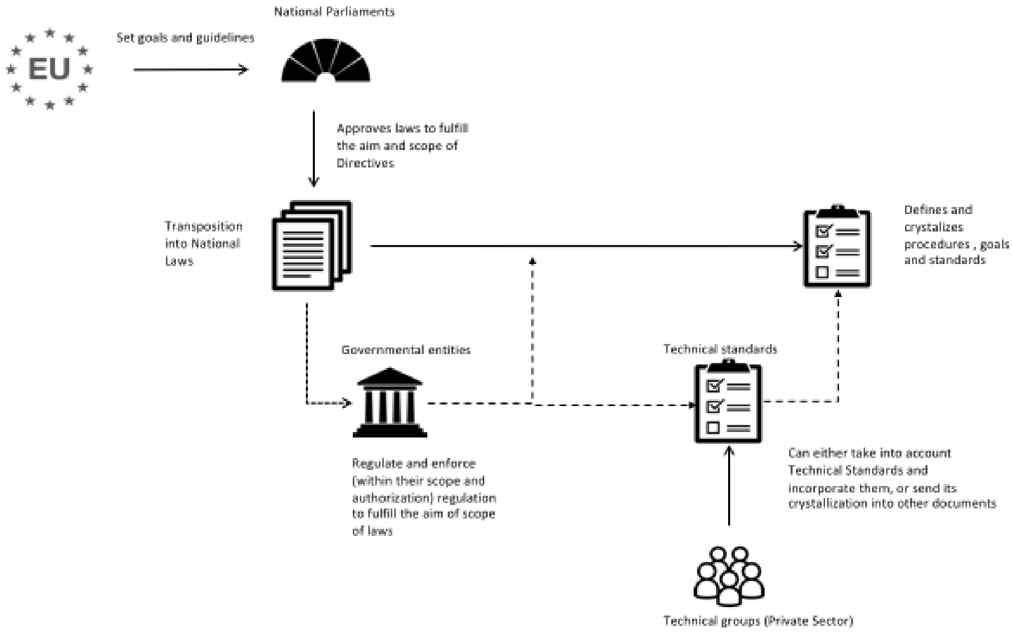


Figure 21 - Transition from EU directive to Member state regulation

Directives are approved, and Member States (MS) have a certain period to transpose these Directives into national Law. Usually there is some freedom for adaptation, since each country has its own realities and system. The objective is that, when the EU states a goal, MS produce the mechanics to fulfil that goal, internally, through their own legal tools.

Parliaments can either decide to incorporate all definitions and procedures into a single piece of legislation, or attribute competence and authorization to a certain governmental entity for fulfilling the details. These entities have also the mandate to execute and regulate the application of such regulations.

Technical standards can also be incorporated into legislation and acquire a similar strength, because they will be used by enforceable legal pieces of legislation or regulation.

A typical example would be:

1. EU sets a Directive to improve EE
2. The country’s Parliament transposes the Directive into national law and mandates a regulatory agency to execute the attributions within this law
3. The regulatory agency writes a regulation that uses as standards an international standard to define what EE means, and how it is measured

5.3 History of regulation

5.3.1 World regulation

During the 70s, many organizations started to point out some evidence and acknowledgement of the impacts from the use of fossil fuels in the energy sector and other especially pollutant industries. Consensus began to form in the 1980´s, and in 1988 the United Nations established the Intergovernmental Panel on Climate Change (IPCC) to analyse these impacts in detail.

The Kyoto protocol was the first agreement between nations to mandate country-by-country reductions in greenhouse-gas emissions. Kyoto emerged from the UN Framework Convention on Climate Change (UNFCCC), which was signed by nearly all nations in 1992. The framework pledged to stabilize greenhouse-gas concentrations “at a level that would prevent dangerous anthropogenic interference with the climate system”. The treaty was finalized in Kyoto, Japan, in 1997, and went into force in 2005.

As a replacement of the Kyoto Protocol, in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal, which became known as the Paris Agreement. This agreement sets out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C.

Although these agreements are binding, the point is that there is not yet a way to make sure the signing countries comply with the agreements, and it has happened that when the politicians responsible for a country at certain moment did not agree with these agreements, their countries have stopped to follow them. The most paradigmatic case is the fact that US under Donald Trump administration has signed off the Paris Agreement that had been signed by Barak Obama.

5.3.2 EU regulation

After the oil crisis in the 70s, EU started to develop a set of regulations in the energy sector to make it more safe, reliable, and with less environmental impacts. Figure 22 describes generically the main milestones. Actually, the EU started in 1952 as European Coal and Steel Community (ECSC) to integrate the steel and coal industries in 6 of the main economies in Europe (France, West Germany, Italy, Belgium, the Netherlands, and Luxembourg).

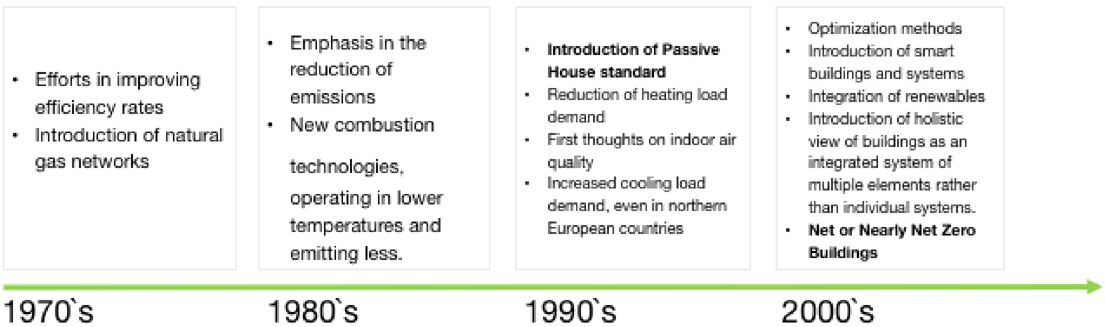


Figure 22 - Evolution of energy regulation in EU over the last 50 years

In the 70’s, more efforts were done to improve efficiency rates and promote the introduction of natural gas. In the 80’s, there was a significant effort to develop more efficient combustion techniques, as the emphasis was to reduce pollutants emissions. In the 90’s, there were significant progresses with standards and regulation arising related to energy demand in buildings, in particular the German standard of the “Passive Haus” (Passive House), regulations on indoor air quality, and reduction of heating and cooling loads. Finally, in the 2000’s, the effort focused more in the development of an holistic view between the different energy systems, the development of smart grids with the beginning of the digitalization of the energy systems, and the development of core directives in the area of renewable recourses and energy markets (2009), energy efficiency (2012), and energy in buildings (2002,2010, 2018).

This holistic view is very well expressed in the fact that the European Council concluded on 19 March 2015 that the EU is committed to building an Energy Union with a forward-looking climate policy based on the Commission's framework strategy, with five priority dimensions:

- Energy security, solidarity and trust
- A fully integrated European energy market
- Energy efficiency contributing to moderation of demand
- Decarbonising the economy
- Research, innovation, and competitiveness.

The strategy includes a minimum 10% electricity interconnection target for all member states by 2020, that the Commission hopes will put downward pressure onto the energy prices, reduce the need to build new power plants, reduce the risk of blackouts or other forms of electrical grid instability, improve the reliability of renewable energy supply, and encourage market integration.

We can split the different regulatory frameworks in three waves, which reflect concerns and events of that time, as overall incremental regulation, moving from basic needs, as supply and trade, to negative externalities, to full integration of economic and sustainable goals.

5.3.2.1 Directives that impacted the access to goods (trading, tariffs, etc.)

- Council Directive 90/531/EEC of 17 September 1990, on the procurement procedures of entities operating in the water, energy, transport, and telecommunications sectors
- Directive 94/22/EC of the European Parliament and of the Council of 30 May 1994, on the conditions for granting and using authorizations for the prospection, exploration, and production of hydrocarbons
- Directive 2013/30/EU of the European Parliament and of the Council of 12 June 2013, on safety of offshore oil and gas operations, and amending Directive 2004/35/EC
- Council Directive 2009/119/EC (The Oil Stocks Directive) of 14 September 2009, imposing an obligation on Member States to maintain minimum stocks of crude oil and/or petroleum products.
- Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003, concerning common rules for the internal market in electricity

5.3.2.2 Regulation on safety and health standards

- The Directive on industrial emissions 2010/75/EU (IED), that has entered into force on 6 January 2011, and had to be transposed into national legislation by Member States by 7 January 2013
- EU European Trading Scheme (ETS) Policy, launched in 2005, works on the "cap and trade" principle. The number of allowances is reduced over time so that total emissions fall.
- Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009, amending Directive 2003/87/EC, to improve and extend the greenhouse gas emission allowance trading scheme of the Community (Text with EEA relevance)
- Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009, on the geological storage of carbon dioxide, and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC, and Regulation (EC) No 1013/2006

5.3.2.3 Regulation focusing on promoting a decarbonized economy

- Energy Performance in Buildings Directive (2002/91/EC,2006/32/EC, 2010/31/EU)
- Directive 2009/28/EC, on the promotion of the use of energy from renewable sources (RES)
- Directive 2012/27/EC, on energy efficiency
- Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009, concerning common rules for the internal market in electricity, and repealing Directive 2003/54/EC
- Commission Regulation (EU) 2015/1222, establishing a guideline on capacity allocation and congestion management
- Commission Regulation (EU) 2016/1719, establishing a guideline on forward capacity allocation
- Commission Regulation (EU) 2016/1447, establishing a network code on requirements for grid connection of high-voltage direct current system and direct current-connected power park modules
- Commission Regulation (EU) 2016/631, establishing a network code on requirements for grid connection of generators
- Regulation on laying down guidelines relating to the inter-transmission system operator compensation mechanism and a common regulatory approach to transmission charging (838/2010/EU)

5.4 ISO 50001

The International Standard Organization (ISO) is an international organization which includes 160 national standards bodies that has published more than 20000 standards in multiple fields.

The “ISO 50001:2011 Energy management systems – Requirements with guidance for use” is a voluntary International Standard developed by ISO to give organizations the guidelines to implement energy management systems (EnMS). In particular, it establishes a framework to manage energy for industrial plants, commercial, institutional, and governmental facilities.

The ISO 50001 assists organizations in making better use of their existing energy consuming assets, by:

- Creating transparency and facilitating communication on the management of energy resources
- Promoting energy management best practices and reinforcing good energy management behaviours
- Assisting facilities in evaluating and prioritizing the implementation of new energy-efficient technologies
- Providing a framework for promoting energy efficiency throughout the supply chain
- Facilitating energy management improvements for greenhouse gas emission reduction projects
- Allow integration with other organizational management systems such as environmental, and health and safety

As many ISO standards, the ISO50001 relies on four core principles:

- **Plan**, which consists of conducting an energy review and establishing the baseline, energy performance indicators (EnPIs), objectives, targets, and action plans necessary to deliver results in accordance with opportunities to improve energy performance and the organization's energy policy

- **Do**, which consists of implementing the energy management action plans
- **Check**, which consists of monitoring and measuring processes and the key characteristics of its operations that determine energy performance against the energy policy and objectives, and report the results
- **Act**, which consists of taking actions to continually improve energy performance and the EnMS.

6 ENERGY CONTRACTS

In this chapter, we introduce the basic concepts related to energy contracts, and provide an overview of the different types of contracts that can be established.

6.1 Contract definition

In very simple terms, a contract is an agreement between two or more persons or entities with specific terms (Figure 23), in which there is a promise to do something in return for a valuable benefit.

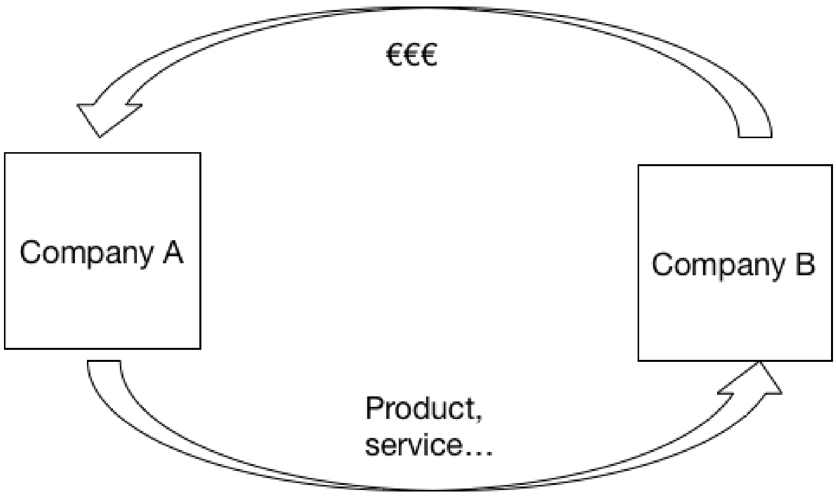


Figure 23 - Contract definition

In particular, the existence of a contract requires finding an offer and an acceptance of that offer, a promise to perform, a valuable consideration (which can be a promise or payment in some form), a time or event when performance must be made, the terms and conditions for performance (including fulfilling promises), and an intention to affect legal obligations. Overall, the following elements must be present:

- Performance
- Payment
- Price
- Terms and conditions

Depending on how the deal is structured, the performance and its payment can be designed differently. It may be based in a single performance (e.g. buy an appliance) and payment, or in several instalments as a recurrent service (e.g. contract of electricity or gas).

6.2 Types of energy contract

Figure 24 summarizes the types of energy contracts that can be found:

- Supply contracts
    - Traditional Energy Supply Contract
    - Power Purchase Agreement (PPA)
- Energy Services Agreement (ESA)
- Energy Performance Contract (EPC)

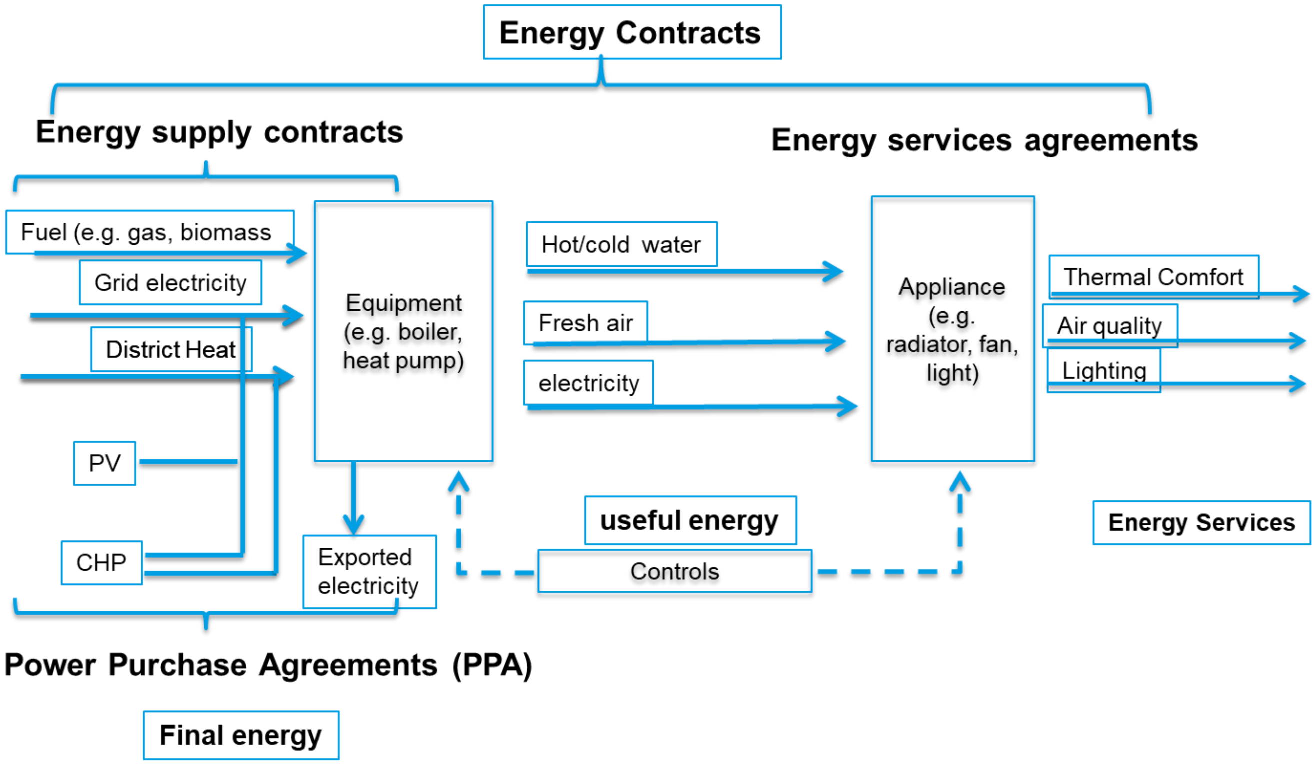


Figure 24 - Types of energy contracts

Usually the contract is established between a person/household (or a company) and an energy utility through an Energy supply contract.

However, over the last decade, this has been evolving and, as established in the Energy Efficiency Directive (EED), the contract may also be established with an energy service provider, which is a company which delivers energy services or other energy efficiency improvement measures in the final customer's facility or premises. These contracts may assume different names, depending on what is actually contracted.

These energy service providers, often called Energy Services Companies (ESCOs), may be Equipment manufacturers, suppliers of building automation and control systems, facility management and operation companies, consulting and engineering firms, independent specialists, energy Data Companies, governmental entities (namely under subsidized schemes), and even banks and other financial institutions (usually as intermediaries for EE related type of investments).

In the following sub-sections, we provide details of the different types of contracts.

6.2.1 Energy supply contracts

These contracts establish the conditions under which a company supplies energy to another company.

6.2.1.1 Traditional energy supply contracts

In this type of contracts, a company promises to pay to the energy supplier a fixed value per each energy unit that is consumed. This value may be fixed for one year, or, more recently, it may vary according to market conditions The periodic payments may be fixed, based on estimates of the consumption. When a real measurement is done, the difference may be settled. The conditions of the contract are reviewed every year.

6.2.1.2 Power purchase agreements (PPA)

A power purchase agreement (PPA) is a contract between two parties, one which generates electricity (the seller) and one which is looking to purchase electricity (the buyer), like in the traditional supply contracts.

The PPA differs from the traditional approach of simply buying energy to a certain retailer in the sense that the buyer imposes some conditions in the supply of energy, being the most common example the case of a company that wants to achieve a certain percentage of renewables (or decrease its carbon footprint) by guaranteeing that the energy is provided by a solar or wind farm.

In general, these contracts are much more complex, but allow both parties to take more advantage directly from energy markets than if they agree on a traditional supply contract, mostly because they share the risk.

There are different types of PPAs:

- **Wholesale PPA** - the generator sells all power supplied back to the grid. Most of the RES were implemented using this structure, where licenses were auctioned to generate a certain amount of energy in exchange for a certain predefined tariff per MWh
- **Onsite sale** – in this case, the generator generates and sells directly to the customer on is premises (e.g. shopping centres, commercial centres, manufacturing industry, airports, ports etc.). The savings are related to the decrease of network costs associated with transmission, distribution, dispatching, general costs of system, etc
- **Sleeved PPA –** the generator is located on the premises of the buyer, but all the electricity is sold to the grid and repurchased by the buyer
- **Virtual/Synthetic PPA –** the generator receives the market price under the PPA and it settles the difference with the buyer, between market price and fixed price

6.2.2 Energy Service Agreements

In an Energy Service Agreement or Contract, the buyer is not actually buying energy supply, but is instead buying an energy service. This service may be hot or cold water (for space heating and cooling), heat (for industrial uses) or it can even be services like thermal comfort or lighting conditions.

There are several types of energy services contracts, most specific to each country, including:

6.2.2.1 Chauffage or heat supply

This is one of the most common contract types in Europe. In general, it concerns the supply of heat for multiple purposes and the fee for the services is normally calculated based on the client’s existing energy bill minus a certain level of (monetary) savings, with a guarantee of the service provided. Alternatively, the customer may pay a rate, for instance, per square meter. The seller takes over the purchase of fuel and electricity.

6.2.2.2 Comfort

In the Nordic countries (Scandinavia), these contracts settle the provision of the level of comfort or level of service, which is outsourced to the ESCO firm. These contracts will go beyond the provision of energy for the level of comfort and take care of full maintenance, including a healthy indoor environment, aesthetics, etc.

6.2.2.3 Contract Energy Management (CEM)

A CEM is a more generic contract that includes not only the provision of energy services, but also other more general energy management features, including the maintenance of the equipment, reporting, training, etc.

6.2.3 Energy Performance Contracts (EPC)

An "'energy performance contracting' means a contractual arrangement between the beneficiary (client) and the provider of an energy efficiency improvement measure, verified and monitored during the whole term of the contract, where investments (work, supply or service) in that measure are paid for in accordance to a contractually agreed level of energy efficiency improvement, or other agreed energy performance criterion, such as financial savings.

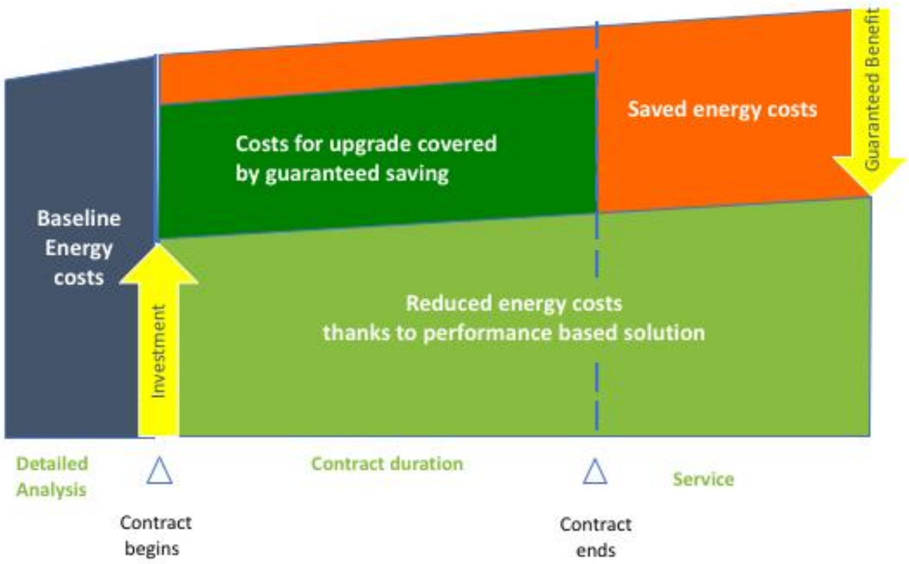


Figure 25 - Energy Performance Contract structure

In the EPC, there are usually three phases (Figure 25):

- The first phase, in which an energy audit is performed, and a set of energy management measures are defined. The ESCO is responsible to implement (procurement, installation) and manage (operate and maintenance) the systems. In this case, it is developed a baseline model – this model describes the energy demand of the installation under different scenarios (for example different weather conditions) before the measures are implemented. This model is used not only to estimate the savings and provide data for the financial analysis, but mostly to define the reference model from which the savings will be calculated. This model should be developed according to the guidelines of measurement and verification protocols like IPMVP

- The second phase, when the measures are implemented. The savings, calculated from the difference between the new consumptions and the baseline model (not the old consumption), are shared between the provider (ESCO) and the beneficiary (client) during a certain period (typically around 7 years). The share of the savings is the way the ESCO is compensated from the investment. Depending on the terms, these savings may be guaranteed (the client gets for sure a certain amount of savings) or shared (the client and ESCO share whatever is saved)
- After the contract, the client will still benefit from such measures but will save the whole saved energy costs

Energy performance contracts are therefore a very good instrument to overcome the two of the main hurdles to implement good energy management programs:

- Most organisations (building owners) don´t have the initial capital upfront to invest in Energy Efficiency measures and banks are not specialised in this type of investment (or able to make an offer)
- The technical complexity is very high, so even many dedicated energy managers do not have the knowledge to go throughout the whole process, from procurement to managing the projects

III. TOOLS

7 ENERGY PROJECT EVALUATION

Projects evaluation can be described as a methodology for assessing the economic and financial impact of a proposed investment.

The economic analysis - which is a systematic approach to determine the optimum use of capital, human resources - involves the comparison of two or more alternatives to achieve a specific objective under certain assumptions and constraints. In particular, it attempts to measure in monetary terms the costs and benefits of the project to the organisation or the community or economy.

The financial analysis aims to determine the financial resources to develop the project, like choosing the funding sources (equity or debt).

In this chapter, we focus mostly on the economic analysis.

7.1 Concepts

7.1.1 Opportunity cost

The analysis of a project implies a comparison between two alternatives, for example doing one project or the other, or simply doing a project and not doing the project. These options usually generate different return on investments.

When we refer to the economic analysis of a project, we are most of the times referring to the idea of the opportunity cost of a given decision.

The opportunity cost is the benefit or value that you give up by choosing the option with the lowest return on investment over the other option. We can express the opportunity cost in terms of a return on investment by using the following mathematical formula:

$$Opportunity\ Cost = Return\ on\ investment\ of\ the\ option\ with\ the\ highest\ return\ -\ Return\ of\ investment\ of\ the\ option\ with\ the\ lowest\ return$$

Unless the investment returns are fixed and guaranteed to be paid (like a treasury bond or the interest of a deposit in the bank), you'll have to base your calculation on the expected returns.

Imagine you want to buy efficient equipment. You have two potential options:

- Change lighting system to LED (20% of return on investment) or,
- Installing a PV system (10% of return on investment).

The opportunity cost is the difference between the benefits you would get from the one option (e.g. Change lighting system to LED) over another (installing a PV system). If you decide to install a new PV system, the opportunity cost is 10% (20% from changing the lighting system - 10% from installing the PV system = 10%).

7.1.2 Time of money

When dealing with financial investments, another basic underlying issue emerges from answering the question "Do you prefer to have 100€ today or collect 100€ in the future?"

The idea of time is quite fundamental in finance, because in general, the money available at the present time is worth more than the same amount in the future, due to its potential earning capacity. So the answer to this question is that it is better to have the 100€ today, because in the future, they will be worth less.

The time-value of money reflects that a certain amount of money today has a certain buying power (value) now, which is different from the buying power the same amount will have in the future, mostly due to inflation. However, it also represents the assumption that money can generate value if it is invested (for example, interests in a bank), so it is better to receive the money now than later.

With 100€ today, you can buy a set of products that will likely cost more in the future. This means that, in order to buy the same products in the future, more than 100€ will be needed. This is the future value, and is given by

$$Future\ Value = Present\ Value \times (1+i)^n \tag{3}$$

where i is the rate at which money evolves and n is the future period (usually years, but it can be months). The rate i is given as a percentage but expressed as a decimal in this formula.

With the same 100€ in the future, less products would be buyable today. This is the present value, and is given by

$$Present\ Value = \frac{Future\ Value}{(1+i)^n} \tag{4}$$

It is also important to note that, with the evolution of time, the future value has an exponential growth, since the same inflation rate is applied in every period to a larger amount. For example, with an inflation rate of 1%, the future value in one year is 101€ (it grew 1€) and in two years is 102.1 (it grew 1.1 € from year 1 to year 2). See Figure 26 for the representation of this in comparison with a linear growth.

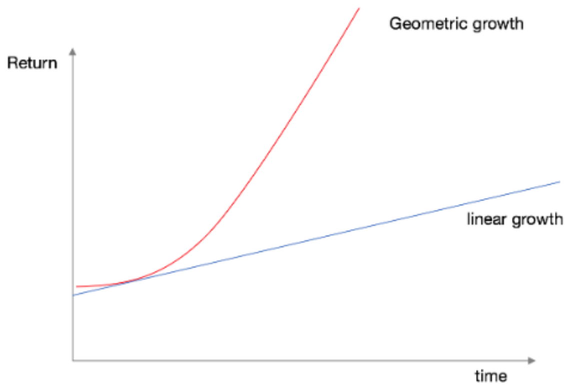


Figure 26 - Evolution of the same amount over time

7.1.3 Discount rate

The rate i at which the money appreciates or depreciates is called the discount rate.

This discount rate may represent different factors like inflation, the cost of capital or the risk of the investment. For risk-free investment, it is often considered as the interest rate given by the treasury bonds of central banks at 10 years. The Weighted average cost of capital (WACC) is the most commonly used discount rate.

7.1.4 Cash flows

When we are dealing with project evaluation, we can split the money flows between costs and revenues, by nature in the following categories:

- Investment (value used to buy an asset required for the project)
- Operating (value used to operate the asset required for the project)
- Financing (The financing costs are related to how much is it necessary to finance the activities of the project)

The cash flow is the net balance between positive and negative money flows in the project and is usually represented by the letter C. Positive cashflows represent gains for the company, while negative cashflows represent losses or expenses to the company.

7.1.4.1 Investment cashflows

The investment cashflow describes the use of money to develop the project. Usually, it is a cashflow spent at the beginning of the project and therefore its value does not need to be updated according to the time-of-money principle, and therefore it is usually represented separately from the other cashflows, through the letter I.

The investment is always a negative cashflow.

In other cases, the investment may be split in different periods, and, in that case, the future investments need to be updated according the discount rate.

The way you decide to finance the project, also called the capital structure, plays a central role in financial analysis. You can use an opportunity cost analysis to help you decide how to best capitalise a project.

The projects may be financed by:

- Equity, which means the company is using its own resources to finance the project. These resources may be the company savings in a bank, or may come from the sale of shares to investors, or even from loans from shareholders
- Debt, which means the company will use a loan from a bank. This loan may be a short, medium or long-term loan, usually with different interest rates
- A mix of both equity and debt

If you use equity, you will use resources that could be used to develop other activities in the company.

If you finance your capital through debt, you must pay it back even if you aren't making any money. And again, money allocated to servicing debt can't be spent on investing in the business or pursuing other investment opportunities.

7.1.4.2 Operation cashflows

The operation cashflows are the flows of money that result from the implementation of the project. They may refer to:

- Revenues or savings generated to the company. In this case, the cashflows are positive
- Operation costs, like acquisition of resources (human or material) or maintenance costs. In these cases, the cashflows are negative

7.1.4.3 Financial cashflows

These are the cashflows associated with the finance of the project. These may refer to

- Interest rates of loans, in case the investment was made through debt (and are negative)
- Taxes (negative cashflows) or tax abatements (positive cashflows)
- Depreciation of the assets (reduction of the actual value of an asset)
- Salvage (if you are able to sell assets used in the project to other company, and in that way make a positive cashflow at the end of the project)

7.2 Project evaluation indicators

There are three basic indicators that should be computed to evaluate a project and aid in the decision of developing it or not: net present value, internal rate of return and payback period.

7.2.1 Payback Period

The easiest metric to evaluate is the payback period, which provides an indication of how much time is required for the investment to “repay” the sum of the original investment.

It can be calculated using the following formula:

$$Payback\ Period = \frac{Investment}{Net\ cash\ flow} \tag{5}$$

The payback can be calculated in a simplified way – where the time value of money is not taken into account - or in a discounted way, where the net cash flows are calculated using the present cost (discounted payback period).

If the payback is smaller than the total period of analysis, the project should be done; if it is higher, than it means the cash flows will never be enough to repay the investment. However, this metric does not provide any indication on how much value will be generated by the project, so it should be only used to make a preliminary assessment of the project.

7.2.2 NPV

The first indicator to evaluate a project is the Net Present Value (NPV), which basically estimates the value that will be gained at present costs by developing the project. This estimate consists in adding all future net earnings (the cashflows) to the initial investment that is required to execute the project (which is a negative cashflow, usually in year 0).

The Net present value (NPV) of a project represents the potential change in an investor’s wealth caused by that project taking into consideration the time value of money.

To calculate the net present value, it is necessary to provide the following inputs:

- the investment
- the cashflows in the successive periods of the project;

- the discount rate.

The formula to calculate it is given by

$$NPV(i,N) = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} = -I_o + \sum_{t=1}^{N} \frac{C_t}{(1+i)^t} \tag{6}$$

where C_t are the cashflows in year t. Remember that the investment I is a negative cashflow in year t=0.

The NPV can have three different results: positive, null or negative (Table 2).

Table 2 - How to interpret the NPV value

NPV	RESULT	DECISION
NPV>0	The investment would add value	The project may be accepted
NPV<0	Theinvestment would subtract value	The project should be rejected
NPV=0	The investment would neither add or subtract value	We should be indifferent in the decision whether to accept or reject the project. This project adds no monetary value. Decision should be based on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

In case of mutually exclusive projects (i.e. competing projects), accept the project with higher NPV.

If the cash flows are even (i.e. the cash flows are equal for all different periods), the present value can be easily calculated by using the following formula:

$$NPV(i,n) = C \times \left(\frac{1-(1+i)^{-n}}{i}\right) - I_o \tag{7}$$

where C is the constant cashflow.

The advantages of using the NPV are:

- it accounts for the time value of money which makes it a sounder approach than other investment appraisal techniques which do not discount future cash flows such payback period
- Net present value is even better than some other discounted cash flows techniques such as IRR. In situations where IRR and NPV give conflicting decisions, NPV decision should be preferred

The disadvantages are:

- NPV is, after all, an estimation. It is sensitive to changes in estimates for future cash flows, salvage value and the cost of capital
- NPV does not take into account the size of the project

For example, say Project A requires an initial investment of 4 million € to generate NPV of 1 million € while a competing Project B requires 2 million € investment to generate an NPV of 0.8 million €. If we base our decision on NPV alone, we will prefer Project A because it has higher NPV (1 million €), but Project B has generated more shareholders' wealth per dollar of initial investment (0.8€ million/2€ million vs 1€ million/4€ million).

To capture this effect, another metric that needs to be applied is the internal rate of return.

7.2.3 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) corresponds to finding out what is the rate of return on the project that makes the NPV equal to 0, as described in the following formula

$$NPV(IRR, N) = \sum_{t=0}^{N} \frac{C_t}{(1 + IRR)^t} = 0 \qquad (8)$$

This metric is used to validate if the project will generate enough return to compensate for an oportunity cost equal to the IRR.

In practice, imagine that, in average, the activity of the company generates 5% of earnings every year. So, any project that you develop should generate at least this 5%. So if the IRR of your project is higher than 5%, than you should develop the project; otherwise you should use the money to develop the other activities.

7.3 Evaluation of energy management projects

An energy management project should be evaluated as any other type of project, but it has features.

7.3.1 Investment

As previously discussed, finding capital to invest in this type of projects is not easy, so it is difficult to invest through debt, but in many cases, the investment costs are very high, so it is not possible to do it through equity. Therefore, in order to solve this, companies often use Energy Performance Contracts (see section 6.2.3), which means that the investment may be zero, but the initial savings (or cashflows) will be small (as they will be shared with the ESCO).

7.3.2 The "savings" cashflow

When we implement an energy management measures, we do not receive money for it (except in few cases, like selling electricity to the grid), but we spend less money on energy. Therefore, the cash flows have a special nature as they, in general, they do not represent a real money inflow to the company, but rather a saving, i.e. a smaller expense on the company's operational costs.

Notice also that from the accounting perspective, there is no actual flow of cash entering the company. What happens is that the company spends less, which may impact in the way the detailed financial analysis of the project is done.

7.3.3 The metric Levelized Cost Of Energy (LCOE)

In energy management projects it is also common to use the Levelized Cost Of Energy (LCOE), which is a metric that was defined to compare the cost of energy when supplied by different technologies, with different investment and operational costs and lifetime. It is measured in €/kWh and provides an average cost of the energy generated after implementing the project.

This can be used to compare with the current energy costs of the company and, if smaller, it means the company should invest in the project.

The LCOE measures all the costs incurred during the lifetime of the project divided by energy generation (if we are analysing generation technologies) or energy consumption (if we are analysing end use technologies):

$$LCOE = \frac{sum\ of\ costs\ over\ the\ lifetime}{sum\ of\ energy \frac{produced}{consumed} over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+i)^n}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^n}} \quad (9)$$

where I_t is the Investment expenditure in year t (including financing), M_t is the operation and maintenance expenditures in year t and F_t is the fuel expenditures in year t. E_t is the energy generated or consumed in year t, i is the discount rate and n is the lifetime of the system.

7.4 Example of application

Now, look at this example of a project of installing a PV power plant in our facility, as represented in Figure 27. Here, the green boxes represent positive cashflows (from selling electricity to the grid) and the red boxes represent negative cashflows (from investment, operational costs and financial costs).

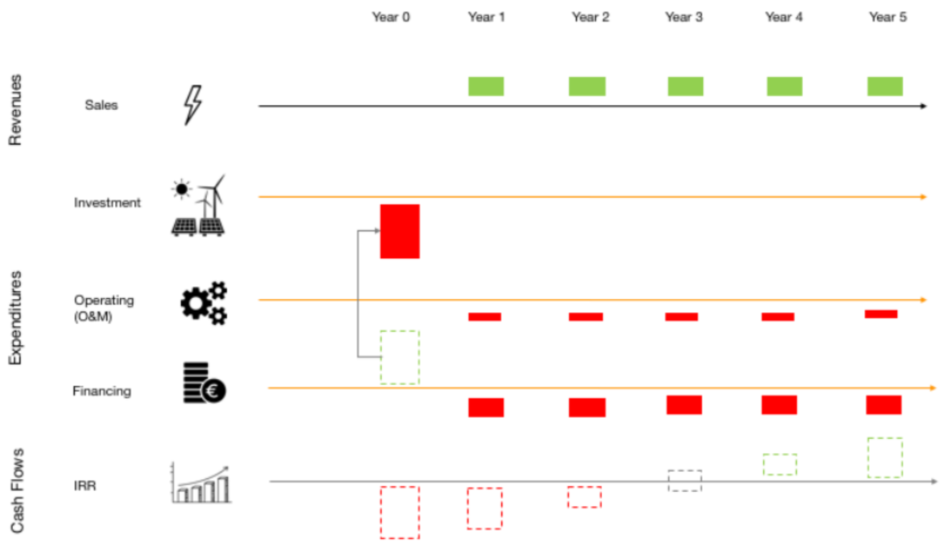


Figure 27 - Representation fo the project evaluation of a energy management project

The investment in the power plant has an initial investment that will be done in year 0 (the present). We will be able to sell some electricity back to the grid, and for that, we will have some positive cash flow from sales, but there will be some operation and maintenance costs. We also need to ask for a loan to develop the project so that we will have some financing expenses throughout the years.

In the end, the balance between the investment, and the sales from power plant minus the expenses in operating and financing will generate enough cash flows not only to payback the investment in 3 years, but also to generate additional earnings. Now, of course, this depends on the considered interest rate.

One important aspect of project evaluation is to look to the evolution of cash flows and not only to the result (NPV, IRR or Payback Period). The reason is that the NPV, IRR and Payback Period are aggregated indicators, and even if they are all positive, they may be hiding some aspects that may compromise the project.

It is important to observe if in one of the periods there is the risk that the generated cashflows are not enough to cover the negative cashflows. This would represent a situation (even if it occurs in only one year) where, in practice, the company would not be able to cover the expenses, and therefore it would be necessary to ask for an additional loan, or use other financial resources from the company.

8 ENERGY AUDIT

8.1 Objective

An energy audit is a process to perform the detailed analysis of the energy use in a certain equipment, activity, installation, building, or campus.

The objective is to characterize in detail where, when and how the energy is used, in order to identify and develop solutions to improve the energy management by increasing the efficiency in the demand and/or supply. These measures can span from installing or replacing an equipment, to changing how a process in done (for example, the order or the period of the day when it is done), or even by promoting user behaviour changes.

8.2 Activities

An energy audit involves, to a less or greater detail, all the following activities

- Quantify the uses and the costs of all energy vectors, through the analysis of energy bills from previous years
- Identify and characterize the main energy systems in the facility, by characterizing the main end-uses, and evaluating the main systems technologies (lighting, HVAC, HW)
- Analyse the envelope features regarding the thermal performance
- Verify the status of the energy generation and distribution equipment's, like boilers, chillers, co-generation, etc.
- Monitoring and control of energy uses
- Develop a baseline model to estimate and validate potential savings
- Identify main energy efficiency measures
- Develop an implementation plan, called the Energy Management Plan or the Action Plan, which is a strategy to increase the energy efficiency of the facility. This plan describes the solutions, efficiency objectives to be achieved, and the implementation plan

8.3 Energy audit protocol

Energy audits usually follow a protocol that consists of six main steps:

- Preparing and planning
- Facility inspection
- Field work
- Data analysis
- Energy audit reporting
- Energy action plan

8.3.1 Preparation and planning

The main objective of this phase is to collect data regarding the energy use of the system that is being audited. This may include collecting energy bills (3 or more years if available), collect data regarding building envelope from building description (blueprints, bill of materials, etc.), inventory and characteristics of the main equipments. It is also important to collect additional info, like the organization functional chart, weather data, electric, lighting and mechanical systems, energy policy documents describing the vision and objectives of the company (if there are no such documents, the

Energy Plan should develop them), and, most importantly, the contacts of the maintenance and energy managers and teams.

The main objective of this phase is to get acquainted with the installation, perform a preliminary data analysis, and find any awkward result, which can be used to identify specific systems and operations that need to be analysed in detail.

This phase should include a preliminary visit, together with the facility manager, to see how the facility operates. This visit should be used to collect missing data (if required), observe the building envelope and the systems and eventually to identify energy management measures that could create immediate savings.

8.3.2 Facility inspection

The objective of this phase is to perform a detailed analysis of the installation by collecting additional data that is missing from the first analysis, including the development of an energy consumption baseline (which should consider normalized climate data), the development of an energy balance of the system, an identification of the energy services, the drawing of reference energy systems schemes and a characterization of the equipment's performance.

With the collected data and the characterization of the facility, this phase is used to prepare the field work (next phase), in particular by identifying the list of equipment that will be measured, the list of equipment that needs to be used for measurement, the measuring procedure (one point measure, long data collection), and eventually prepare some interviews to complete information.

8.3.3 Field work

The field work phase is used to complete the collection of data process. It usually involves the following activities:

- Measure energy consumption of main sectors/equipment, like hot water, heating and ventilation
- Verify electric installations and other main systems, in particular to assess the lack of maintenance
- Continuous monitoring of main consumption points of energy to obtain load diagrams. This can involve one-point measures, one-day or one-week campaigns

Complementary measurements to collect more information can be done, including

- Measuring oom temperatures and illuminance
- Characterization of the schedule of the main equipments (through interviews, or direct observations)
- Characterization of the envelope in detail, and how users interact with it (again, through interviews or observations)
- Characterization of utilization patterns

8.3.4 Data analysis

The data analysis phase is the most important, since it is when the disaggregation of energy consumption by energy services is done, the detailed energy balance is completed, the detailed load diagrams (daily, weekly and if possible annual evolution) are developed, and from these the energy indicators and specific consumptions are evaluated.

The deviations from specific consumptions and indicators should provide hints regarding energy efficiency measures that need to be implemented. In particular, in this phase it is necessary to evaluate the efficiency of the equipment and installations and estimate savings from equipment replacement, process change or behaviour change or installation of generation equipment. It is also in this phase that the evaluation of the technical feasibility of implementing these measures, as well as the economic evaluation, is done.

To do the technical and economic evaluation, it is necessary to develop a simulation model that estimates the energy consumption considering the utilization, the equipment, and the envelope. The model should be adjusted and calibrated to the field measurements, and it will be used to test the different energy efficiency measures, along with their energy and economic impact.

8.3.5 Energy audit reporting

The energy audit reporting is usually a document that summarizes all the collected data (for future use) and the developed models that describe the installation.

8.3.6 Energy action plan

The Energy Action Plan is a document that suggests the energy management measures that could be implemented, by indicating the technical details of its implementation, the economic impact and the impact in the energy policy of the company (if there is none, this action plan can be used to suggest it).

The plan should also include an implementation plan, including a financial analysis on how to implement the measures, comparing different options (governmental subsidies, potential ESCO partners, evaluate the capacity to manage this project internally, etc.)

9 MEASUREMENT AND VERIFICATION

"Measurement and Verification" (M&V) is a process to quantify the savings associated with the implementation of energy efficiency measures.

This process measures energy and not the cost of energy, and therefore it is fundamental to perform the accurate evaluation of the economic savings associated with the implementation of energy management measures.

There are widely used standards that define the best practices to implement M&V procedures:

- International Performance Measurement and Verification Protocol (IPMVP)
- ASHRAE Guideline 14: Measurement of Energy and Demand Savings

AS IPMVP is the one that is most recognized by the industry, we will focus on this standard.

9.1 IPMPV scope

The IPMVP is a standard developed and maintained by the Energy Valuation Organization, since 1997. This protocol was originally developed to aid in the investment in energy management through the implementation of energy efficiency, demand management and renewable energy projects around the world.

The IPMVP promotes efficiency investments by:

- Defining common terms and methods to evaluate performance of efficiency projects for buyers, sellers and financiers. Some of these terms and methods may be used in project agreements, though IPMVP does not offer contractual language
- Describing methods, with different levels of cost and accuracy, for determining savings either for the whole facility or for individual energy measures
- Specifying the contents of Measurement and Verification Plan (M&V Plan), in order to produce verifiable savings reports

M&V plans should be developed by qualified professionals.

9.2 IPMVP documents

IPMVP is published in four core documents:

- **IPMVP Core Concepts**: defines the commonly used terminology and guiding principles for applying M&V. It also describes the project framework in which M&V activities take place and the contents and requirements of adherent M&V Plans and saving reports
- **IPMVP Volume I**: defines M&V, presents the fundamental principles of M&V, describes a framework for a detailed M&V Plan and provides details of an M&V Plan and savings report. It also contains a summary of common M&V design issues and lists other M&V resources. Twelve example projects are described in Appendix A and basic uncertainty analysis methods are summarized in Appendix B. Region-specific materials are in Appendix C. Specific guidance for different types of users is in Appendix D
- **IPMVP Volume II:** provides a comprehensive approach to evaluating building indoor-environmental-quality issues that are related to energy efficiency design, implementation and maintenance. Volume II suggests measurements of indoor conditions to identify changes from conditions of the baseline period

- **IPMVP Volume III**: provides greater detail on M&V methods associated with new building construction, and with renewable energy systems added to existing facilities

9.3 IPMPV principle

After implementing energy management measures, the energy savings cannot be directly measured, because savings represent the absence of energy consumption.

Instead, the IPMVP suggests that savings are determined by comparing measured consumption or demand before and after implementation of a program, making suitable adjustments for changes in conditions. The comparison of before and after energy consumption or demand should be made on a consistent basis, using the following general M&V equation:

$$\text{Savings} = (\text{Baseline Period Energy} - \text{Reporting Period Energy}) \pm \text{Adjustments} \qquad (10)$$

As previously explained in section 6.2.3, it requires the development of a model that represents the consumption before implementing the energy management measures, which will be used to estimate how the facility would consume if the measures had not been implemented. It is with this predicted value that we will compare the current consumption, and not with the energy consumption before the measures implementation.

The fundamental concept introduced by the IPMVP is the adjustments concept, which means that the model has to take into consideration the factors that influence the demand.

Figure 28 clearly explains the importance of the M&V protocol. After implemented the energy management measure (called EMC for energy measure conservation in IPMVP), the demand of the facility decreased initially but then increased. What happened was that the facility increased the production. Even so, had the measures not been implemented, the total consumption would have been much higher.

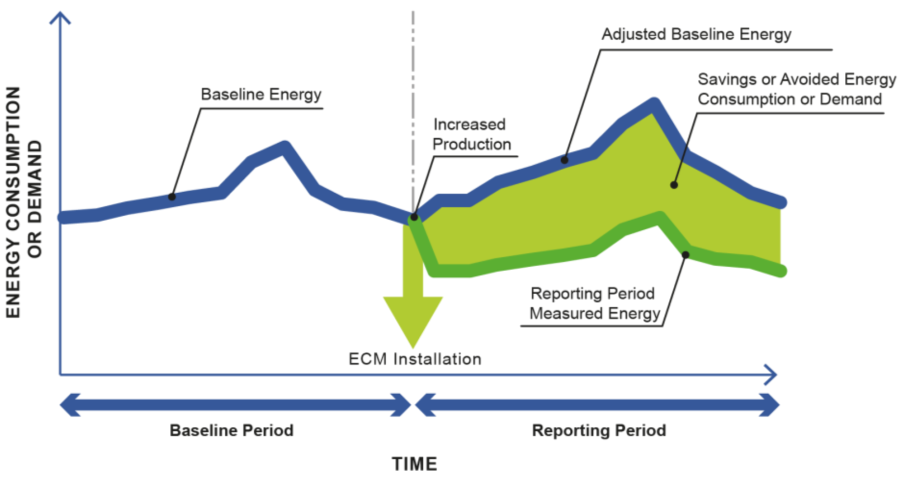


Figure 28 - IPMVP principle (Source: evo-world.org)

10 LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a multi-step procedure for compiling and examining the inputs and outputs of materials and energy, and the associated potential environmental aspects, directly resulting from the functioning of products, processes or services through their life cycle. Furthermore, the results of the inventory and impact phases in relation to the objectives of the study will be interpreted.

The life cycle is constituted by consecutive and interlinked stages of a product or service system, from the extraction of raw materials, the processing, manufacturing, and fabrication of the product, the transportation or distribution of the product, the usage by the consumer, and the disposal or recovery of the product after its useful life (Figure 29). The process is naturally iterative, as the quality and completeness of information, along with its probability, are constantly being tested.

Figure 29 - Example of a schematic representation of a Life Cycle Assessment

Electric Vehicles are a good example of the insights provided by this methodology. It is true that the use of these vehicles has very low environmental impacts, like green-house-gas emissions. However, their manufacturing process has at least as much impact as the conventional vehicles, and their disposal has more impacts, since the recycling of batteries is a complex process. Therefore, one of the policy recommendations that may arise from the application of LCA to electric vehicles is the need to define processes to recycle batteries.

The advantages of LCA are:

- It provides a holistic view, enabling the assessment of global and regional environmental impacts
- It adds objectivity to impact assessment
- It provides information for improvements, communication, etc.

As any methodology, it has its limitations, since:

- It is based on simplified models of a complex reality
- It depends on the definition of the scope
- Its implementation depends significantly on the data availability
- It could be time consuming, depending on the scope and objectives

LCA involves analyses of production systems and provides evaluations of all upstream and downstream energy inputs and various environmental emissions. There are four phases in the LCA study (a fifth one can also be considered) (Figure 30):

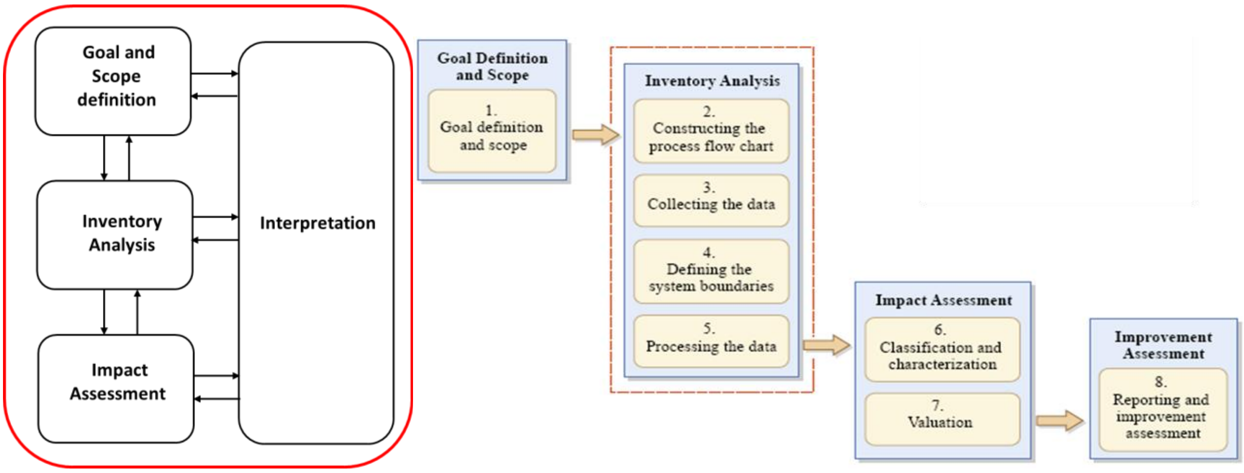


Figure 30 - Life cycle assessment framework.

1. **Goal and Scope Definition** – in which the product(s) or service(s) to be assessed are defined, the functional unit is chosen, and the required level of detail is defined
2. **Inventory Analysis** (also known as LCI - **life cycle inventory**) – in which extractions and emissions, the energy and raw materials used, emissions to the atmosphere, water and land, are quantified for each process, then combined in the process flow chart and related to the functional basis
3. **Impact Assessment** (also known as LCIA **- life cycle impact assessment**) – in which the effects of the resource use and emissions generated are grouped and quantified into a limited number of impact categories which may then be weighted for importance
4. **Interpretation** - in which the results are reported in the most informative way possible and the need and opportunities to reduce the impact of the product(s) or service(s) on the environment are systematically evaluated
5. **Improvement** – in which the system is modified in some way to reduce or ameliorate the observed environmental impact. As said previously, this phase is optional.

Data used in LCA should be consistent, quality assured, and reflect actual industrial process chains. Methodologies should reflect a best consensus based on current practice.

LCA is used in decision making as a tool to improve product design, for example when choosing materials, selecting technologies, specifying design criteria, and when considering recycling. LCA allows for the benchmarking of product system options, and can therefore be used in decision making regarding purchases, technology investments, innovation systems, etc.

The main benefit of LCA is that it provides a single tool that is able to provide insights into upstream and downstream trade-offs associated with environmental pressures, human health, and the consumption of resources. These macro-scale insights complement other social, economic, and environmental assessments. LCA should not be used to compare environmental impacts of totally different products and does not replace local dependency assessments (e.g. Environmental Impact Assessment).

10.1 Goal and scope definition

For each phase, it is outlined the steps to be considered. In the 1st phase, the reasons for the study, the intended audience, the functional unit, etc., are defined. The fundamental concept always associated is the Product /Service: Functional Unit.

10.1.1 Goal Definition

The points to indicate for defining the goal are:

The goal definition includes:

- The purpose of the analysis
- The intended use of the results
    - Product development and improvement
    - Strategic planning
    - Public decision making
    - Marketing
    - Other
- The study stakeholders
    - Researcher(s)
    - Commissioner(s)
    - Target audience(s)
    - Steering/supervising committee
    - Expert reviewer(s)

10.1.2 Scope Definition

Scope definition includes:

- Product system to be studied
- Functions of the product system or, in the case of comparative studies, the systems
- Functional unit
- System boundary (process included)
- Allocation procedures
- Methodology of impact assessment, impact categories selected and subsequent interpretation to be used
- Data requirements (temporal, spatial and technological coverage)
- Assumptions
- Limitations
- Initial data quality requirements
- Type of critical review, if any
- Type and format of the report required for the study

The scope should be sufficiently well defined to ensure that the depth and detail of the study are compatible and enough to address the stated goal.

Nevertheless, the initial goal and scope definition (LCA step 1) is to be revised interactively, according to intermediate and final results, as well with choices made during the LCA (e.g. allocation made in specific process).

10.1.3 Scope and Objectives

The system boundaries describe the limits of the analysis. The analysis can be made at different levels:

- “Cradle to gate” – describes the flows from the extraction in the mines to the gate of the warehouse
- “Gate to gate” - describes the flows of the manufacturing facility, from the entrance of the raw materials to the final product
- “Gate to grave” – describes the flows of the distribution, use and disposal of the products
- “Cradle to grave” - describes the flows of the total cycle of the product

10.1.4 Functional unit

The functional unit describes the primary function(s) fulfilled by a (product) system and indicates how much of this function is to be considered in the intended LCA study.

It will be used as a basis for selecting one or more alternative (product) systems that can provide this function (these functions). The functional unit enables different systems to be treated as functionally equivalent, and allows reference flows to be determined for each of them.

Having defined the functional unit, the amount of product which is necessary to fulfill the function shall be quantified.

For example, let us consider the example of a light bulb (Figure 31). There are many different types of lightbulbs, and within each type there are several manufacturers, models, etc. To compare light bulbs, we need to quantify the service, and so we need to know how many lumens are provided by the light bulb, and how many hours will the light bulb operate. In this case, the functional unit could be a light bulb with 1000 lumens, which works for 10000 hours.

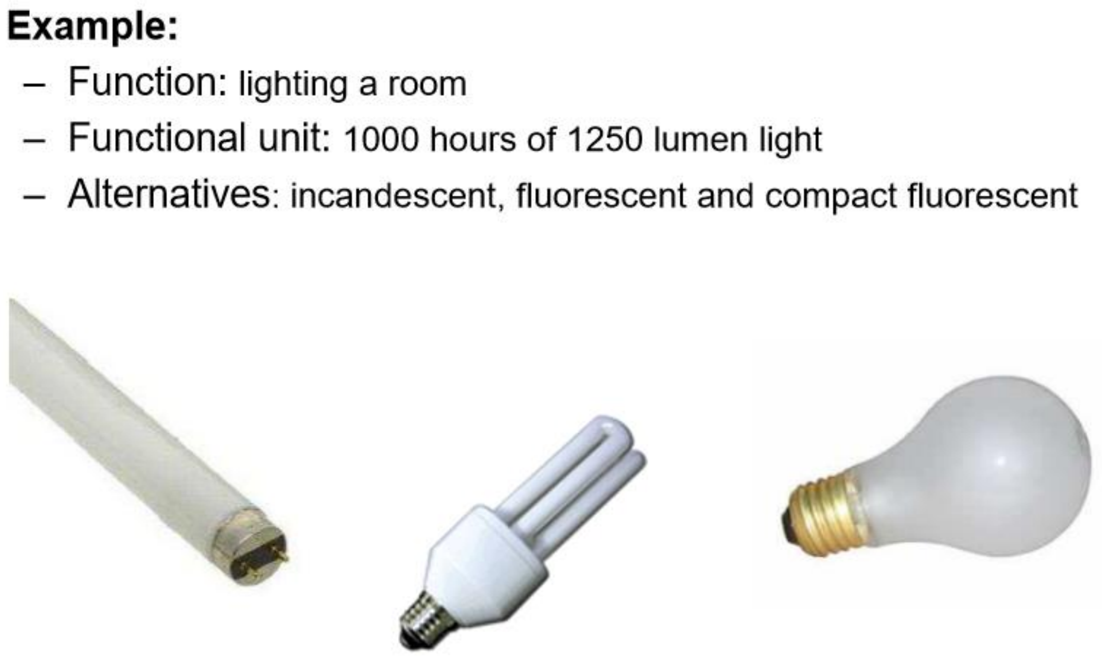


Figure 31 - Functional Unit Example.

10.2 Inventory Analysis

In this phase, the data describing the system is collected and converted to a standard format to provide a description of the physical characteristics of the system of interest (Figure 32).

The inventory describes the flows between the system and the environment for a certain (product) system. Inventory flows include inputs of water, energy and raw materials, and releases to air, land, and water (Figure 33).

To develop the inventory, a flow model of the technical system is constructed using data on inputs and outputs. The input and output data needed for the construction of the model are collected for all activities within the system boundary, including from the supply chain.

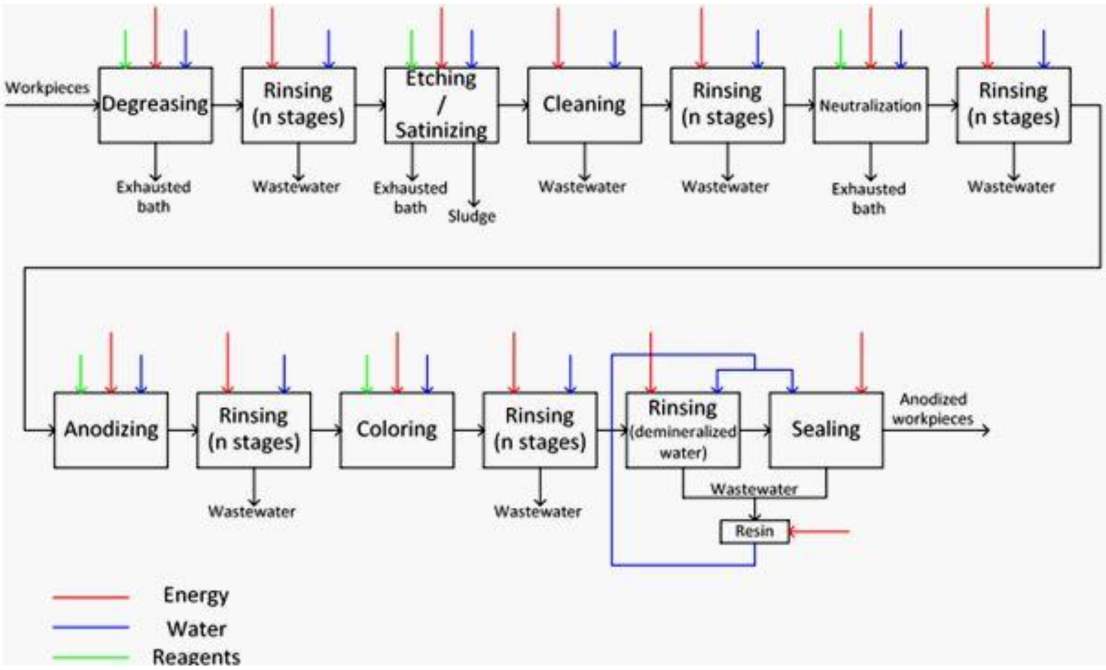


Figure 32 - Flow chart of an industrial process - typical anodising line.

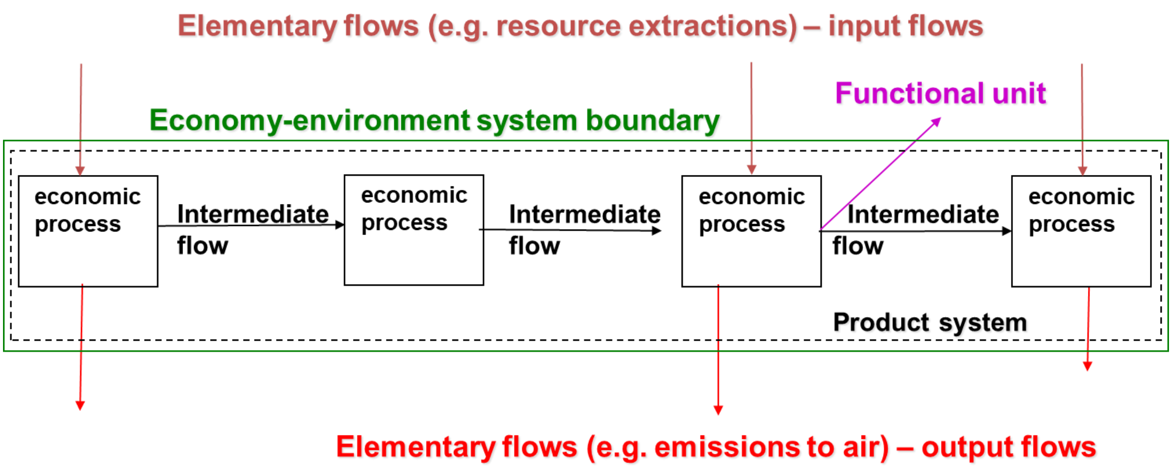


Figure 33 - Life cycle assessment terminology (according to ISO 14040:2006).

Data must be related to the functional unit defined in the goal and scope definition.

Two types of data may be used:

- Primary data, which is data that is specific to the product or service studied (generally collected in the form of a questionnaire which is sent to manufacturers and suppliers)
- Secondary data, which is generic data that is representative of the product or service studied (in the form of environmental datasets available for transport, waste treatment, etc.

Primary and secondary data can then be combined to create an inventory.

10.2.1 *Allocation methods*

Most industrial processes yield more than one product and they recycle intermediate or discarded products as raw materials. For example, a cow can generate milk, leather and meat. In these cases, it is necessary to allocate the impacts to each product. The difficulty comes regarding which part of the original inputs (for example the water and food eaten by the cow) is allocated to each product.

As this can change significantly the results, allocation should always be avoided. This can be done by splitting the process in such a way that it can be described as two separate processes, where each has a single output.

Another option is to expand the system boundaries to allow the inventory of alternative processes that can produce the same product (Figure 34).

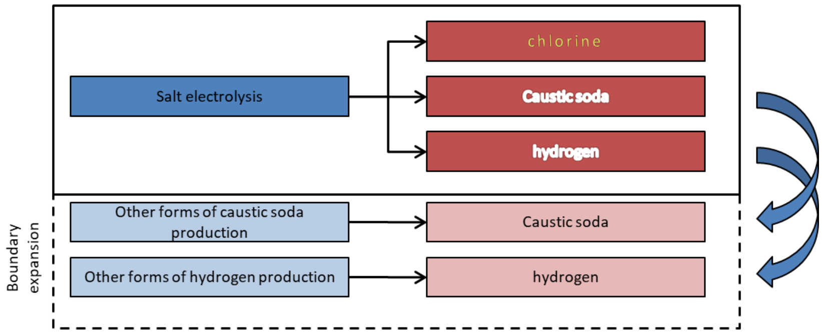
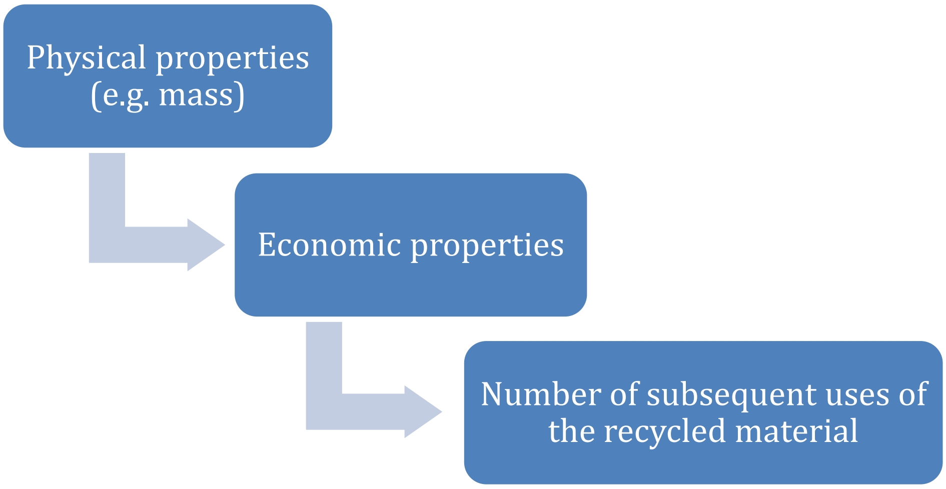


Figure 34 – System boundary expansion example on how to avoid allocation.

Often, this is not possible, and allocation needs to be done. In that case, there should be allocation based on the following order:



Nonetheless, the two main options for allocation methods are (Figure 35):

- Physical allocation - Use of physical causality (mass allocation, but energy could be also applied, e.g. incineration – electricity and heat). If not possible
- Use other relationships – For example, economic allocation

	Mass allocation (mass percentage)	Economic allocation (added value allocation)
Wooden planks	60%	95%
Saw dust	40%	5%

Figure 35 - Physical and Economic Allocation example.

How is the economic allocation done?

- Market value of the scrap material or recycled material in relation to market value of primary material
- Ratio between waste (Product system 1 to recycling) or secondary material (recycling to Product system 2) prices, in relation with their sum. Who drives the market?

However, note that prices can fluctuate significantly (which interferes with the analysis), and economic values are not always easy to obtain.

10.3 Impact Assessment

In this phase, the physical flows are translated into potential environmental impacts.

It consists in the following steps:

- Selection of the impact categories and best available models for their quantification. This is generally related to the selection of the environmental models used to promote the characterization of the environmental impacts
- Identification of the environmental interventions that contribute to a given impact category
- Quantification of the contribution of the environmental interventions to a given impact category
- Normalization of the results of the previous phases, using reference values
- Aggregation of the different impacts to reduce the number of the impact categories in the final result

10.3.1 Classification

The results must be assigned to impact categories. For example, CH_4 or CO_2 could be assigned to an impact category called "Climate change".

It is possible to assign emissions to more than one impact category at the same time, for example, SO_2 is simultaneously responsible for an impact on "Acidification" as well as in "Human health" or "Respiratory diseases".

There are several impact categories that can be analysed, including:

- Climate Change
- Global warming impact
- Acidification
- Human Health
- Respiratory diseases
- Primary Energy
- …many others

10.3.2 Characterization

Once the impact categories are defined and the results are assigned to the impact categories, it is necessary to define characterization factors (Figure 36). These factors should reflect the relative contribution of a result to the impact category indicator. For example, on a time scale of 100 years, the contribution of 1 kg CH_4 to global warming is 25 times as high as the emission of 1 kg CO_2.

This means that if the characterization factor of CO_2 is 1, the characterization factor of CH_4 is 25. Thus, the impact category indicator result for global warming can be calculated by multiplying the result with the characterization factor.

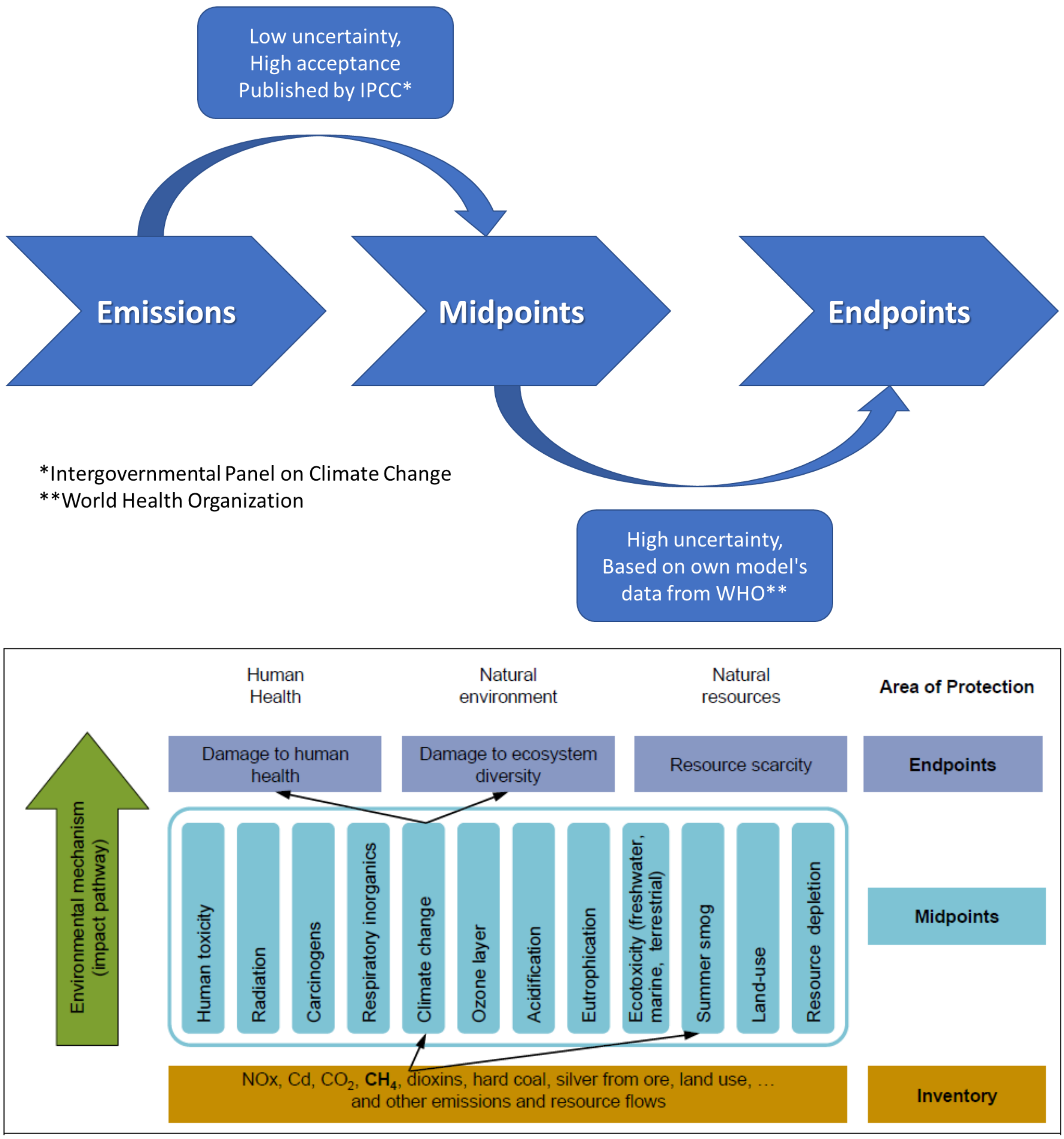


Figure 36 - Principles of Characterization.

Figure 37 shows the characterization factors for the previous example of a light bulb.

- **Example of a characterisation table**

Impact category	Incandescent lamp	Fluorescent lamp
Climate change	120000 kg CO2-eq.	40000 kg CO2-eq.
Ecotoxicity	320 kg DCB-eq.	440 kg DCB-eq.
Acidification	45 kg SO2-eq.	21 kg SO2-eq.
Depletion of resources	0.8 kg antimony-eq.	0.3 kg antimony-eq.

Figure 37 - Example of a characterization table.

10.3.3 Normalization

Normalization is a procedure needed to show to what extent an impact category has a significant contribution to the overall environmental problem. This is done by dividing the impact category indicators by a "Normal" value. There are different ways to determine the "Normal" value. The most common procedure is to determine the impact category indicators for a region during a year and, if desired, divide this result by the number of inhabitants in that area.

Normalization serves two purposes:

1. Impact categories that contribute only a very small amount compared to other impact categories can be left out of consideration, thus reducing the number of issues that need to be evaluated
2. The normalized results show the order of magnitude of the environmental problems generated by the products life cycle, compared to the total environmental loads in Europe

Figure 38 shows the normalized characterization factors for the previous example of a light bulb.

- **Example of a normalisation table**

Impact category	Incandescent lamp	Fluorescent lamp
Climate change	1.2×10^{-11} yr	4×10^{-12} yr
Ecotoxicity	1.6×10^{-10} yr	2.2×10^{-10} yr
Acidification	9×10^{-11} yr	4.2×10^{-11} yr
Depletion of resources	24×10^{-12} yr	9×10^{-13} yr

Figure 38 - Example of Normalization Table.

Considering the case of methane, the steps for doing an analysis of its impact assessment are exemplified on Figure 39.

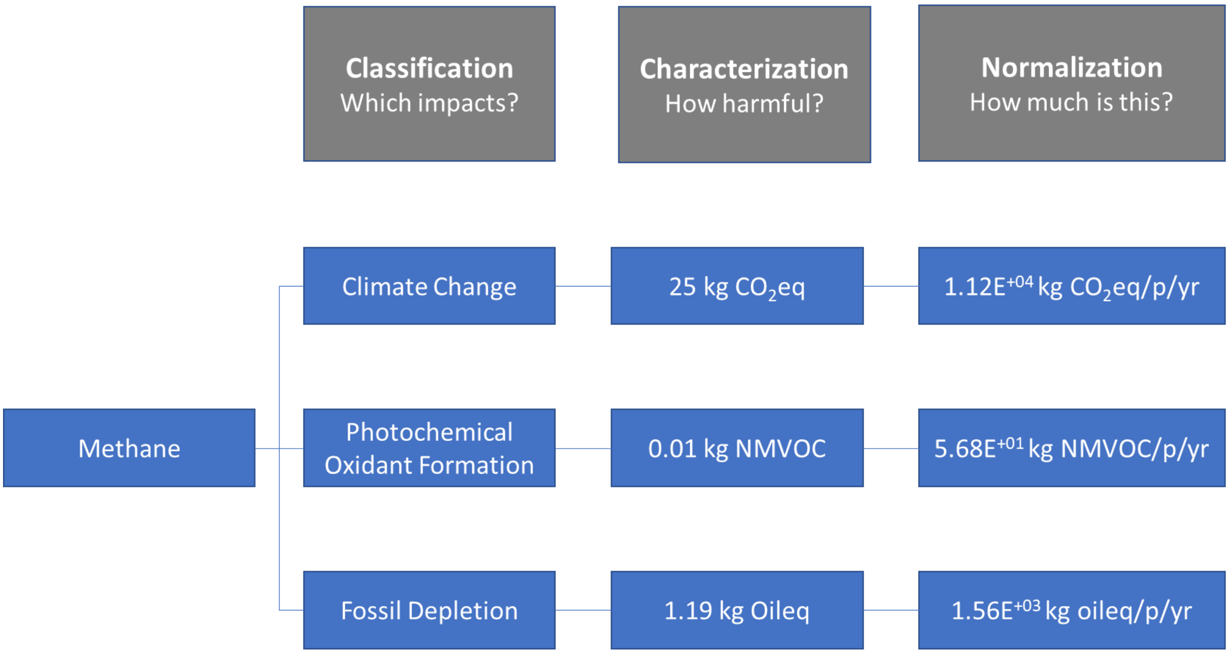


Figure 39 - Impact Assessment steps example.

10.4 Interpretation

In this phase, the results are evaluated and interpreted in the context of their significance, uncertainty, etc. LCA must be used for decision making by primary drivers for:

- Learning more about the environmental performance of products and services
- Minimizing production costs
- Minimizing environmental and human health damage

- Understanding trade-offs between multiple impact categories and product phases

10.5 Improvements

After performing these 4 phases the system should be modified in some way to reduce or ameliorate the observed environmental impacts.

11 SYSTEM ANALYSIS (MATERIAL FLOW AND ENERGY ANALYSIS)

Material Flow and Energy Analysis are methodologies meant to quantify the material and energy flows and stocks of materials or substances in a well-defined system. They contemplate the systems and its processes as a 'living organism' analogy, allowing the researcher to investigate its 'metabolism'.

11.1 Material Flow Analysis (MFA)

Material Flow Analysis (MFA) is a simple material balance of input, stock and output of a system and its processes.

MFA is an appropriate tool to investigate the flows and stocks of any material-based system. It gives insight into the behaviour of the system, and when combined with other disciplines such as energy-flow analysis, economic analysis, and consumer-oriented analysis, it facilitates the control of an anthropogenic system.

The objectives of method are:

- Delineate a system of material flows and stocks by well-defined, uniform terms
- Assess the relevant flows and stocks in quantitative terms, thereby applying the balance principle and revealing sensitivities and uncertainties
- Present results on flows and stocks of a system in a reproducible, understandable, and transparent way, and use them as a basis for managing resources, the environment, and wastes

11.2 Energy Flow Analysis (EA)

Energy Analysis (EA) may be shortly defined as the process of determining the embodied energy of a product or service, that is, the energy required directly and indirectly to produce it.

EA examines the energy requirements in the whole production chain of a product. Not only does it concern the direct energy use in manufacturing a product, but also the indirect energy requirements of the production process.

These indirect energy requirements involve, for example, the energy requirements of production and transport of the material input, or the energy requirements of capital goods.

Energy Analysis is then useful to:

- Determine the energy needed to produce a product
- Compare the energy needed to produce a product in different places
- Compute energy savings due to changes in the production processes, for example by recycling waste glass produced inside a glass factory back to the furnace

Both methods are very useful for decision-making in resource, waste, or environmental management, providing policymakers with insight that can positively affect and improve inefficient guidelines.
Two fundamental steps are required to implement these methods: the system definition, and the mass and energy balance calculation.

11.3 System definition

The system under analysis can be a model of an industrial plant (but also of an industrial sector, or even an entire country) (Figure 40). The level of detail of the system model is chosen to fit the purpose of the study. It is very important to define the system boundary, one or more processes that are part of the system, the material and energy flows between the processes, and the stocks of materials within processes. The physical exchange between the system and its environment happens via flows that cross the system boundary.

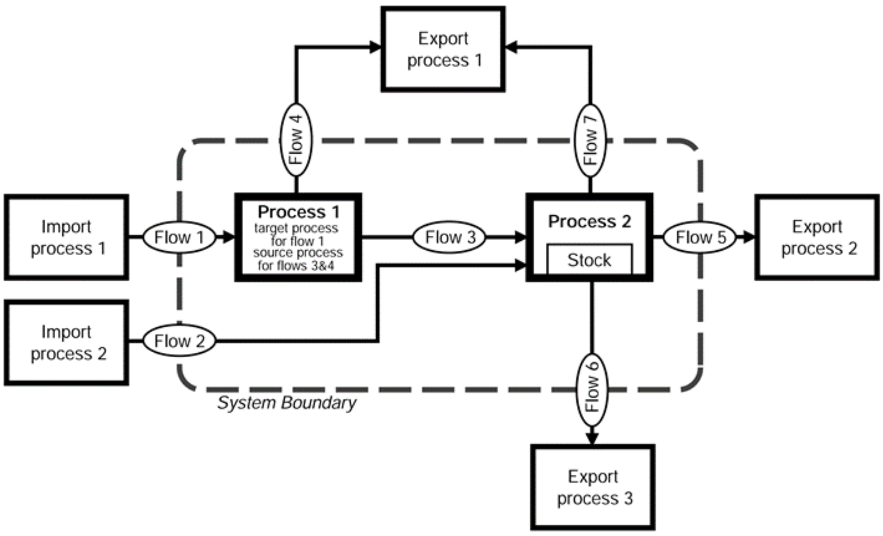


Figure 40 - Example of the schematic representation of a system (Brunner and Rechberger, 2005).

11.3.1 System representation – Block Diagrams

The systems are usually represented by a block diagram, where:

- The blocks of the diagram describe the processes, which are designated by letters;
- The arrows of the diagram describe the material and energy flows (inputs and outputs) of each process.

Figure 41 presents an example of a system with one process (A), which consumes energy (E_A) and two products (m_1 and m_2) to generate a product 3 (m_3), along with a residue (M_R).

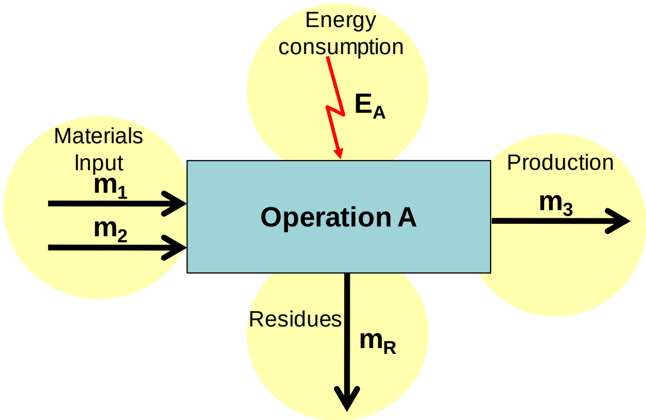


Figure 41 - Example of a system with one process

11.3.2 Specific energy consumption of the process

Each process is described by a Specific Consumption (CE) of energy and materials, which is a measure of energy consumed per unit mass of production.

In the case of process A, in Figure 41, the specific energy is given by:

$$\boldsymbol{CE_A} = \frac{\text{Energy consumption of operation A}}{\text{Useful Production of operation A}} = \frac{\boldsymbol{E_A}}{\boldsymbol{m_3}} [kJ/kg] \quad (11)$$

11.3.3 Specific energy consumption of the product

11.3.3.1 Specific Consumption of Production

The specific energy consumption of a product is given by the energy required to produce the product, which includes both the energy used by the process itself and the energy used in the previous processes of the materials that are being used at the current product (embed energy).

In the case of material 1 (m_1), in Figure 41, the specific energy is given by:

$$\boldsymbol{CE_1} = \frac{\text{Energy consumption in previous operations}}{\text{Mass of 1}} = \frac{\boldsymbol{E_1}}{\boldsymbol{m_1}} [kJ/kg] \quad (12)$$

*Note that, (like in the case depicted in Figure 41), if the material inputs (m_1 and m_2) come from outside the system border, it is only possible to calculate it's specific energy consumption if it is supplied enough information regarding the energy that was used to create that material input up to that point.

Product 3 includes materials 1 and 2, and hence it is necessary to consider the energy used to produce those inputs. Therefore, the specific consumption of product 3 is:

$$\boldsymbol{CE_3} = \frac{E_A}{m_3} + \frac{m_1 + m_2}{m_3}\left(\frac{m_1}{m_1 + m_2}\frac{E_1}{m_1} + \frac{m_2}{m_1 + m_2}\frac{E_2}{m_2}\right) = \boldsymbol{CE_A + S_A(f_1\ CE_1 + f_2\ CE_2)} \quad (13)$$

where S_A is the residues formation factor, f_1 and f_2 are mass proportions of the product and CE_1 and CE_2 are the specific energy consumption of products 1 and 2, the results being in $[kJ/kg]$.

11.3.3.2 Residues formation factor

For the same example, the residue formation factor is given by:

$$S_A = \frac{\text{Materials input of A}}{\text{Production of A}} = \frac{m_1 + m_2}{m_3} \quad (S_A \geq 1) \tag{14}$$

which is 1 in case there is no residues and higher than 1 when there are residues. Remember that based on the mass balance $\mathbf{M_R = M_1 + M_2 - M_3}$

11.3.3.3 Mass Proportion

The mass proportion is given by the following formula.

$$f_{\#} = \frac{\text{Material input \#}}{\text{Total materials input}} \tag{15}$$

Then for the case depicted in Figure 41 the mass proportions of the inputs in Operation A are:

$$f_1 = \frac{m_1}{m_1 + m_2},\ f_2 = \frac{m_2}{m_1 + m_2},\ (f_i < 1 \ \ and \ \sum_i f_i = 1) \tag{16}$$

11.3.3.4 In a nutshell

An overview of a specific consumption of production is depicted on Figure 42.

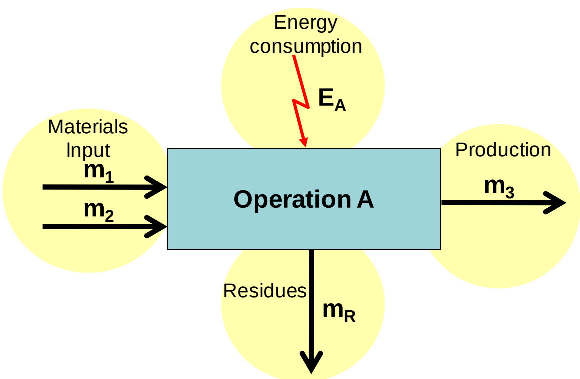


Figure 42 - Specific Consumption of Production Overview.

$$CE_A = \frac{E_A}{m_3}; \qquad CE_1 = \frac{E_1}{m_1}; \qquad CE_2 = \frac{E_2}{m_2} \tag{17}$$

$$S_A = \frac{m_1 + m_2}{m_3}; \qquad f_1 = \frac{m_1}{m_1 + m_2}; \qquad f_2 = \frac{m_2}{m_1 + m_2}$$

Direct Energy Use

Indirect Energy Use

$$CE_3 = \frac{E_A}{m_3} + \frac{m_1 + m_2}{m_3}\left(\frac{m_1}{m_1 + m_2}\frac{E_1}{m_1} + \frac{m_2}{m_1 + m_2}\frac{E_2}{m_2}\right) = CE_A + S_A\left(f_1\,CE_1 + f_2\,CE_2\right)$$

11.3.4 Connections of processes

The systems may be combinations of different types of connections between processes. In general, we have three types of connections that can be found:

- **Sequential processes;**

Sequential processes are computed in the same way the previous consumptions were calculated, that is, the energy consumption of a product is given by the sum of direct energy used to produce it, and the indirect energy that was used in that past to produce its inputs in a chain (Figure 43).

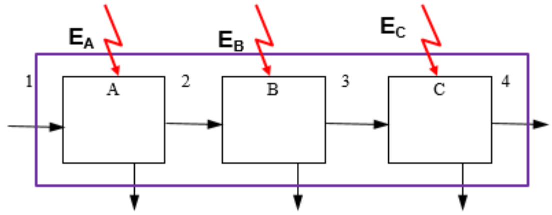


Figure 43 - Example of Sequential processes.

$$\boldsymbol{CE_1} = CE_1\ (Outside\ of\ the\ system\ border) \quad (18)$$
$$\boldsymbol{CE_2} = CE_A + S_A \times CE_1$$
$$\boldsymbol{CE_3} = CE_B + S_B \times CE_2$$
$$\boldsymbol{CE_4} = CE_C + S_C \times CE_3$$

or

$$\boldsymbol{CE_4} = \mathrm{CE}_C + S_C\left(\mathrm{CE}_B + S_B(\mathrm{CE}_A + S_A\mathrm{CE}_1)\right)$$

- **Divergent processes;**

Knowing that the energy consumption of a product is given by the sum of the direct energy used to produce it and the indirect energy that was used in that past to produce its inputs, if two separate products come from the same source then their specific energy consumption will be equal (Figure 44).

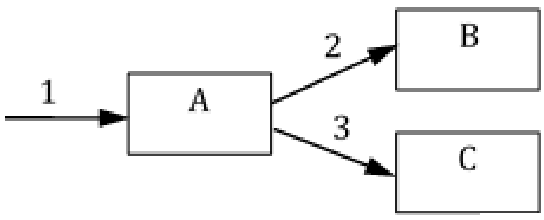


Figure 44 - Example of a divergent process.

$$\boldsymbol{CE_1} = CE_1\ (Outside\ of\ the\ system\ border)$$
$$\boldsymbol{CE_2} = CE_A + S_A \times CE_1 \quad (19)$$

$$\boldsymbol{CE_3} = CE_A + S_A \times CE_1 = \boldsymbol{CE\_2}$$

- **Converging processes.**

When two separate material inputs converge in an operation that outputs one product, the specific energy consumption of that output will also be given by the sum of direct energy used to produce it and the indirect energy that was used in that past to produce its inputs (Figure 45).

However, since there are multiple inputs, and the amount coming from each might differ, each input has to be multiplied by its mass proportion factor.

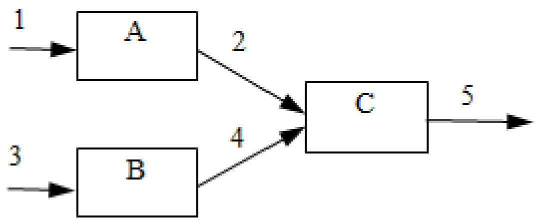


Figure 45 - Example of a convergent process.

$$\boldsymbol{CE_1} = CE_1\ (Outside\ of\ the\ system\ border)$$
$$\boldsymbol{CE_3} = CE_3\ (Outside\ of\ the\ system\ border) \qquad (20)$$

$$\boldsymbol{CE_5 = CE_C + S_C(f_2 \times CE_2 + f_4 \times CE_4)}$$

$$\boldsymbol{CE_2 = CE_A + S_A CE_1}$$
$$\boldsymbol{CE_4 = CE_B + S_B CE_3}$$

$$\boldsymbol{f_2 + f_4 = 1}$$

11.3.5 Specific energy consumption of residues and their treatment operation

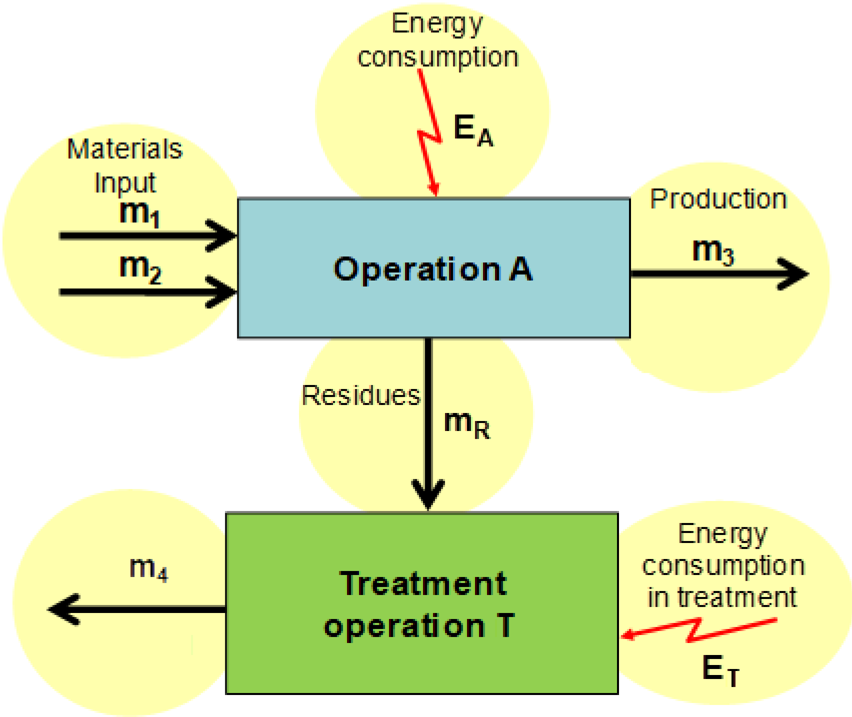


Figure 46 - Example of a system with a transforming operation (A) and a Residue Treatment Operation (T).

While in reality there is a 'Specific Energy consumption' for the residue output, in block diagrams it is usually considered null in the calculations. All the additional energy that is used in 'non-useful' outputs (e.g. residues) is stacked and counted for in the closest useful output (in this case m_3). This is because all of the energy used to create material 3 (m_3) must be considered, and this must include the energy that was used to create the material that ended up being residue (m_R).

Although no energy consumption is attributed to the residues flow (m_R) directly, when calculating the Specific Energy Consumption of the closest useful output (in this case m_3), the value is multiplied by the Residue Factor. This way we guarantee that the extra energy used (because of the residue) is included in the useful output calculations.

Assuming that in Figure 46 there is no treatment operation, CE_3 is then calculated as:

$$\mathbf{CE_3} = \mathrm{CE}_A + S_A(f_1\ \mathrm{CE}_1 + f_2\ \mathrm{CE}_2) \tag{21}$$

However, in case the residues are treated, the treatment energy consumption needs to be considered.

Assuming that in Figure 46 there is a residue treatment operation, we first need to evaluate the treated residues formation factor, given by:

$$\boldsymbol{S_{AT}^{T}} = \frac{m_R}{m_3} \tag{22}$$

Then, we need to define the specific energy consumption of the treatment process, given by

$$\boldsymbol{CE_T^T} = \frac{E_T}{m_R} \tag{23}$$

Finally, the specific energy consumption of material 3 is given by

$$\boldsymbol{CE_3} = CE_A + S_A \times (f_{1\times} \times CE_1 + f_{2\times} \times CE_2) + S^T_{AT} \times CE^T{}_T \quad (24)$$

Note that the specific energy consumption of the residue (CE_R) and the outputs of the Treatment operation (CE_4) will continue to be considered as null, again due to the fact that this extra consumption is counted as part of the total energy required to create the useful output (m_3).

CE_3 must consider ***all*** the energy that was consumed to manufacture Product 3 (m_3), thus including the extra energy that was (unintentionally) used to create the residue (m_R), and also the energy used to treat that same residue.

11.3.6 Specific energy consumption of Recovery Processes (Recycling, Re-use, etc…)

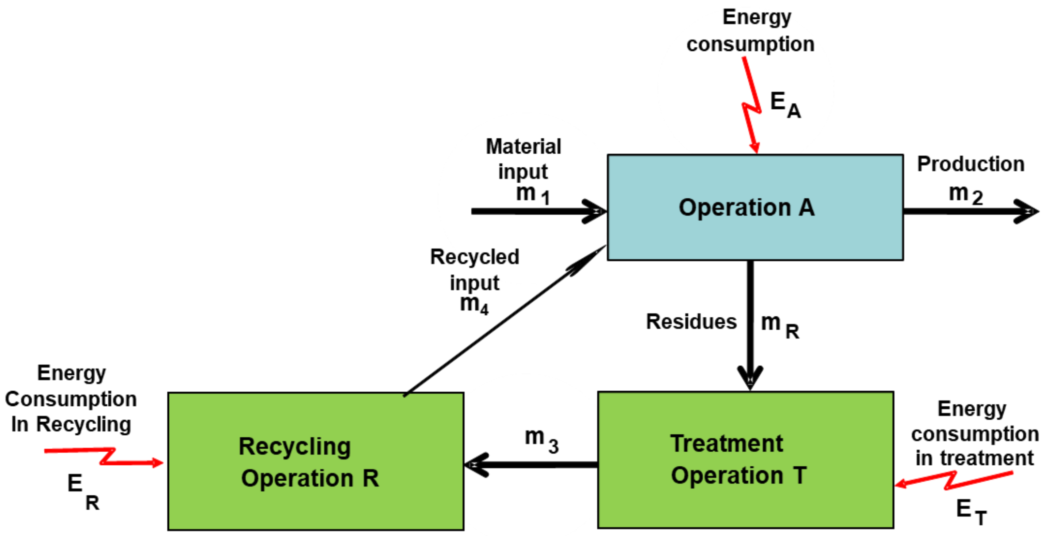


Figure 47 - Example of a system with a transforming operation (A), Residue Treatment (T) and Recycling Operation (T).

Consider the case depicted in Figure 47. Like the previous examples, the energy consumption directly related to non-useful outputs (m_R and m_3 in this case) should be considered null and included in the consumption of the useful output (m_2). However, if a recycling process is introduced in the system, it will create a new useful output (in this case m_4). Operation A will then have two material inputs instead of one: one from Raw Materials from outside of the system boundary (m_1), and another from the Recycling Operation (m_4) within the system boundary (such as seen in Figure 47). Note that recycling procedures can be outsourced. In that case, it can be considered to be and out of the system boundary.

A direct consequence of recycling is that the amount of Raw Material (m_1) required will reduce as there will be another material source. But how about the Energy Consumption?

The Recycling Operation receives input originated from waste flows whose energy consumption is considered null. Therefore, the specific energy consumption of the material output (m_4) will only consider the Energy Consumption of the Recycling Operation itself:

$$\boldsymbol{CE_4} = CE_R + S_R \times CE_3 \quad (25)$$
$$\boldsymbol{CE_3} = 0 \; (by\ convention)$$
$$\boldsymbol{CE_4} = CE_R$$

$$\mathbf{CE_2} = \mathrm{CE_A} + \mathrm{S}_A(\mathrm{f_1 CE_1} + \mathrm{f_4 CE_4}) + \mathrm{S}_A{}^T \mathrm{CE_T^T}$$

11.4 Example

Presented in Figure 48, is an example of the representation of an industrial system with 6 processes.

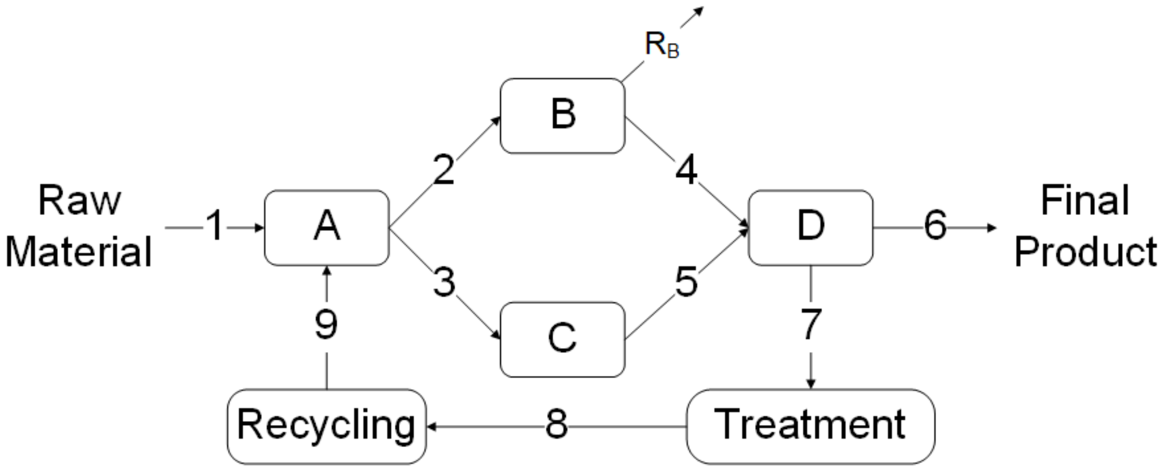
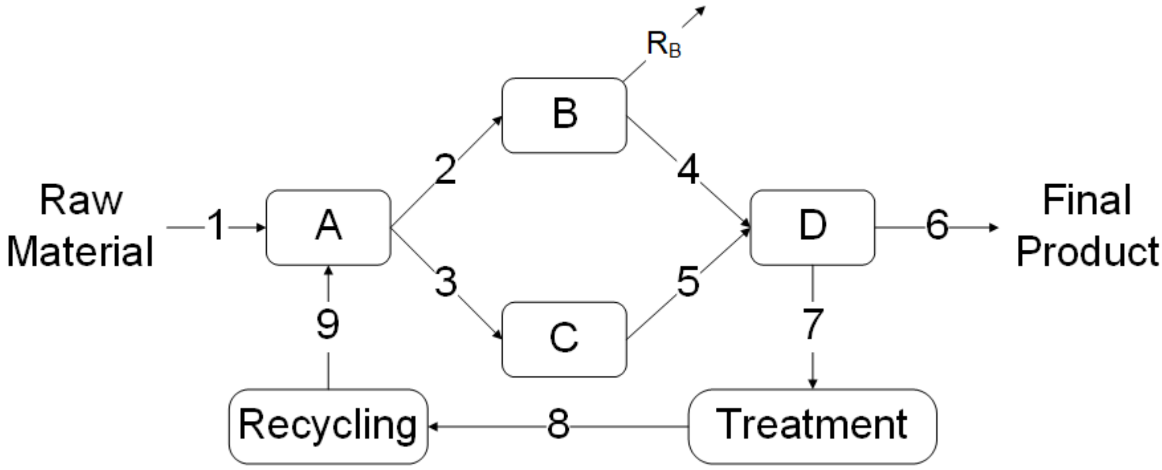


Figure 48 - Example of an industrial system

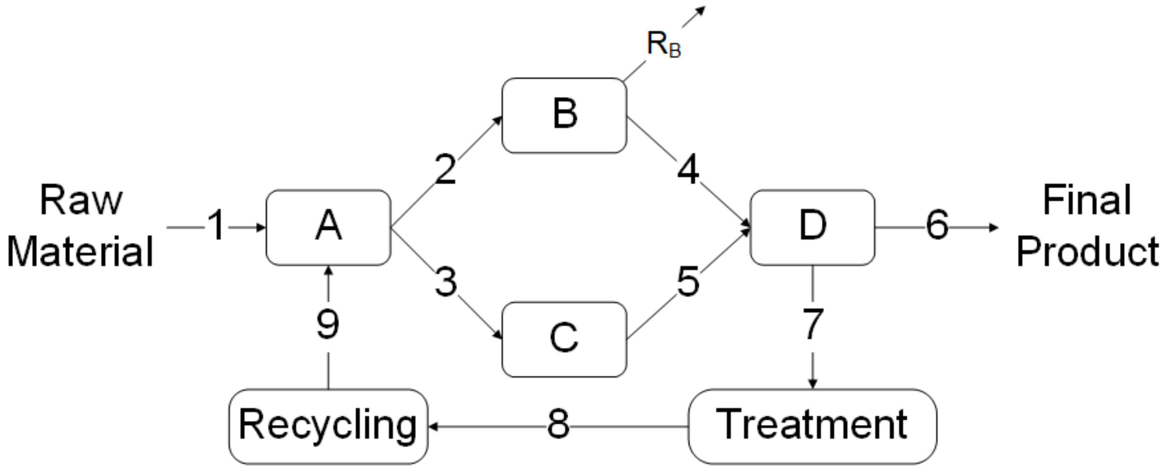
1. **How to calculate Mass Flows? (with the mass flow of the final product provided).**

$Residue\ Formation\ Factor: S \geq 1 = \frac{Input\ in\ Operation}{Useful\ Output} = S^T + 1$	
$Residue\ To\ be\ Treated\ Factor:\ S^T < 1 = \frac{Residue\ that\ comes\ from\ the\ Operation}{Useful\ Outuput\ from\ that\ Operation}$	
$S_D > 1 = \frac{m_4 + m_5}{m_6} = (S_D^T + 1)$	$S_D^T = \frac{m_7}{m_6} = (S_D - 1)$
$\boldsymbol{(m_4 + m_5) = m_6 \times S_D}$	$\boldsymbol{m_7 = (S_D - 1) \times m_6 = S_D^T \times m_6}$
$Mass\ Flow\ Proportions: f_x \leq 1 = \frac{Input\ from\ flow\ x}{Sum\ of\ all\ Inputs},\ \sum f\ = 1$	
$f_4 = \frac{m_4}{m_4 + m_5}\ (=)\ \boldsymbol{m_4 = (m_4 + m_5) \times f_4}$	$f_5 = \frac{m_5}{m_4 + m_5}\ (=)\ \boldsymbol{m_5 = (m_4 + m_5) \times f_5}$
$f_4 + f_5 = 1$	
$S_C = 1 = \frac{m_3}{m_5}\ (=)\ \boldsymbol{m_3 = m_5}$	$S_B > 1 = \frac{m_2}{m_4} (=)\ \boldsymbol{m_2 = m_4 \times S_B}\ (=)\ \boldsymbol{R_B = (1 - S_B) \times m_4}$
$f_1 = \frac{m_1}{m_1 + m_9}\ (=)\ \boldsymbol{m_1 = (m_1 + m_9) \times f_1}$	$f_9 = \frac{m_9}{m_1 + m_9}\ (=)\ \boldsymbol{m_9 = (m_1 + m_9) \times f_9}$
$f_1 + f_9 = 1$	
$S_R = 1 = \frac{m_9}{m_8}\ (=)\ \boldsymbol{m_9 = m_8}$	$All\ treated\ Residue\ goes\ to\ Recycling,\quad \boldsymbol{m_8 = m_7}$
Hint: If the diagram shows a residue flow, S>1. If not stated otherwise, consider it to be 1.	



2. **Calculate Operation Specific Energy Consumption (CE)**

$$Operation\ Specific\ Energy\ Consumption = \frac{Energy\ Consumed\ By\ Operation}{Useful\ Output\ from\ Operation}$$
$$Treatment\ Specific\ Energy\ Consumption = \frac{Energy\ Consumed\ By\ Treatment}{Input\ of\ residue\ to\ be\ treated}$$
Energy consumed per operation is supplied by the available data. Nevertheless, usually it must be converted to a single unit (usually either in Joules or kg-ton of Primary Energy).
One must pay attention to the magnitude of the units and convert if needed!
$$CE_A = \frac{E_A \times coversion\ coeficient}{m_2 + m_3} \times Magnitude\ Correction$$
$$CE_B = \frac{E_B \times coversion\ coeficient}{m_4} \times Magnitude\ Correction$$
$$CE_C = \frac{E_C \times coversion\ coeficient}{m_5} \times Magnitude\ Correction$$
$$CE_D = \frac{E_D \times coversion\ coeficient}{m_6} \times Magnitude\ Correction$$
$$CE_T^T = \frac{E_T \times coversion\ coeficient}{m_7} \times Magnitude\ Correction$$
$$CE_R = \frac{E_R \times coversion\ coeficient}{m_9} \times Magnitude\ Correction$$



3. Calculate Specific Energy Consumption of the Final product, CE_6

$CE_{Flow} = CE_{Operation\ of\ Origin} + S_{Origin\ Operation} \times [\sum(f_{origin\ inputs} \times CE_{origin\ inputs})]$
CE_1 *is usually supplied since normally it comes externally.*
$CE_2 = CE_A + S_A \times [f_1 \times CE_1 + f_9 \times CE_9]$
$CE_3 = CE_A + S_A \times CE_1 = CE_1, if\ it\ comes\ from\ the\ same\ operation\ CE\ is\ the\ same$
$CE_4 = CE_B + S_B \times CE_2$
$CE_5 = CE_B + S_B \times CE_3$
$CE_6 = CE_D + S_D \times\ [(f_4 \times CE_4) + (f_5 \times CE_5)] + S_D^T \times CE_T^T$
The Specific Energy consumption that comes from an operation that includes a treatment procedure "absorbs" the Specific Energy of that Treatment. The Specific Energy Consumption of the Final Product, CE_6 includes the energy consumed by the treatment procedure S^TCE^T, so that the "stored energy" that the product consumed to be manufactured includes the waste treatment. Consequently, the non-useful treatment flows (CE_7 and CE_8) are considered zero since their consumption are already included.
$CE_7 = CE_8 = 0$
Even if the recycling procedure input is supposedly "non-useful" flows of residue, its output is useful, and by re-entering its output (m_9) the product processing chain, its specific energy consumption must be considered.
$CE_9 = CE_R + S_R \times \cancel{CE_8} = CE_R$