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Market study on energy usage in European heat intensive industries

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Summary

This study investigate the European heat market of heat intensive industries and evaluate the quantity of heat consumed by these industries and the way it is consumed. The study provides some recommendations to pursue the development of nuclear cogeneration in Europe.

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1. Introduction

1.1. Objective and scope of the study

Objective

The objective of this study is to quantify the European industrial heat market and qualify the energy usage in European heat intensive industries. This is a key input for the successful deployment strategy of nuclear cogeneration technologies in Europe.

Scope

The study has the following scope:

- Geographic: European coverage
- Topic: the study estimates the European industrial demand for heat but not the feasibility of nuclear cogeneration.
- Functional:
  - The temperature segmentation is 100°C - 250°C - 550°C - 700°C - 1000°C and beyond.
  - Basic industrial sectors with large productions and massive heat consumption are covered. Sectors manufacturing public goods are left aside since the public acceptance for nuclear technologies is arguably too low to make them support it publicly. It must be noted that the important sector of synthetic fuels was not covered by the study.

Sectors included		Sectors excluded
District heating Desalination Pulp and paper Oil refining Chemical industry Soda ash Ammonia and fertilisers Industrial gases	Hydrogen Lime Aluminium Iron and steel Glass Cement Non-ferrous metals Ceramics	Manufactured products Pharmaceuticals Agricultural products Consumer goods Synthetic fuels

Table 1.1-1 List of industrial sectors included and excluded from the scope of the study

Definition of "heat" and "heat market"

"Heat" is defined as:

- the heat transmitted by a hot heat carrier through heat exchangers or by electrical resistance
- the steam which may be used as heat carrier, process feedstock, mechanical medium (to action compressors or valves) or vacuum medium (to create vacuum conditions).

The “heat market” is defined as any kind of heat consumed in the industrial sectors within the scope of the study.

This heat market encompasses many paradigms which yet can be distributed into two main sub-markets:

- “plug-in” covering all combined heat and power cogeneration plants supplying one or more industrial facilities
- “extended” covering all boilers and burners operated internally within an industrial facility and/or embedded directly into the production processes

The interest of the plug-in market is obvious: the existing cogeneration plant could be replaced by a nuclear cogeneration plant by simply switching the pipes. The extended market relates to a market which may be difficultly reached today but could yet be interested in the future in high temperature nuclear steam.

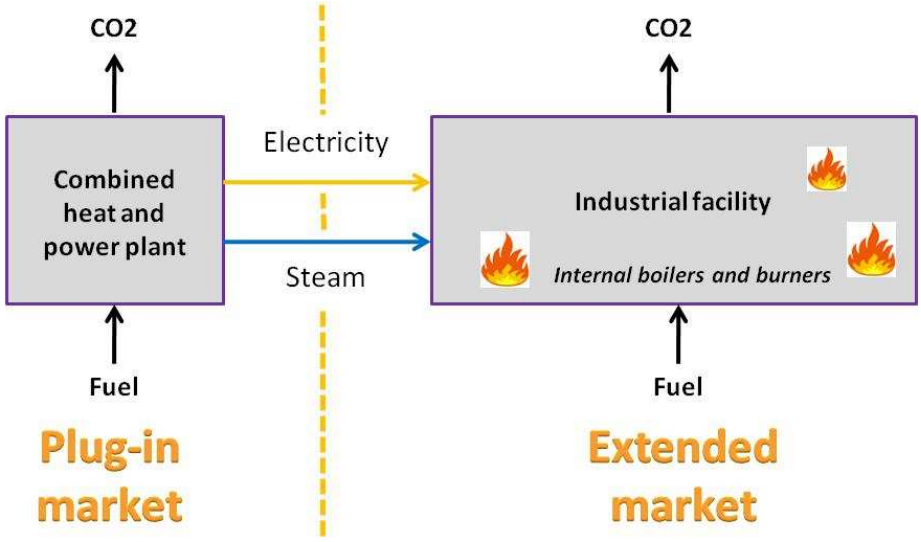

Figure 1.1-1 Schematic picture of the scope of the heat market

Two additional hypothetical submarkets were considered:

- “polygeneration” relates to the co-production of base raw materials beyond the sole cogeneration of heat and electricity such as industrial gases (e.g. hydrogen nitrogen, oxygen) near or within the nuclear plant; this takes into consideration the potential of hydrogen production technologies based on nuclear energy.
- “pre-heating” considers the share that could be technically externalised if a low-carbon, competitive high temperature steam was available.

Results of the study

The study evaluates the heat market, i.e. an energy consumption. The polygeneration and pre-heating submarkets are a first attempt to evaluate additional heat submarkets that could be supplied by nuclear energy.

However, the study does not evaluate the market potential of nuclear cogeneration. This requires evaluating the technical feasibility and the economic rationale of applying nuclear cogeneration to the heat markets.

The study does not cover the possible business model for nuclear cogeneration.

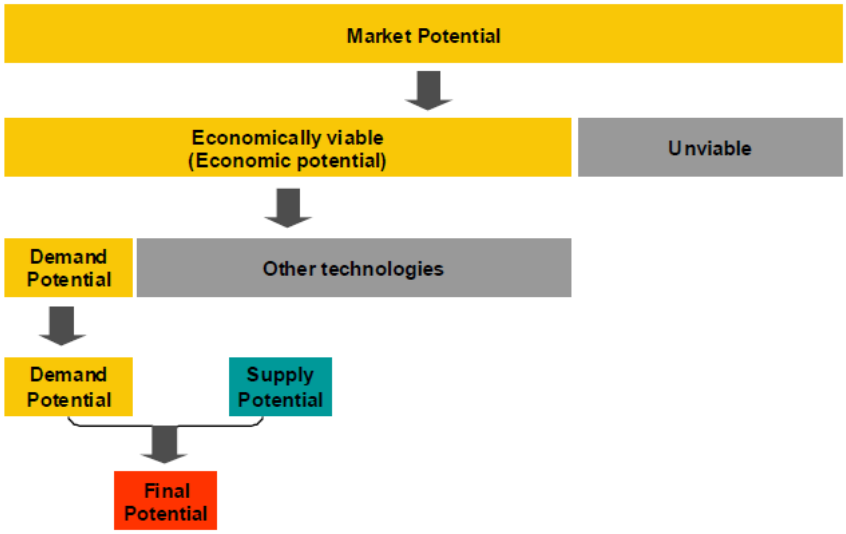

Figure 1.1-2 Overview of technical potential and market potential for a single technology (Source NERA 2009)

1.2. Context and bibliography

1.2.1. Context

The project takes place in a time where European industrial actors are concerned by CO2 emissions, environmental performance, energy supply and costs, industrial competitiveness and globalisation.

Cogeneration has been increasingly used in industrial sectors on the basis of fossil fuels, mainly gas. Concerns over the security of gas supply and the expectations of stringent climate policies make nuclear cogeneration a realistic option.

Knowing how large the current heat market is and how energy is used by industrial consumers is a critical information to orientate the development and demonstration of a first of a kind.

1.2.2. Bilbiography and statistics on the European heat market

Several market studies on combined heat and power and nuclear cogeneration were carried out in the US, most of them stating the existence of a market for cogeneration, especially when considering H2 production beyond the sole co-production of steam and electricity (RDC 2003, EEA 2004, 2005, EPRI 2005, USDOE 2002, MPR 2008)

There is to our knowledge no such detailed market study which was carried out in the European Union. We can just report the statistics from OECD International Energy Agency (IEA 2009 and 2010) and the European statistic institute Eurostat (released from the website in April 2010). Both organisations use the same information source, i.e. a questionnaire sent to Member States.

Organisation for Economic Cooperation and Development / International Energy Agency

According to the OECD International Energy Agency, the total heat consumption is of 766 TWh in EU27 in 2007, as compared to 3 362 TWh of electricity produced.

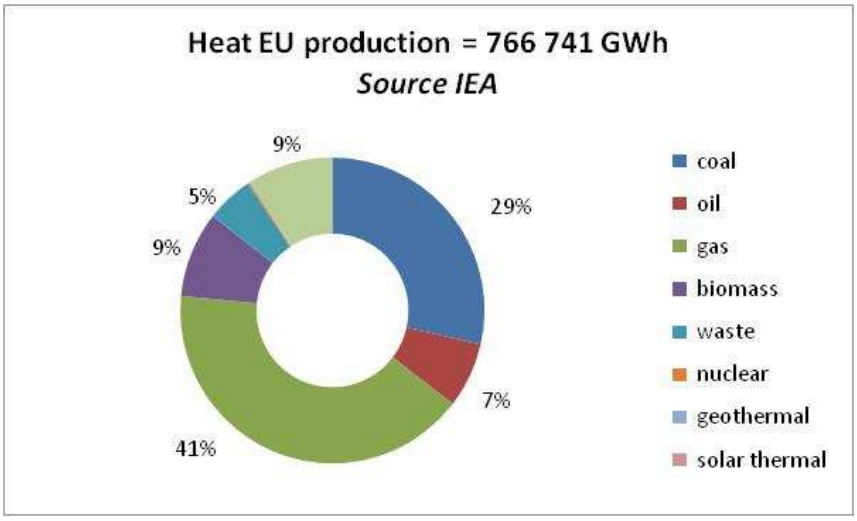

Figure 1.2-1 Total heat production in EU27 in 2007 according to IEA (2010)

The main fuel for heating is gas, followed by coal and biomass. Nuclear is reported to cogenerate a small amount of heat of 1 766 GWh in 2007.

The heat consuming sectors are industry (29%, 197 TWh), residential (27%, 182 TWh) and commercial/public service (10%, 68 TWh). It must be noted that one third of the heat consuming sectors is not specified.

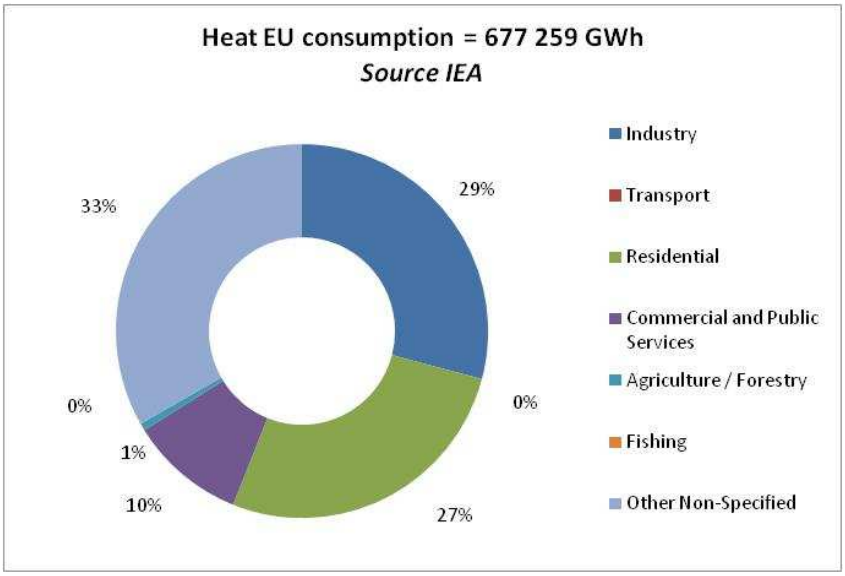

Figure 1.2-2 Total heat consumption in EU27 in 2007 according to IEA (2010)

European statistical institute EUROSTAT

Despite sharing the same information source, Eurostat's statistics are significantly different from OECD/IEA and a little more detailed.

Production of heat in EU 27 in 2007	GWh
Conventional power plants	440 485
Nuclear power plants	1 766
District heating	147 049
Public thermal power stations	365 843
Autoproducers	74 643
Other	589 301
TOTAL	**1 619 086**

Table 1.2-1 Production of heat in EU 27 in 2007 (Source: Eurostat)

As regards the production side,

- conventional power plants (whether gas, fuel oil or coal) produce the major part of the heat (440 TWh); this includes both large power plants operated by a utility and cogeneration power plants, whose operation is externalised to an operator.
- Nuclear power plants do cogenerate heat, but as a marginal part (reporting countries are Bulgaria, Czech Republic, Lithuania, Hungary and Slovakia); the amount of heat cogenerated by nuclear power plants is in accordance with IEA.
- District heating amounts to 147 TWh and "public thermal power stations" to 386 TWh. The difference between both is unclear and both were assumed to be district heating (for a total of 533 TWh).
- Auto-producers are companies "generating electricity and/or heat, wholly or partly for their own use, as an activity which supports their primary activity" (IEA 2009). The amount is very low due to the fact that only the heat which is sold outside the industrial facility is reported. This does not reflect the heat consumption of the industrial site.
- It must be noted that the non-attributed heat production source amounts to around one third of the total amount of heat reported.

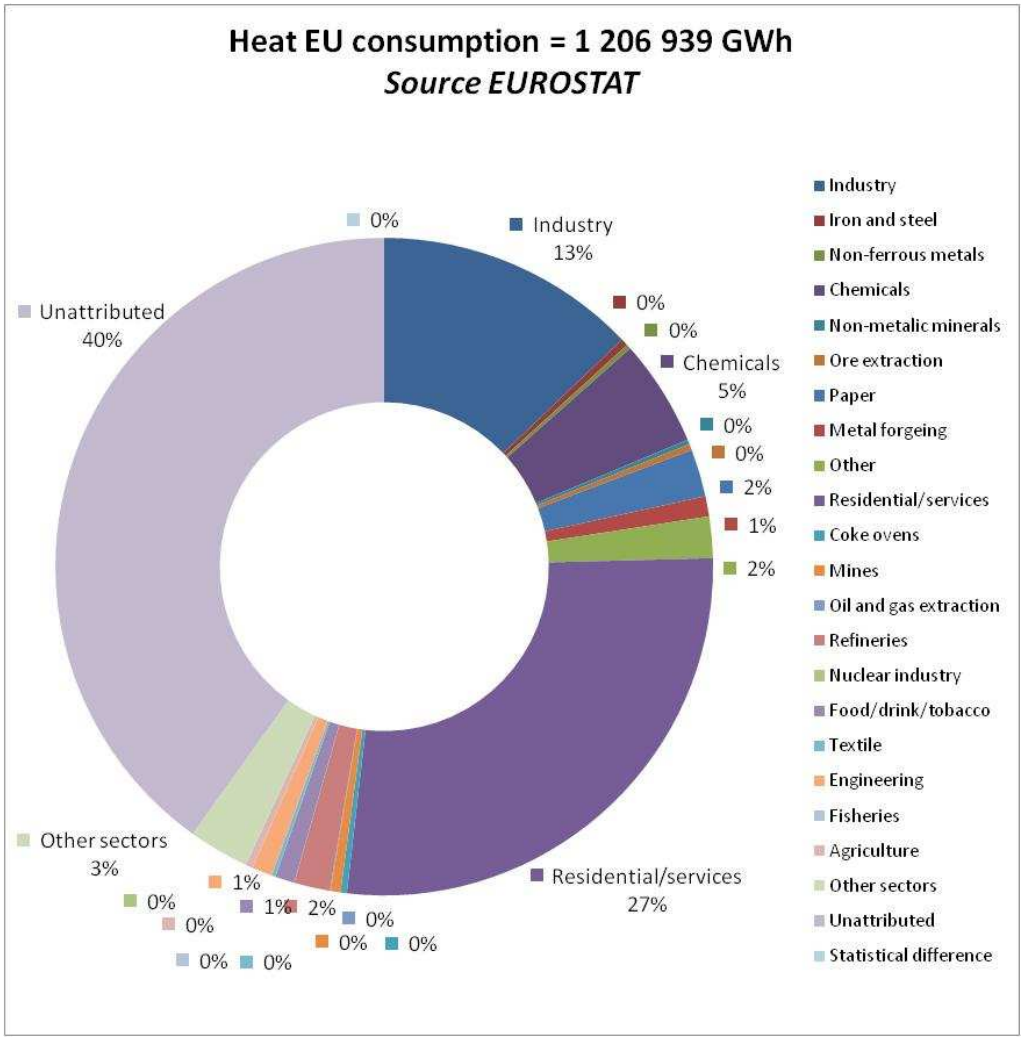

Figure 1.2-3 Heat consuming sectors in EU27 in 2007 according to Eurostat (2010)

As regards the consumption,

- The difference between the total consumption and the total production arises mainly from heat losses and net heat exports
- A major part (40%) of the heat is not attributed; the sector in which this heat is consumed is unknown.
- The main sectors are residential/services (27%, 329TWh), non-attributed industry (13%, 155TWh, this line refers to industry in general) and chemicals (5%, 63TWh).
- Most identified industrial sectors report rather low consumptions (less than 2%): iron and steel, non-ferrous metals, paper, metal forgeing, coke, refineries, etc.

The large difference between EUROSTAT (1 619TWh of heat production in EU27) and IEA statistics (766TWh heat production) may come from:

- the low sample representativeness as regards the considerable mass of information asked
- the different interpretations of the questions of the questionnaire by Member States
- the statistical processing which uses different rules (e.g. electrical/net heating ratios, energy a priori produced from a declared plant thermal capacity, etc.).

Conclusion on existing statistics: unreliable, incomprehensive and imprecise

The above results demonstrate that these sources of information are sadly unreliable for evaluating the heat market. The information is sparse, the statistical treatment is not fully reliable and large amounts of energy consumption and production are not attributed. Yet, this data is a valuable input and may serve as reference.

This statistical unreliability makes it necessary to study further the heat consuming market.

1.3. Methodology

1.3.1. Objective

The objective is to quantify the heat consumption by temperature and sector and to qualify the energy usage for several key heat intensive industrial sectors, in order to identify opportunities and challenges to overcome and to recommend a best market approach.

1.3.2. Methodology

The methodology uses a dual approach:

1. The heat consumption was first evaluated indirectly from the greenhouse gases emissions declared in the EU Emissions Trading Scheme.
2. A market survey was organised from April to September 2010 for several key sectors in order to understand better the operated processes and industrial reality and to make a direct evaluation possible.

1.3.3. Indirect calculation from greenhouse gases emissions

The indirect calculation has the advantages to:

- streamline the analysis as regards the wide scope of the study: around 50 industrial sectors operating each a dozen of processes
- report rather accurately on the large energy intensive industrial sites which are subject to CO2 taxation and are arguably the best candidates for nuclear cogeneration.

It is important to note that:

a. Greenhouse gases (GHG) emission is one variable which depends on more than one parameter. Indeed GHG can be emitted from the combustion of fossil fuels or from the production process itself
b. GHG emissions related to energy do not show the difference between energy used as heat and energy used as electricity
c. GHG emissions that could be attributed to heat do not differentiate the heat from cogeneration plants and from internal boilers. The first refer to a “plug-in” energy market and the second refer to an extended market which would require some process redesign and the management of additional by-products if it was supplied externally.

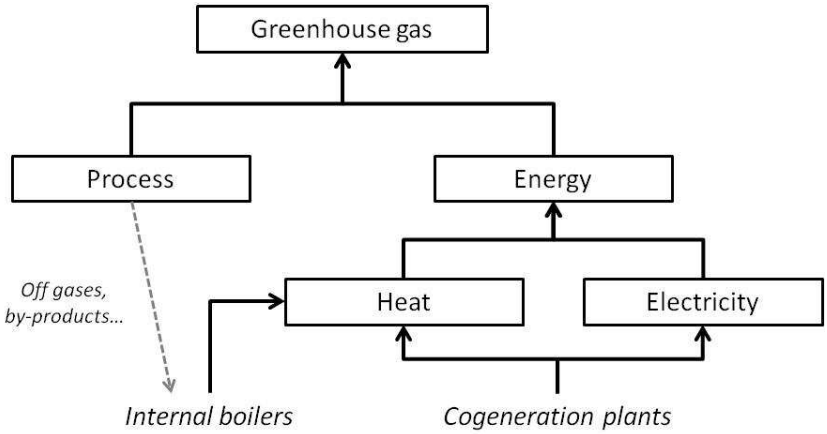

Figure 1.3-1 Sources of emissions of greenhouse gases

The methodology for the indirect calculation is discussed in more details in the next parts.

1.3.4. Direct calculation and market survey

The direct calculation is based on a detailed analysis of energy usages in several heat intensive industries. It is complemented by a market survey which was carried out in the form of confidential interviews. Surveyed organisations were European professional associations and leading market players in the following sectors:

- Cogeneration
- Biomass
- Pulp and paper
- Aluminium
- Steel
- Oil refining
- Chemistry
- Industrial gases
- Soda ash
- Lime
- Fertilisers
- Nuclear cogeneration

These interviews covered the detailed analysis of the industrial context, the operated production processes and energy systems, case studies where possible and the potential for nuclear cogeneration. Understanding more finely the processes by sectors made it possible to evaluate directly the energy consumption for a sector and the potential of nuclear polygeneration and nuclear pre-heating.

1.4. Temperatures of processes

A detailed review of the production processes used in the main heat intensive sectors was necessary to evaluate the process temperatures. Most sectors have process temperatures in the same range but several processes, in particular high temperature processes may have production phases operating at very different temperatures. The table below gives a summary of the situation:

Sectors with processes temperatures in the same range	Sectors with production processes at different temperatures
• Pulp an paper • Desalination • District heating • Soda ash • Chemical industry (cogeneration plants), including plastics, fertilisers • Refinery (except hydrogen production) • Industrial gases • Secondary aluminium • Glassmaking • Cement	• Primary aluminium (alumina hydration at 140-290°C and calcinations at 700-1000°C) • Ceramics (drying at 90-350°C and firing from 700°C to above 1000°C, depending on product) • Non-ferrous metals (process temperatures depending on the metal) • Iron and steelmaking (with processes operating on a significant temperature range)

Table 1.4-1 Sectors with homogeneous and heterogeneous process temperatures

The graph below summarises the process temperatures of the main heat intensive industries:

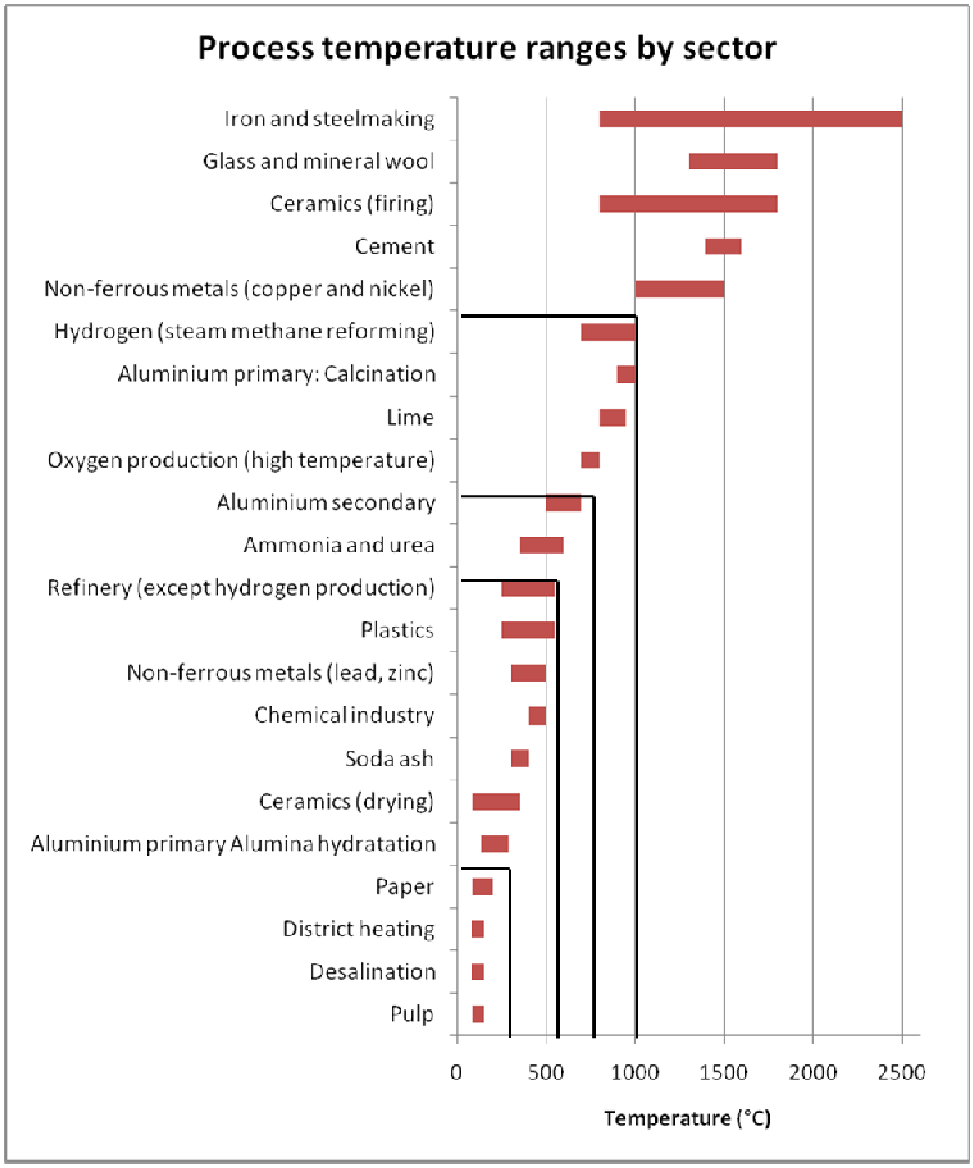

Figure 1.4-1 Process temperature ranges of the main heat intensive industries and temperature classes

For more detailed information, please refer to the detailed descriptions in the part related to each industrial sector.

Based on the detailed study by sector, all heat related to the line “combustion of fuel” was assumed to be in the temperature class 250-550°C, except pulp, paper, desalination, “electricity, gas, steam and how water supply” and “steam and hot water supply” assigned in the temperature class 100-250°C.

For the temperature classes in the main ETS table, the temperature classes were derived from the above graph. For the sectors having processes operating at different temperatures classes, a breakdown was made based on the results from the direct calculation as follows:

- Refineries: from the direct calculation, it was estimated that 94% of heat originated from normal refining processes in temperature class 250-550°C and 6% from hydrogen production from steam methane reforming or partial oxidation in temperature class 700-1 000°C.

- Primary aluminium: based on the direct calculation, 55% of heat was assigned to alumina hydration in temperature class 250-550°C and 45% for alumna calcinations in temperature class 700-1 000°C
- Ceramics: based on direct calculation, 40% for heat was assigned to ceramic raw material drying in temperature class 250-550°C and 60% for ceramic firing in temperature class >1 000°C.
- Non-ferrous metals: based on direct calculation (covering lead, zinc, nickel and copper only), 10% of heat was assigned to lead production in temperature class 250-550°C and 90% to temperature class > 1 000°C.

2. Indirect calculation from emissions declared within the EU Emissions Trading Scheme

2.1. Precisions on the EU Emissions Trading Scheme

2.1.1. EU ETS directive

The EU Emissions Trading Scheme (EU ETS) is a European Parliament and Council directive, dated from 1996, updated on the 13th October 2003 and amended several times in 2004, 2008 and 2009 (see consolidated version in (EC, 2003)).

The directive establishes a trading scheme for certain greenhouse gases emissions and certain sectors. Allowances are delivered to companies – currently for free, later after auctions. Companies falling under the scope of the directive can emit greenhouse gases under the amount of allowances freely. In case they emit less, they can sell the allowances on an organised market. If they emit more, they can either buy allowances from the market or pay a fixed tax.

The directive covers most of the energy intensive industries. Within a sector, only large individual emitters are considered. Small production sites are generally excluded in order to avoid putting an economic burden on small enterprises.

In consequence, the installations covered in EU ETS represent a good fraction of the total energy market and certainly the most concerned with energy and CO2 costs.

2.1.2. ETS implementation and reporting system

The implementation of the directive is relatively complex and involves the European Commission, Member States, operators and possibly other organisations as follows:

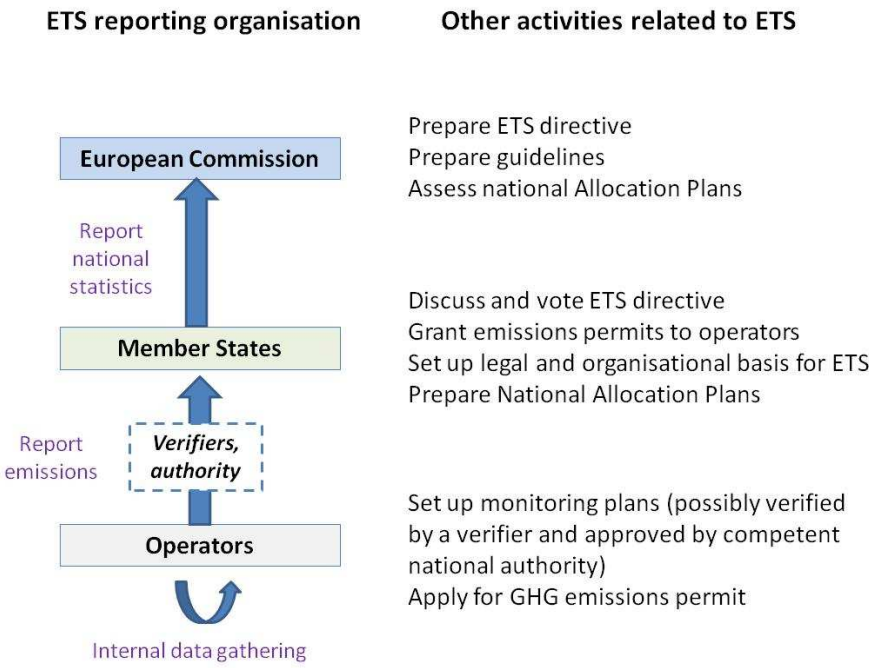

Figure 2.1-1 Emissions Trading Scheme reporting organisation

2.1.3. Scope of the ETS directive

The scope of the ETS directive is summarised in the table below:

Sectors out of ETS scope
Research demonstration facilities
Units burning exclusively biomass, even if fossil fuels are used for start-up and shutdown
Units with thermal input of less than 3 MW
Units of incineration of hazardous or municipal waste

Table 2.1-1 Sectors out of ETS scope

Sectors included in ETS Scope	Restrictions for sectors in scope
Combustion of fuels	Total rated thermal input of unit > 20 MWth
Refining of mineral oil	
Coke production	
Metal ore roasting or sintering	
Production of pig iron or steel (primary or secondary)	
Production or processing of ferrous metals	Total rated thermal input of unit > 20 MWth
Primary aluminium	
Secondary aluminium	Total rated thermal input of unit > 20 MWth
Non-ferrous metals production	Total rated thermal input of unit > 20 MWth
Cement	Kilns capacity > 500 t/d or other furnaces >50 t/d

Lime	Kiln capacity > 50 t/d
Glass	Production capacity > 20 t/d
Ceramic products	Production capacity > 75 t/d
Mineral wool	Production capacity > 20 t/d
Gypsum drying / calcination	Total rated thermal input of unit > 20 MWth
Pulp production	
Papermaking	Production capacity > 20 t/d
Carbon black	Total rated thermal input of unit > 20 MWth
Nitric acid	
Adipic acid	
Glyoxal and glyoxylic acid	
Ammonia	
Bulk organic chemicals by cracking, reforming partial or full oxidation	Production capacity > 100 t/d
Production of hydrogen and synthesis gas by reforming or partial oxidation	Production capacity > 25 t/d
Soda ash and sodium bicarbonate	
Capture, transport and geological storage of greenhouse gases from installations covered by ETS	

Table 2.1-2 Sectors covered by EU ETS and the applicable restrictions

The sectors and attributed greenhouse gases on the basis of the EC directive (2003), as reported by Member States (Ecofys 2009), is reported in the main table below:

Activities in Annex I of amended Directive	No, of open accounts	2007 Verified emissions (Mt CO2-eq)	Gas covered	
Combustion of fuel	5 971	1 415	CO2	
Refining of mineral oil	149	148	CO2	
Production of coke	26	9	CO2	
Metal ore	17	14	CO2	
Pig iron or steel	257	159	CO2	
Ferrous metals	42	2	CO2	
Primary aluminium	5	3	CO2	PFC
Secondary aluminium	6	0	CO2	
Non-ferrous metals	6	0	CO2	
Cement clinker	238	154	CO2	
Lime, dolomite and magnesite	283	28	CO2	
Glass	403	20	CO2	
Ceramics	1 082	14	CO2	
Mineral wool insulation materials	27	1	CO2	
Gypsum	17	0	CO2	
Pulp	83	4	CO2	
Paper and card board	638	23	CO2	
Carbon black	9	-	CO2	
Nitric acid	6	3	CO2	N2O
Adipic acid	-	-	CO2	N2O
Glyoxal and glyoxilic acid	-	-	CO2	N2O
Ammonia	10	2	CO2	
Bulk organic chemicals	63	12	CO2	
Hydrogen and synthesis gas	-	-	CO2	
Soda ash and sodium bicarbonate	1	0	CO2	
Other activity opted-in	498	3	CO2	
Unknown	1 497	135	CO2	
Total	**11 334**	**2 149**		

Table 2.1-3 Main table of emissions in EU27 in 2007 for the sectors covered by the EU ETS (Ecofys 2009)

Other activity opted-in refers to aviation. It must be noted that around 6% of the emissions could not be attributed to any sector.

2.1.4. Discussion of the line "combustion of fuels"

The "combustion of fuels" line is a major contributor to ETS. It refers to all installations burning fuels as a main activity with a total rated thermal input exceeding 20 MWth. Yet, except power plants (burning

fuels to generate electricity), the other installations are supplying industrial processes with heat and/or electricity and therefore relate to the specific consumption of their industrial customers.

This line therefore covers numerous industrial sectors, from agriculture and textile to automotive and machinery.

A study led by Ecofys for the European Commission identified several reporting inconsistencies and misinterpretations.

The main source of inconsistency relates to the ownership of installations. The situation of two simple cases is illustrated in the figures below:

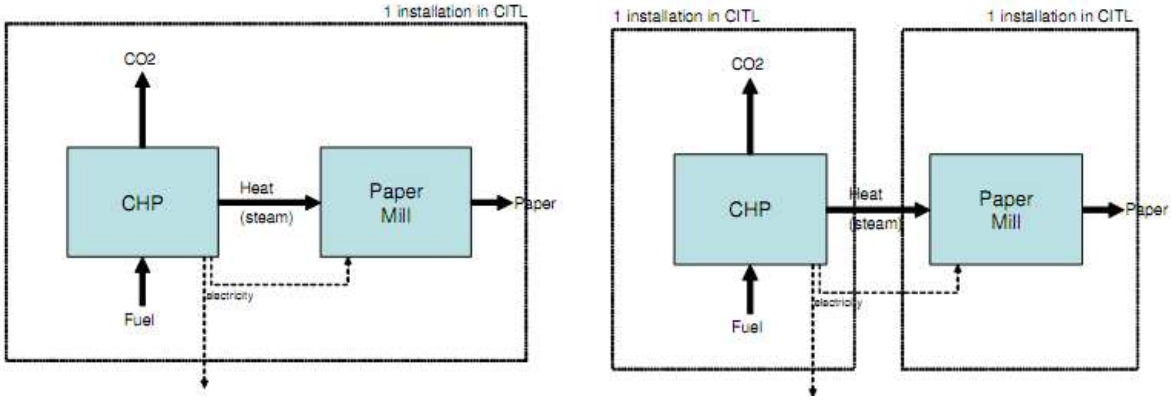

Figure 2.1-2 Paper mill with a CHP plant operated as part of the same EU ETS installation (left) and paper mill with an outsourced heat supply (right) (Source: Ecofys 2009)

In both cases, CO2 emissions will occur from the cogeneration plant. Yet, in the left-hand case, the emissions will be declared by the paper company in its operating sector, i.e. paper sector, whereas in the right-hand case, they will be declared by the utility in the combustion of fuel sector.

Real-case situations can be more complex and lead to further reporting difficulties:

- Cogeneration plants may supply heat to more than one industrial customer
- Industrial customers may operate internal energy systems (dedicated or embedded burners and boilers) which emit CO2
- in industrial complexes (e.g. chemical clusters), operators may recover energy and exchange steam between exothermic and endothermic processes so that a same CO2 emission relates to several processes operating possibly in very different industrial sectors.

The interpretation from Member States of the Directive is also important since they report aggregated statistics; Ecofys noted that Member States may have different interpretations, leading to statistical inconsistencies.

2.1.5. Distribution of the "combustion of fuel" line

The project led by Ecofys sent therefore a questionnaire to all 27 Member States in order to get a breakdown of the combustion of fuel line by industrial application. Ecofys did not carry out any quality check so the breakdown must be considered as indicative.

The complete breakdown of the line "Combustion of fuel" by industrial sector, as reported by Ecofys, is reported in annex 1 of this report (242 sectors).

The largest individual sector is the production, transmission, trade and distribution of electricity with 1 122 Mt CO2 eq out of 1 412 MtCO2eq. This sector does not fall under the scope of this study.

38 sectors are relevant to the study (see scope of the study). They emit 235 MtCO2eq out of 1 412 MtCO2eq. Out of the 38 sectors inside the scope of the study, only 12 sectors emit significant amount of GHG (i.e. more than 1MtCO2eq), for a total of 231 MtCO2eq.

The different sectors families with the number of sites and GHG emissions are reported in the table below:

Sector	Nb of sites	tCO2eq
Desalination	5	169 282
Paper	139	4 090 368
Pulp	1	137 063
Coke	3	658 870
Refinery	22	787 352
Basic chemicals	5	940 379
Industrial gases	3	484 098
Inorganic chemicals	36	4 798 232
Organic chemicals	81	10 769 424
Fertilizers	27	3 682 877
Plastics	41	2 356 543
Glass	4	75 622
Ceramics	8	46 329
Cement	3	12 302
Non-metallic minerals	35	2 995 482
Iron and steel	42	18 716 493
Aluminium	9	313 841
Non-ferrous metals	5	1 496 270
Electricity, gas, steam and hot water supply	145	53 321 630
Steam and hot water supply	2192	129 359 714

Table 2.1-4 Breakdown by sector of the emissions in the line "Combustion of fuels" as reported in Ecofys (2009)

“Electricity, gas, steam and hot water supply” and “Steam and hot water supply” account for 182 MtCO2eq. It must be noted that the line “Electricity, gas, steam and hot water supply” corresponds to unattributed emissions from the electricity and heat sector.

These two lines are again subject to discussion:

- This may encompass both large power plants cogenerating marginally heat, industrial cogeneration power plants and district heating plants
- due to the ownership structure of industrial cogeneration power plants, these lines may only refer to the cogeneration plants externalised to an operator owner which are declared by the plant operator ; other plants may be declared within the related industrial sector of the facility.

2.1.6. Interpretation of the ETS reporting lines

In a first approach, the "combustion of fuels" may be seen as a "plug-in" market where industrial cogeneration plants are declared separately (inferring therefore that their operation is physically separated from the process). On the other side, the main ETS table can be assumed as an "extended" market where emissions are attributed to the process and its internal boilers and burners.

This will be double checked by the direct calculation.

The graph below summarises the imbrications of the different tables:

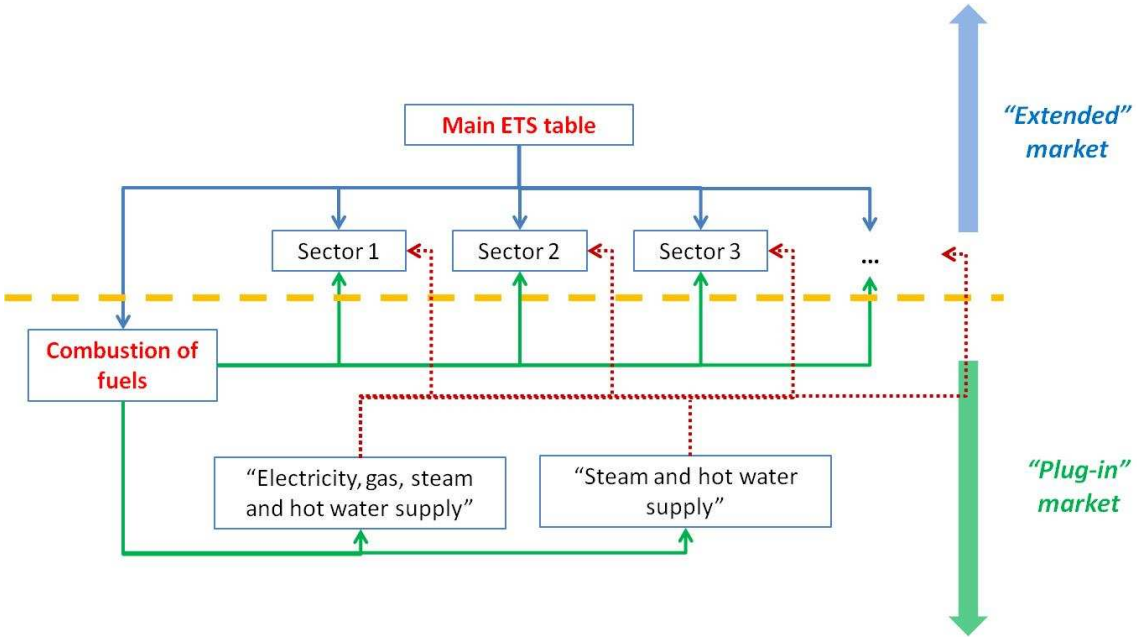

Figure 2.1-3 Imbrications of the tables for data reporting in the EU ETS

2.2. Energy and carbon content and CO2 emissions from the different fossil fuels

The key parameter is the emissions of tCO2 by energy carrier (oil, gas, coal, wood) from their combustion. Knowing this parameter and the sector emissions, we can obtain an amount of energy.

Since one atom of carbon (atomic mass = 12) combines with two oxygen atoms (atomic mass = 16) to produce CO2 (atomic mass = 44), any ton of carbon will emit 3,667 ton CO2. For instance, one ton of pure natural gas (CH4, atomic mass of H = 1) emits 2,75 tCO2.

The carbon content is reported below (source: ORNL 2010, figures in italic are calculated):

Fuel	Carbon content tC / TJ	CO2 emissions tCO2/TJ	C / energy content
Coal	25,4	*93,1*	
Oil	19,9	*73,0*	
Gas	14,4	*52,8*	
Wood	*27,8*	*101,9*	50% / 18GJ/t

Table 2.2-1 Carbon content and CO2 content by fossil fuel (Source: ORNL 2010)

To illustrate these data, if a process has emitted 1MtCO2 from the combustion of coal, the energy produced was:

$$1\ MtCO2 / 93.1\ tCO2.TJ^{-1} = 10\ 741\ TJ = 2\ 984\ GWh$$

This corresponds to one 373 MWth coal fired plant operating 8 000 hours a year.

Some processes emit CO2 from their production reaction. Taking the example of lime, the production reaction is:

$$CaCO3 + heat \rightarrow CaO + CO2\ (\Delta H = 178\ kJ.mole^{-1}, T > 840°C)$$

Thus, the production of one ton CaO (atomic mass of Ca = 56) has emitted 0,786 tCO2.

Finally, it is important to note that the ETS Directive uses the CO2 equivalent unit. Indeed, all greenhouse gases do not have the same greenhouse “power”: if the greenhouse power of CO2 is 1, then 1t CH4 is equivalent to 21 tCO2eq, and 1t N2O is equivalent to 310 tCO2eq.

2.3. Summary and sources of energy by ETS sector

The next important parameter is to attribute a main primary fuel by sector. Indeed, if CO2 is emitted by gas for instance, it is possible to evaluate the market by dividing the sector CO2 emissions by the tCO2/TJ factor of the main fuel.

It must be noted that many sectors use more than one fuel so assigning a primary fuel to a sector does not represent absolutely the reality . This approach gives though a first estimate of the market.

The table below gives a short summary of each sector and the assumptions made. For each sector, the assumption regarding the main primary fuel is reported in the second column. The third column lists other fuels that are used in the sector. The fourth column reports on the heat production schemes that are usually observed in the sector, i.e. if heat production is:

- Externalised: heat plant operated in a separated plant isolated from the process
- Internal: heat is produced by the process itself or by burning energetic process by-products
- Cogeneration: the production of heat is coupled with electricity generation

For more details on each industrial sector, please refer to the part related to direct calculations which contains more detailed descriptions by sector.

Table 2.3-1 Sector summaries and assumptions of primary fuel and heat production type by sector

Sector	Primary fuel attributed	Usable fuels	General heat production schemes	Sector summary
Paper	Wood	Wood, gas	Externalised	Paper covers a wide variety of products with significantly different production processes, depending on the grade and envisaged application of paper and the recycling level of scrap paper. The sector is very electro-intensive. Most emissions come from heat/steam for de-inking scrap paper, drying the paper and fired-heaters for coating processes. Biomass accounts for 52% of energy on-site production and gas 38% (CEPI 2009)
Pulp	Wood	Wood, gas	Mostly internal	There are two main pulp production process: - mechanical pulp (rotating stone, 1/3 of the EU production) ; mechanical pulp uses only electricity but the thermo-mechanical and chemical thermo-mechanical processes use some steam to soften the wood and clean the rotating stone - chemical pulp (wood is digested in a cooking chemical liquor to separate lignin from fibres, 2/3 of the EU production); the Kraft process is one chemical pulp process and requires the production of lime, which emits CO2. Best available techniques recover the heat from both processes. Pulp making could therefore be a net heat exporter. 25% of the GHG emissions can be attributed to electricity generation (ECOFYS 2009b)

				Biomass accounts for 52% of energy on-site production and gas 38% (CEPI 2009)
Refinery	Oil	Oil, gas	Mostly internal although cogeneration is applied	A refinery encompasses the following processes: - atmospheric distillation of crude oil, - upgrading and retreating capacities to transform the distilled products into consuming standards oil products, - production of primary petrochemicals (like benzene and ethylene), - production of secondary petrochemicals (PVC, polystyrene, nylon...). The first two bullets are attributed to the refinery sector per se, whereas the two last bullets are attributed to the organic chemistry sector. Refineries burn mostly by-products like heavy fuel oil or off-gases inside boilers. They cover the vast majority of their energy need (more than 90%) internally (Ecofys 2009j).
Basic organic and inorganic chemicals	Gas	Gas, oil	Cogeneration applied in several complexes but significant amounts of heat are produced internally	The chemical industry sector stands apart from the other sectors. This sector runs an outstanding number of processes usually in large integrated chemical complexes. Each complex operates a unique mix of processes, optimising the heat exchanges between endothermic and exothermic processes. The main products are (Ecofys 2009f, BREF 2003) - nitrogenous compounds (especially nitric acid and ammonia) which are produced out of nitrogen. These reactions are generally exothermic. Nitric acid and adipic acid production releases N2O (1tN2O = 310 tCO2, 28,4% of the chemical industry emissions) and ammonia releases CO2 as a result of the on-site production of hydrogen (steam reforming or partial oxidation, both endothermic). Both emission gases can be re-used as feedstock in other reaction. N20 can also be decomposed into N2 and O2 either by catalytic cracking (exothermic) or thermal cracking (endothermic, thus emitting CO2). - Hydrocarbon made of C, H and O (mainly ethylene, propylene, vinyl). The chemistry of these molecules consist of breaking heavy molecules in crackers and recomposing into higher value molecules (e.g. aromatics) out of refinery by-products. Both types of processes are strongly endothermic and consume large amounts of energy. Most chemical complexes use gas as a feedstock and as a fuel. It must also be noted that even if a process is a net energy exporter, it may still consume energy (e.g. export of low-pressure steam and import of high-pressure steam)
Industrial gases	Gas		Externalised	Industrial gases include H2, O2, CO, CO2, syngas (CO + H2). O2 is mostly produced by cryogenic distillation consuming electricity. The main emitters – and very important industrial gases – are H2 and syngas. The processes are steam reforming (90%) and partial oxidation (10%). Most hydrogen is used in refineries.

Fertilisers	Gas		Cogeneration applied in several complexes but significant amounts of heat are produced internally	Fertilisers are chemicals mostly based on nitrogen, phosphorous and potassium compounds. 97%% of nitrogen fertilisers are derived from ammonia and 70% of phosphate fertilisers come from phosphoric acid (BREF 2007b). Fertilisers are a part of the chemical industry and share with it the complexity of many different chemical reactions. A same production process runs usually exothermic reactions (mainly when using ammonia) and endothermic reactions. The key products are: - NPK fertilisers (N for nitrogen, P for phosphorous and K for potassium). The production route is energy intensive. The different acids containing NPK are mixed, digested and evaporated to obtain a certain fertiliser composition. The main emissions are NOx (excluded from ETS) and CO2 as a result of fuel combustion, mainly for heat. - Ammonium nitrate (AN) and Calcium ammonium nitrate (CAN, made from AN): AN neutralisation is strongly exothermic and the produced steam is used for the rest of the process. The process does not emit CO2 except for the combustion of fuel for electricity. - Urea and UAN: urea is a key raw material (like ammonia): its production consumes a lot of energy in the form of heat and steam (as heat carrier and mechanical medium). The process consumes CO2 and steam. The main fuel is gas (used also as feedstock).
Plastics	Gas	Gas, oil	Cogeneration applied in several complexes but significant amounts of heat are produced internally	This sector encompasses three main types of processes: polymerisation, polycondensation and polyaddition. Raw materials are basic monomers from the petrochemical industry. The number of produced polymers is very large since they derive from many possible combinations: polymer may be produced from one monomer or more than one monomer, then arranged randomly, by blocks or alternating, or even from monomers and inorganic compounds. Polymerisation is usually exothermic, although it needs an energy input to activate the monomers and initiate the polymerisation reaction. Energy may also be required to purify raw materials or separate products. Plastics producers are usually located in chemical complexes, using gas as main fuel (BREF 2007c).
Glass and mineral wool	Gas	Gas, oil, electricity	Mostly internal (except electric heating)	The glass products comprise container glass (60% of total EU production in 1996), flat glass (22%) and specialty glasses (continuous filament, 1.8%, domestic glass 3,6%, special glass 5,8% and mineral wool 6.8%) (BREF2001c). The production techniques are: - Regenerative and recuperative furnaces (heat recovery of waste gas for preheating air prior to combustion) are the most common for container and flat glasses production. - Oxy-fuel furnaces (replacement of air by oxygen) - Electric furnaces (through resistive heating) which are mainly

				used in small furnaces, particularly for special glasses. - Combined fossil fuel and electric melting (as a heating boost). Glass making is very energy intensive. The energy for melting glass accounts for 75% of the total energy requirements. Gas and heavy oil are the most common fuels. CO2 emissions are mainly due to fuel combustion (85%, Ecofys 2009g)
Ceramics	Gas	All	Mostly internal	Ceramics span many products: wall and floor tiles, bricks, roof tiles, refractory products, vitrified clay pipes, sanitaryware, expanded clay aggregates. Each product has a specific process. For most of them, the general production process can be summarised as follows: - mixing and casting of raw materials, drying to evaporate water, firing with an exact temperature gradient CO2 occurs mainly by the combustion of fuels for heating. All types of fuels may be used but natural gas is largely predominant (BREF 2007)
Desalination	Gas	All	Externalised	Three main techniques exist for desalinating sea water (FRS 2008, Miller 2003): - Thermal distillation (15Mm3/day worldwide in 2003) using heat - Membrane technologies (20Mm3/day) using electricity to compress water - Electrolysis of water, as a marginal production route, using electricity. Desalination plants may be co-located with power plants. All fuels are therefore used but gas may be assumed to be the main primary fuel.
Cement	Coal	Coal, gas, oil, waste	Internal	Cement is produced mainly from limestone, clay, iron ore and bauxite. The most energy-intensive phase is the production of clinker. The limestone (CaCO3) is thermally transformed into lime (CaO) which releases CO2. There are many types of kilns to produce clinker, with a wide scope of energy efficiencies. The CO2 emissions are usually distributed as follows: - Calcination 55% (these emissions are due to the production of lime and are unavoidable) - 35% of thermal energy (22% for calcination and 13% from heat losses) - 5% from electricity and 5% from transportation (Ecofys 2009e) Many fuels may be used but coal products are the largest source of energy (81%) with waste, fuel oil, gas being alternatives (BREF 2001b).
Lime	Gas	All	Internal	Lime (CaO or Ca(OH)2) is produced from limestone (CaCO3) through

				the process CaCO3 → CaO+CO2. The lime industry is energy intensive. CO2 is emitted from the production process (65% on average) and the combustion of fuels (35%) (Ecofys. 2009h). Gas is the main used fuel (48%) followed by coal (36%), oil (15%) and other fuels (BREF 2001b)
Non-metallic minerals and inorganic chemicals	Gas	Gas, oil, coal, electricity	Depending on sector	This includes a very large scope of products. The main ones are: - Chlorine and caustic soda may be produced simultaneously by the electrolysis of salt in water; hydrogen is a by-product. 11Mt were produced in EU in 2001. Electricity is the main energy requirement (BREF2001d). - Soda ash (15Mt in EU in 2004). The production process is mainly the Solvay process consuming salt and limestone. Low-pressure steam is an important energy input as mechanical medium and heat carrier. The Solvay process has the particularity of consuming CO2, although excess CO2 from the lime production is discharged into the atmosphere. The main fuel used is coal (ESAPA 2004). - Titanium dioxide (1,5 Mt in EU in 2007). Both the chloride and sulphate production processes consume gas, steam and electricity. The first emits CO2 during the chlorination, which consumes coke (as fuel and feedstock). - Carbon black (1,7Mt in EU in 2007): the main manufacturing process is the Furnace Black process (95% of EU capacity) which consumes oil, coal and gas, emitting CO2 from fuel combustion. - Synthetic silica (620kt in EU in 2007): this includes pyrogenic silica (consuming H2, requiring heat for gas preheating and distillation and emitting CO2 only from the process), precipitated silica and silica gel (requiring important heat for melting and drying; usually from gas). - Inorganic phosphates (3Mt in EU in 2007); uses steam, electricity and natural gas and CO2 emissions are arising from the fuel combustion during the calcinations phase. - Gypsum: the production process is solely thermal (drying, and calcinating). The main fuel is natural gas and CO2 is solely emitted from fuel combustion (Ecofys 2009j).
Coke	Coal	Coal	Internal	Coke is produced after drying and calcinating coal in an oxidation free atmosphere (BREF 201e). Emissions are mainly coming from coal processing.
Iron and steel	Coal	Coal, electricity	Mostly internal	Two production routes exist: - The Blast Furnace route (BF, 2/3 of the EU production) iron ore is sintered, introduced in a blast furnace with coke to produce cast iron; the hot metal is transported to the BOF where cast iron is converted into crude steel; this route use mainly coke as a fuel, carbon raw material and reducing agent - the Electric Arc Furnace (EAF, 1/3 of the EU production) uses solely electricity to smelt metal scrap or direct reduced iron; coke is used to increase the carbon content.

				BF will emit CO2 from coke and from the conversion process (since C in cast iron is removed by blowing O2, producing CO2) whereas EAF emit CO2 mainly from fuel and carbon oxidation of electrodes (BREF 2001e). 95% of an integrated works' energy input comes from solid fuels, primarily coal; approximately three quarters of the carbon content is consumed in the reduction reaction of iron (ESTEP 2005). Downstream processes like foundry casting, hot and cold rolling, surface treatments emit only 12% of the whole chain (Ecofys 2009c)
Ferrous metals	Gas	Gas, oil	Mostly internal	This sector processes mainly steel though different techniques: - hot rolling (128Mt in EU in 1996) by compressing repeatedly the hot metal (> 1000°C) - cold rolling (40Mt in EU in 1996) compressions without heating the metal - Wire drawing (7Mt in EU in 1996) - Hot dip coating (15Mt in EU in 1997) for galvanising or aluminising - Batch galvanising (15Mt in EU in 1997) All techniques burn fuel, mainly gas and oil, and consume electricity. CO2 emissions are mainly due to fuel combustion.
Aluminium	Gas	Electricity gas	Mostly internal	There are two main kinds of product: - primary aluminium is the electrolysis of alumina (produced from bauxite through the Bayer process) in a fluorinated cryolite; this is an electro-intensive process. CO2 is emitted from the carbon anode oxidation and PFC from the cryolite. - secondary aluminium is produced from primary and scrap aluminium (cans, foils, scrap, automotive parts...); many processes exist depending on the grade and the raw material. Most installations use natural gas as fuel but electricity based installations consume much less fossil fuel (Ecofys 2009d, BREF 2001). CO2 is emitted mainly from fuel combustion.
Non-ferrous metals	Gas	Coal, gas, electricity	Mostly internal	This sector covers many products (2007 EU27 production): copper (2,3Mt/y), zinc (2,1Mt/y), lead (1,6 Mt/y), nickel (0,1 Mt/y), tin, tungsten, cadmium, silver, mercury, antinomy, magnesium, precious metals (less than 10 kt/y) (Ecofys 2009i). - Primary and secondary copper require significant amount of energy, in the form of heat (for roasting, smelting, drying, conversion) and especially electricity (for electrolysis and refining). CO2 is emitted from the fuel combustion. - The main zinc production route is Roasting – Leaching – Electrolysis (>95% of production). Roasting is strongly exothermic (although heating is required at start-up). Foundries may be heated with either gas or electricity. - Lead production derives at 60% from recycling. CO2 emissions occur from smelting and reducing with gas and coal

Gas was assumed to be the main fuel for “electricity, gas, steam and hot water supply” and “steam and hot water supply”.

2.4. Synthesis of input parameters

	Plug-in market			Extended market		
Sector	**Primary fuel attributed**	**Assumed CO2 from heat**	**Temperature class**	**Primary fuel attributed**	**Assumed CO2 from heat**	**Temperature class**
Paper	Gas	100%	100-250	Wood	100%	100-250
Pulp	Gas	100%	100-250	Wood	75%	100-250
Iron and steel (including coke)	Coal	100%	250-550	Coal	100%	1000-
Refinery	Gas	100%	250-550	Oil	100%	250-550 (94%) 700-1000 (6%)
Chemical industry	Gas	100%	250-550	Gas	100%	250-550
Industrial gases	Gas	0%	250-550			700-1000
Glass	Gas	100%	250-550	Gas	85%	1000-
Ceramics	Gas	100%	250-550	Gas	100%	250-550 (40%) 1000- (60%)
Desalination	Gas	100%	100-250			100-250
Cement	Coal	100%	250-550	Coal	60%	1000-
Non-metallic minerals	Gas	100%	250-550			250-550 (10%) 1000- (90%)
Primary aluminium	Gas	100%	250-550	Coal	100%	250-550 (55%) 700-1000 (45%)
Secondary aluminium			250-550	Gas	100%	550-700
Non-ferrous metals	Gas	100%	250-550	Gas	80%	250-550 (10%) 1000- (90%)
Metal ore			250-550	Coal	100%	250-550
Ferrous metals			250-550	Gas	100%	700-1000
Lime, dolomite and magnesite			250-550	Gas	35%	700-1000
Mineral wool insulation materials			250-550	Gas	35%	1000-
Gypsum			250-550	Gas	100%	1000-
Soda ash and sodium bicarbonate			250-550	Coal	100%	250-550
Electricity, gas, steam and hot water supply	Gas	50%	100-250			
Steam and hot water supply	Coal	100%	100-250			

Table 2.4-1 Synthesis of input parameters

2.5. Market evaluation via the indirect calculation

Based on the assumptions listed in the previous sections, the European heat market was evaluated as follows:

	Plug-in	Extended market	TOTAL
Indirect calculation	755 730	1 771 021	2 526 751
Equivalent thermal power (GWth)	87	202	289
Equivalent number of 500 MWth reactors	173	404	577
Share of total	30%	70%	100%

Table 2.5-1 Market evaluation following the indirect calculation

The estimated heat market reaches a significant total of 2 529 298 GWh, which is to be compared with the 3 374 182 GWh of electricity production in EU27 (Eurostat 2009).

30% of the heat market is externalised (plug-in market) and 70% is embedded within industrial facilities.

The distribution of the heat market by temperature class, market and sector is as follows:

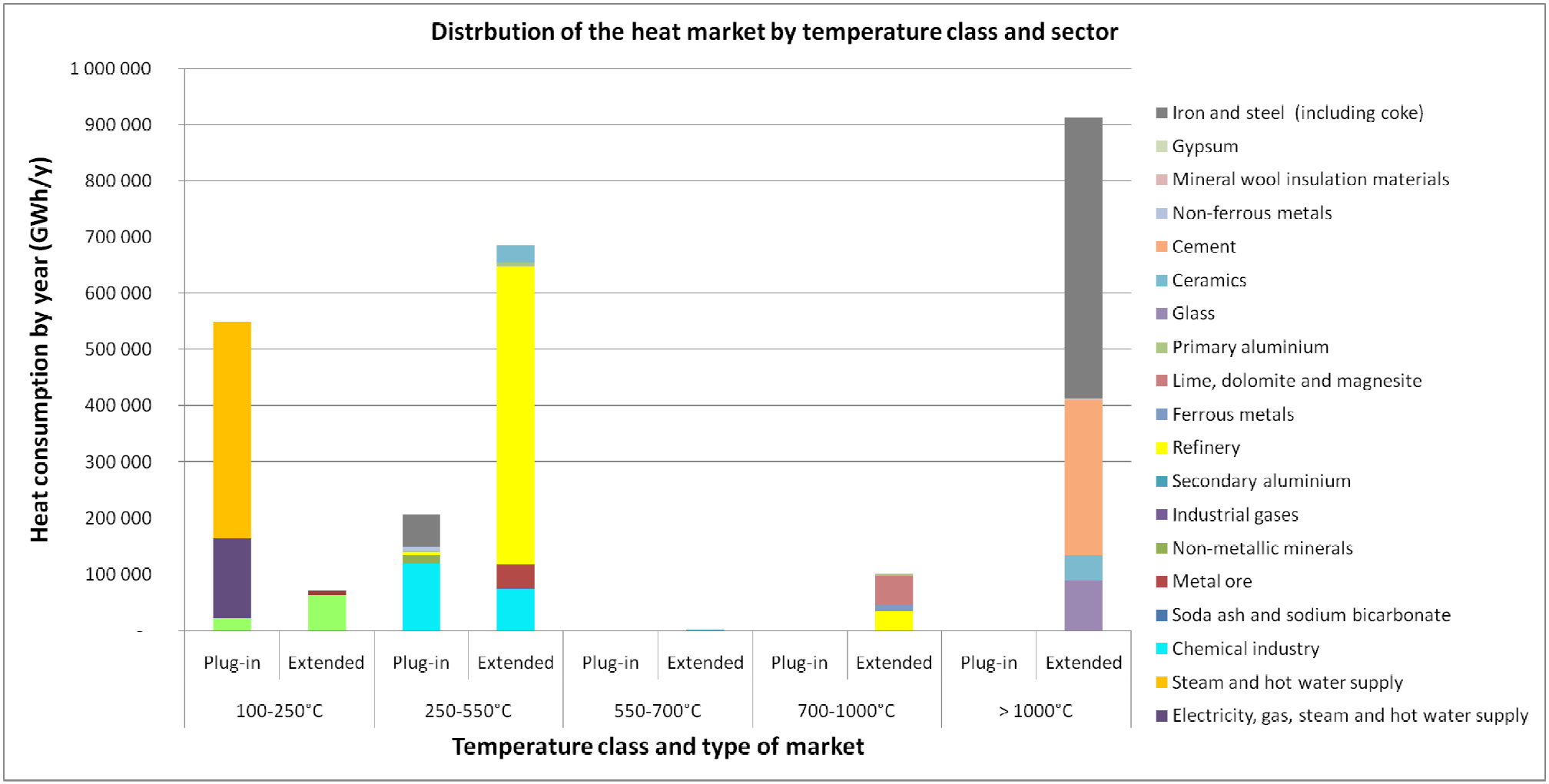

Figure 2.5-1 Distribution of heat market by temperature and sector

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The following remarks can be drawn:

- The heat market is mainly distributed in temperatures below 550°C and above 1000°C; very few processes were found to be operated between 550 and 700°C and industrial gases and lime are the most important sectors in the class 700-1000°C
- The plug-in sectors are restricted to temperature classes below 550°C. The most significant sectors are steam and hot water supply and electricity, gas, steam and hot water supply (assumed to be district heating) and the chemical industry; the iron and steel plug-in market is taken by calorific off-gases (see section dedicated to steel).
- Oil refining, iron and steel and cement are the largest industrial sectors in the extended market; they consume heat mostly via embedded boilers or burners.

The average thermal capacity per site by sector and market is an important input for the sizing of nuclear cogeneration plants and is reported below:

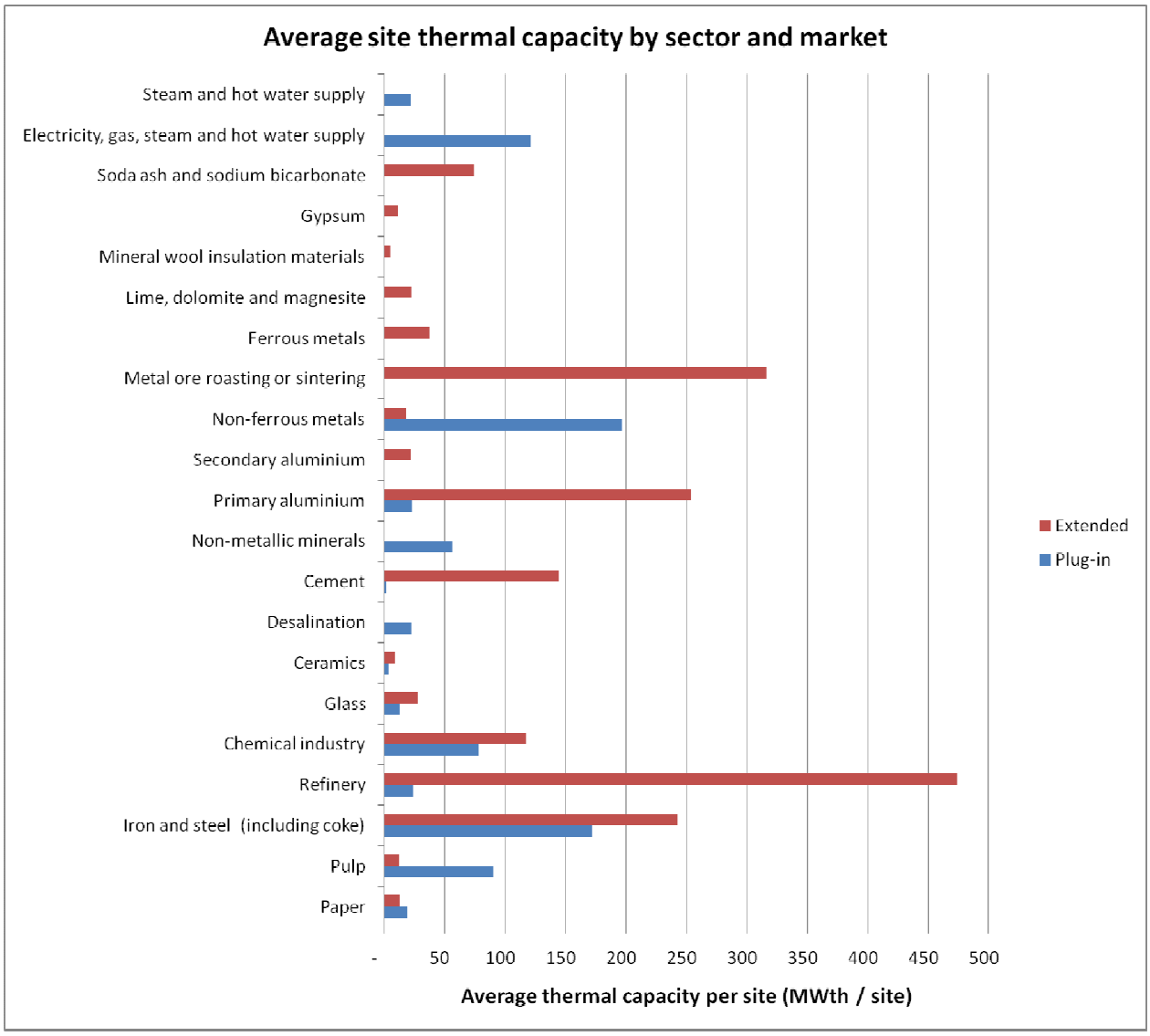


Figure 2.5-2 Average installed site thermal capacity by sector and market

The average installed site thermal capacities can be calculated by dividing the total capacity by the number of declared installations. The average thermal capacity per site in the plug-in market is 34 MWth and in the extended market 66 MWth.

It must be noted that this calculation is only indicative. An average value may relate to very different situations and the statistical basis cannot be considered as representative in several sectors, in particular:

- For the plug-in market: pulp, industrial gases, glass, ceramics, desalination, cement, aluminium, non-ferrous metals have less than 10 declaring installations and are not representative.
- For the extended market: aluminium, non-ferrous metals and soda ash have less than 10 declaring installations and are not representative

The average site thermal capacity is usually higher in the extended than in the plug-in market. This is in accordance with the fact that the extended market is larger than the plug-in one, i.e. the majority of the heat and the related thermal capacities are embedded directly into production processes rather than externalised.

No industrial sector has an average site capacity above 500 MW. The sectors with the highest average thermal capacity per site are oil refining, chemical industry, iron and steel, cement.

The number of sites where a single cogeneration plant would have a higher capacity than 500 MW could not be estimated precisely. It could be expected that around 10 to 20 sites (e.g. large complex refineries, large chemical clusters, large integrated paper mills) could possibly consume steam from a cogeneration plant with a thermal capacity higher than 500 MWth.

3. Detailed study of several key industrial sectors

Several industrial sectors are analysed in more details below. They span both key plug-in energy-intensive sectors, which may be the early adopters of nuclear high-temperature cogeneration, as well as sectors of interest for nuclear polygeneration and nuclear pre-heating.

3.1. Nuclear cogeneration today, desalination and district heating

Summary

Low temperature nuclear cogeneration is a proven technology. It was already demonstrated at industrial scale for district heating, desalination and to a lesser extent process heat, with temperatures up to 200°C. District heating and desalination are low-temperature processes which may be interesting back-end processes from high temperature reactors. Both processes represent large heat market in Europe. District heating is yet a seasonal market but high temperature reactors may offer the advantage of supplying more numerous and distant customers. The economic rationale of district heating must yet be assessed. Nuclear cogeneration for industry was demonstrated at a large scale in Canada with a complete industrial cluster being supplied with nuclear steam, and to a lesser extent in Germany and Switzerland for one specific industrial customer.

This part uses most information from reports of the International Atomic Energy Agency, in particular IAEA (2000, 2002, 2005, 2007 and 2007b).

3.1.1. Nuclear cogeneration today

Nuclear energy supplies around 15% of the world's electricity and around one third of the European electricity. The reactors in operation in August 2007 were 359 light water reactors, 43 heavy water reactors, 16 light water cooled graphite moderated reactors, 2 liquid metal fast reactors and 18 gas cooled reactors.

Out of these 438 reactors, 69 have been supplying heat for non-electric applications, principally in Russia (27 reactors), Ukraine (13 reactors), Japan (9) and India (6). The complete table can be found in annex VII. These non-electric applications include district heating mainly (6 204 GWh in 2006), process heat (978 GWh in 2006) and desalination (2 bnm3 in 2006 in 2006 in Japan).

Russia has accumulated the largest experience in non-electric nuclear applications worldwide with almost 900 reactors-years of experience (IAEA 2007):

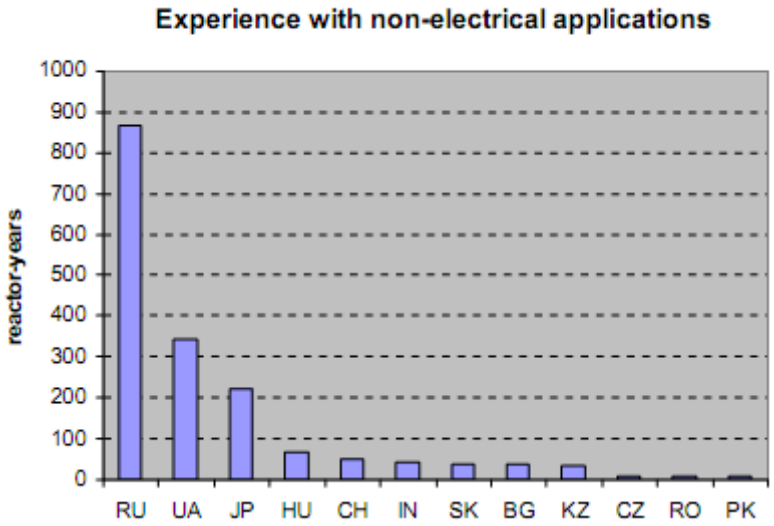


Figure 3.1-1 Experience with nonelectrical applications by country (reactors years, Source: IAEA 2007)

Europe has 13 reactors which provide heat for district heating and process heat as it is reported below (IAEA 2007, the complete table can be found in annex VII):

Country	Reactor	District heating (GWh in 2006)	Process heat (GWh in 2006)	Total (GWh in 2006)	Equivalent thermal power (MWth, 8 000 h/y)
Bulgaria	Kozloduy-5	142	N/A	142	18
	Kozloduy-6	21	N/A	21	3
Czech Republic	Temelin-1	49	N/A	49	6
	Temelin-2	6	N/A	6	1
Hungary	PAKS-2	3	N/A	3	0
	PAKS-3	30	N/A	30	4
	PAKS-4	249	N/A	249	31
Romania	Cernavoda-1	32	N/A	32	4
Slovakia	Bohunice-3	261	-	261	33
	Bohunice-4	225	-	225	28
Switzerland	Beznau-1	0	N/A	0	0
	Beznau-2	0	N/A	0	0
	Goesgen	N/A	73	73	9
TOTAL		**1 016**	**73**	**1 089**	**10**

Table 3.1-1 Energy production by nuclear cogeneration in Europe by application (Source: IAEA 2007)

The average site equivalent thermal capacity remains low (maximum 33 MWth for one reactor, 61MWth for one site in Slovak Bohunice). The largest thermal capacity can be found in Russian nuclear plant in Kursk with a total of 138 MWth. It must be noted that peak loads can be more than the double of these annual average thermal capacities for district heating since it operates only in the coldest part of the year (see next paragraph).

High temperature reactors

Russia, China, Japan South Korea and the United States are particularly active in developing high temperature reactors with the American NGNP programme, the Chinese HTGR demonstration plant (10MWth, 700-950°C output), Japanese HTTR (30 MWth, 950°C output) and Russian VGM design (200 MWth, 900°C output).

3.1.2. District heating

Applications

District heating covers the heat generation or cogeneration, its transport and distribution via a set of steam networks and the return of cold water to the heat plants.

The main applications are summarised in the table below (ECOHEATCOOL 2006):

Applications	Main parameters	Main statistics
Residential heating	• Number of dwellings, • Total residential floor area • Residential floor area per capita • GDP per capita • Residential central heating development • Climate conditions • Hot water consumption	• Number of dwellings (EU27 + accessing countries + EFTA3): 240 millions • Total residential floor area: 21 bn m2 • Residential floor per capita: 37 m2 • Hot water consumption: 50L/d/cap
Public and commercial buildings	• Development of the services • Composition of the services sector (hotels, restaurants, health, education, research, offices, commercial centers, warehouses, etc.) • Service sector useful floor per capita • Climate conditions	• Total service sector area: 7 bnm2 • Average service sector space per capita: 12,2 m2 • European composition of service sector: 12% hotels and restaurants, 13% health, 18% education and research, 26% offices and public administration, 22% commercial centres, 10% other

Table 3.1-2 Main parameters and statistics for district heating for residential customers and public and commercial buildings (Source: ECOHEATCOOL 2006)

Mapping

A potential market for district heating appears in climatic zones with relatively long and cold winters.

District heating is therefore differently spread in Europe. Southern European countries have lower heating requirements and have a low penetration of district heating. On the contrary, Northern and Central European countries, in particular Scandinavian countries, use district heating widely.

District heating accounts for 11% of total energy consumption in Central Europe and Ukraine and over 30% in Russia and Belarus (IAEA 2007); district heating accounts for more than 40% of the heat market in Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Czech Republic and Slovakia.

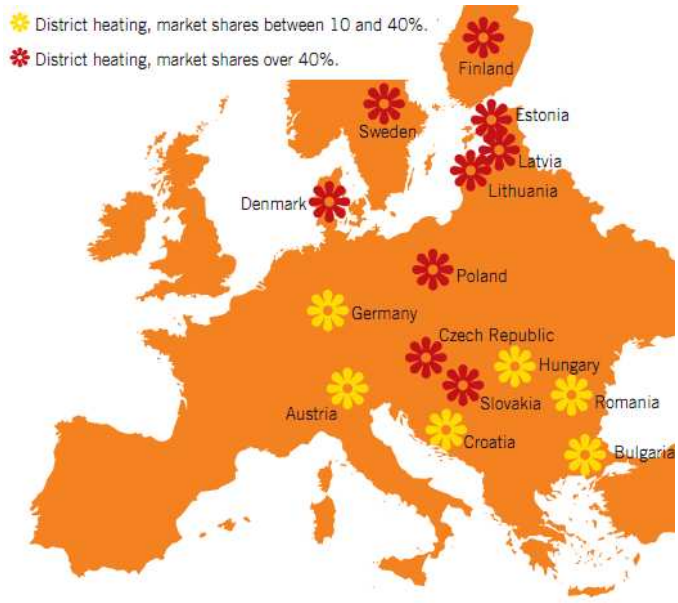


Figure 3.1-2 District heating significant market shares in European countries (Source: EHP 2010)

Industry characteristics

District heating networks generally have installed thermal capacities of 600 to 1 200 MWth in large cities and 10 to 50 MWth in smaller ones (IAEA 2007). This capacity is distributed between several plants which may back-up each other.

Due to the capital intensity of building heat networks, district heating may compete economically with individual heating modes in densely populated regions.

Water is usually transported at temperatures in the range 80-150°C and heating plants are located close to the customers, typically 10-15 km.

It must be noted that the annual load factor is low, below 50%, because district heating is required only during cold periods. Yet, the required availability of the system must be 100% when it operates since no shortage can be accepted. Heating plants are therefore redundantly built to back-up each other.

Coal and gas are the dominant fuels for district heating; other fuels include biomass, waste and waste heat from industrial processes.

Nuclear power plants have been supplying limited amounts of district heating in Bulgaria, Hungary, Romania, Slovakia, Sweden and Switzerland, as well as Russia and Ukraine. Steam is usually taken from waste heat of the electrical turbine.

As illustrative examples, the Swiss Beznau power plant (2 x 360 MWe PWR) has been supplying heat to 2 100 private consumers with peak loads of about 80 MWth. In Russia several nuclear power plants are

supplying typically 50 000 habitants each, living 3 to 15 km around the sites. The heat output capacities range from 50 to 230 MWth.

Another example is Sweden. Half of all houses and homes are supplied with district heating. Most cities with more than 10 000 habitants have a district heading network. The fuel mix is 45% biomass, 15% fossil fuels, 15% electricity, 10% waste, 10% residual heat and 5% miscellaneous (IAEA 2007).

The district heating hot water system is operated with a temperature of 70 to 110°C depending on the time of the year and a return temperature 40-50°C lower. For European nuclear power plants supplying district heating, the temperatures were around 130-150°C for the feed hot water and 60-70°C for the return cold water.

Experience in Romania's Cernavoda nuclear power plant

Cernavoda NPP consists of two pressurised heavy water CANDU reactors. It has been supplying 60% of the district heating to the city of Cernavoda since 1997. Steam is extracted at high pressure with a maximum capacity of 2 x 23 MWth. The main parameters are reported below (IAEA 2007):

Winter/summer regime	Heat demand (MWth)	Hot water temperature departure / arrival (°C)
Maximum winter	46	150 / 70°C
Average winter	35	120 / 70°C
Minimum summer	7	75 / 40°C

Table 3.1-3 Minimum and maximum heat demand from Cernavoda nuclear power plant (Source: IAEA 2007)

Due to the colder cooling water in winter, the electricity production is not seriously affected in winter time. The peaks are supplied by auxiliary oil boilers, which act also as back-up capacities.

Evaluation of the market

Statistics on the district heating market depend on the source:

Source	Scope	Value district heating
Eurostat (Source: Eurostat)	UE27 in 2007	147 049 GWh ("district heating") + 365 843 GWh ("public thermal power stations")
Cogen Europe	Austria, Denmark, Estonia, Spain, Germany, France, Finlande, Hungary, Ireland, Italy, Lithuania, Latvia, Netherlands, Poland, Portugal, Sweden, Slovakia, Slovenia, and the UK in 2003	275 152 GWh ("public heat supply")
EuroHeat & Power (Source: website)	Austria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden, Switzerland	451 009 GWh ("district heat delivered")

Table 3.1-4 Main statistics on the district heating market by information source (Sources: Eurostat, Cogen Europe and EuroHeat and Power)

The distribution by country for EuroHeat & Power is as follows:

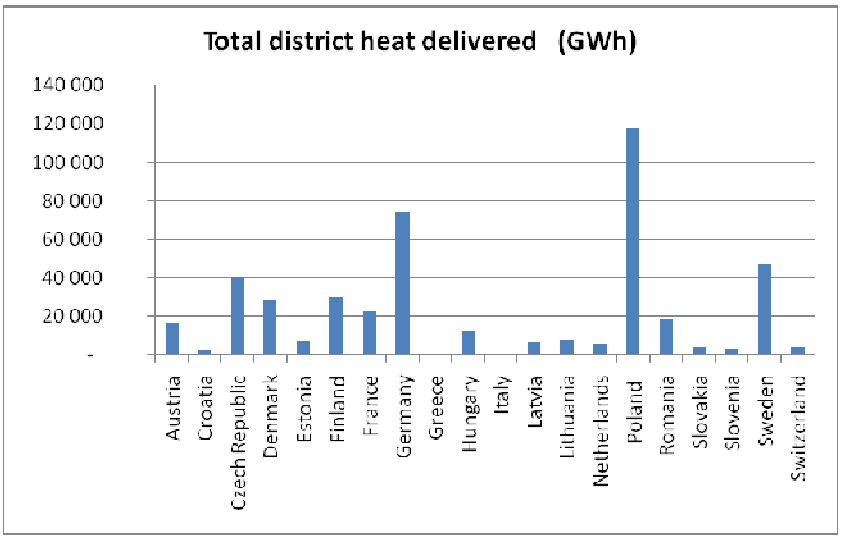


Figure 3.1-3 Delivered district heat by country (Source: EuroHeat & Power)

In volume, the main European countries for district heating are Poland (mainly from coal), Germany (from coal and gas), Sweden (renewable and waste) and Czech Republic (mainly coal).

Potential for nuclear district heating

The steam properties required for district heating are compatible with the operational conditions of all nuclear reactors, whether current light water reactors (as demonstrated in several Eastern European countries) or by future high temperature reactors.

Although district heating is not required all year round and demands redundancy to ensure there is no outage during colder periods, this may be an interesting market for high temperature reactors:

- a high temperature reactor could reach a large number of distant customers by cogenerating higher temperature steam to be transported on long distances and could therefore have large thermal capacities.
- Since district heating is a low temperature process, the combination with electricity generation may be optimised

The issue of the nuclear acceptability by the large number of citizens to be supplied with nuclear steam may hinder this applications, although it must be noted that the nuclear acceptability in Eastern European countries which use district heating, is better than in Western European countries.

3.1.3. Desalination

Background

Desalination is to produce potable water for individual consumption (10%), agriculture (70%) and industry (20%) from water which could not be consumed otherwise. The main type of processed water

is seawater or brackish water because salt is detrimental to human health and plants but also a strongly corrosive substance.

Two dimensions for desalination are to be taken into account: the water withdrawal (which is not equivalent to water consumption because a part of withdrawn water may be returned to the source like power plant cooling water) and the distribution of water resources worldwide.

Region	Renewable water resources	Total water withdrawals	Water withdrawals						Withdrawals as percent of renewable resources
			Agriculture		Industry		Domestic (urban)		
			Amount	Percent	Amount	Percent	Amount	Percent	
Africa	3,936	217	186	86	9	4	22	10	5.5
Asia	11,594	2,378	1,936	81	270	11	172	7	20.5
Latin America	13,477	252	178	71	26	10	47	19	1.9
Caribbean	93	13	9	69	1	8	3	23	14.0
North America	6,253	525	203	39	252	48	70	13	8.4
Oceania	1,703	26	18	73	3	12	5	19	1.5
Europe	6,603	418	132	32	223	53	63	15	6.3
World	43,659	3,829	2,663	70	784	20	382	10	8.8

Table 3.1-5 Water resources and withdrawals in 2000 (Source: UN 2007)

The total renewable water resources amount to 43 660 km3 worldwide. Less than 10% of this water is withdrawn globally and 5% is effectively consumed. Agriculture is the principal sector, followed by industry and domestic (drinking water + other social uses like swimming pools).

Yet, the uneven distribution of resources puts stress in many countries worldwide, principally in Africa:

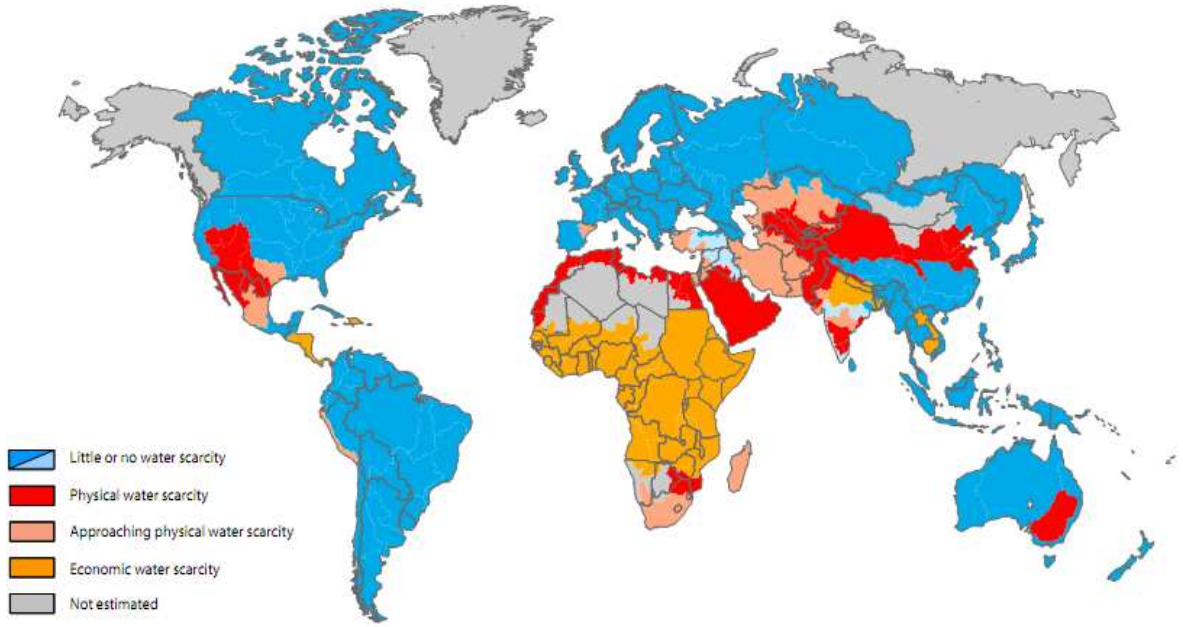


Figure 3.1-4 Areas of physical and economic water scarcity (Source: IWMI 2006)

Developed countries are mostly not threatened by water scarcity, which hurts far more developing countries. In Europe especially, water is not considered as a scarce resource today but may become partially scarce in the future (DG ENV 2007).

Desalination represents a very small portion of water use worldwide (0,3%) and is mostly used for producing drinking water:

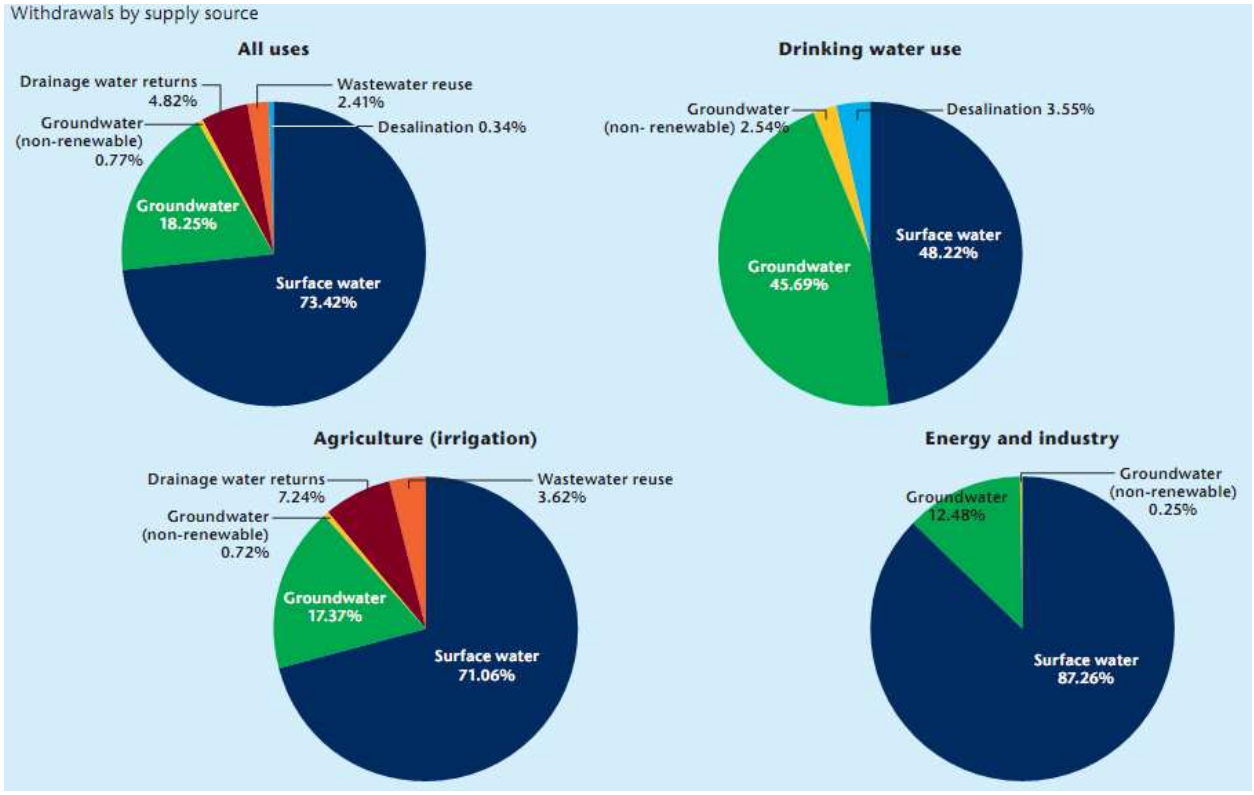


Figure 3.1-5 Sources of water use globally and for major sectors (Source: UN 2007)

Desalination industry

The desalination capacity worldwide amounted to around 35 Mm3/d in 2003 or 13 km3 per year and the capacity has been steadily growing at around 10% a year (Galland 2008).

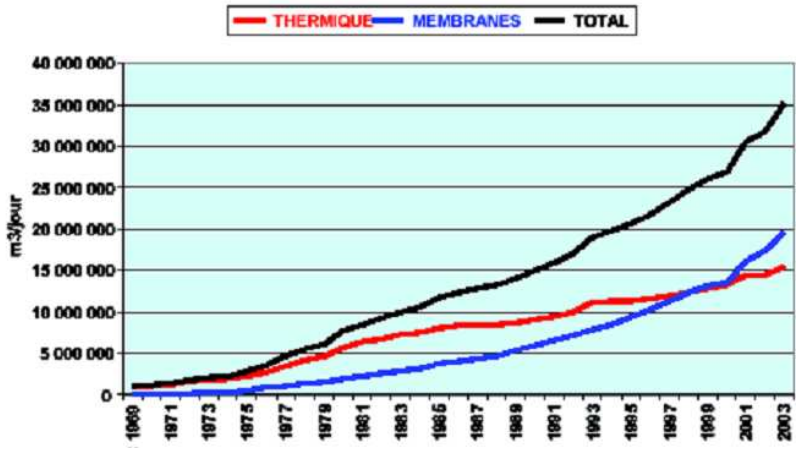


Figure 3.1-6 Desalination capacities worldwide spread between thermal processes (red curve) and membrane technologies (blue curve) (Source: Galland 2008)

A different technology mix was found by IAEA (2000) and is reported below:

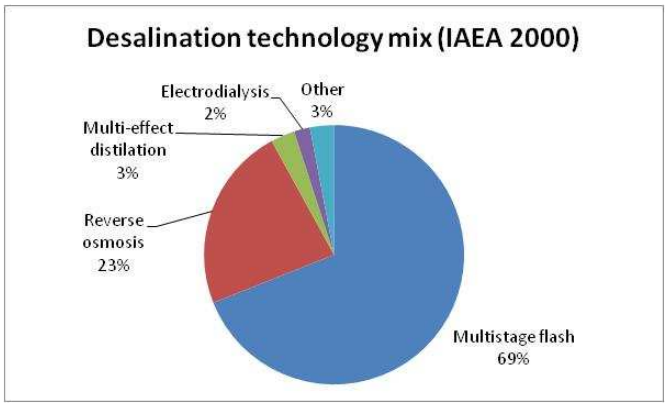


Figure 3.1-7 Desalination technology mix (Source: IAEA 2000)

Europe counts several leading technology providers for water treatment and desalination like French Suez/Degrement and Veolia Water (which will build the world's largest MED plant in Bahrain), Spanish Acciona or German Siemens. Other non-European companies include US General Electric and Korean Doosan.

Most desalting plants are to supply cities in desert regions. They are located in the Middle East (60%) followed by North America (20%) and Europe and Asia (around 8 to 10% each). In Europe, Spain is the largest market. A list of large plants worldwide is reported below (IAEA 2000).

Country	Location	Capacity (m^3/d)	Process
Saudi Arabia	Al-Jubail	236 180	MSF
Saudi Arabia	Al-Jubail	236 390	MSF
Saudi Arabia	Al-Jubail	237 000	MSF
Saudi Arabia	Al-Jubail	235 000	MSF
Saudi Arabia	Alkhobar II	267 000	MSF
Saudi Arabia	Alkhobar III	280 000	MSF
Saudi Arabia	Jeddah I	56 800	SWRO
Saudi Arabia	Jeddah IV	227 100	MSF
Saudi Arabia	Makkah	223 000	MSF
Saudi Arabia	Shouiba II	454 000	MSF
Saudi Arabia	Yanbu-Madina II	128 000	SWRO
		144 000	MSF
USA	Yuma	81 750	RO
USA	Yuma	276 672	RO
UAE	Taweelah B	345 600	MSF
UAE	Dubai	272 760	MSF
Kuwait	Az Zour	262 400	MSF
Kuwait	Doha West	392 400	MSF
Maldives	Male	13 440	MED
India	Jamnagar, Gujarat	48 000	MED
Italy	Trapani, Sicily	36 000	MED
Antigua	Crabbs Peninsula	9 000	MED
Malta	Gar Lapsi	20 000	RO

Table 3.1-6 Large desalting plants in the world (Source: IAEA 2007)

One individual plant may produce 200 000-250 000 m3/d. A large desalting facility like Saudi Arabia's Al-Jubail may reach up to 1 bn m3/d.

Desalination technologies: overview

Desalination aims at removing salt from a given feedwater. Two main technology families exist using distillation, a thermal process, or by passing water into selective membranes, a mechanical or electrical process.

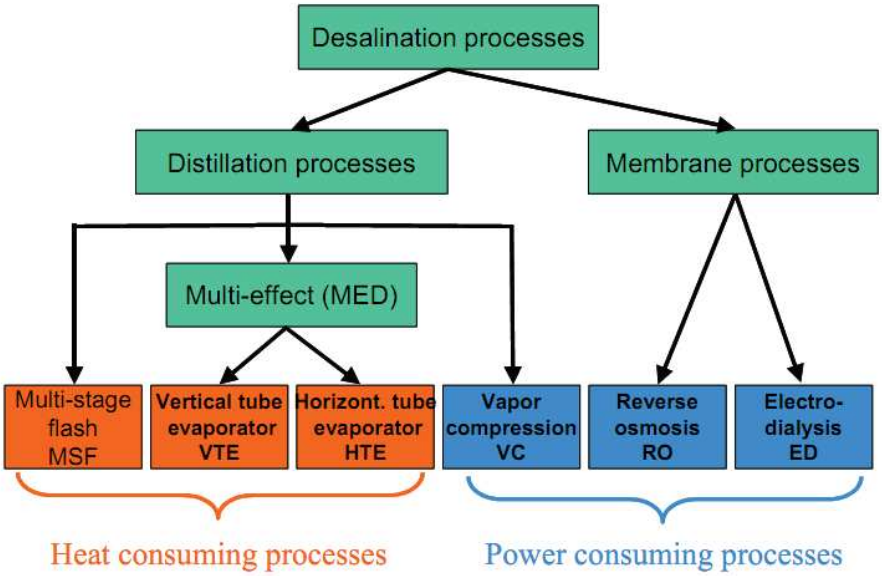


Figure 3.1-8 Desalination processes (Source: IAEA 2007)

Desalination technologies: Multi-stage flash (MSF)

The principle of flash distillation is to evaporate suddenly water by heating it in an under-pressurized vessel:

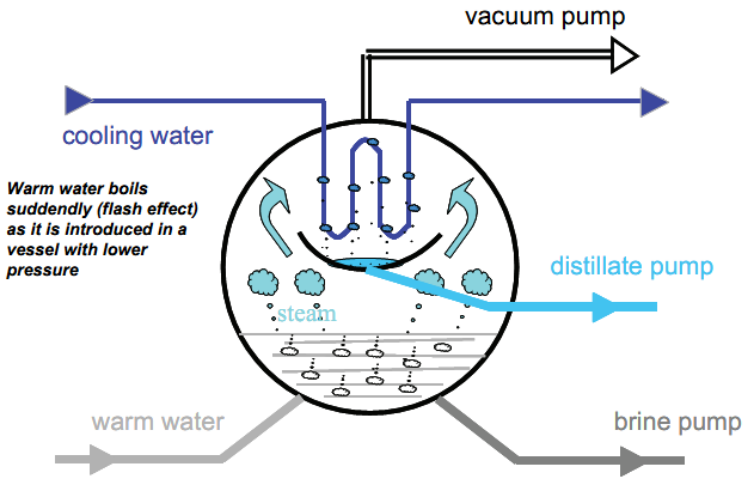


Figure 3.1-9 Operating principle of a single stage MSF (Source IAEA 2007b)

As one stage is not sufficient to flash all the seawater, several stages, assembled in a complex way, are put in line.

The incoming seawater passes through several stages and gets heated up to 80 to 120°C and fed in the first MSF stage where it flashes and passes to other stages with decreasing pressures which ensure a total flash.

MSF is particularly interesting where heat is easily available in large quantity.

The heat consumption of the MSF pant depends on the temperature of the heat source and on the gain output ratio and ranges usually from 55 to 120 kWth/m3.

MSF can reach very high purity distillate water. MSF is a proven technology but seems to have reach its limits. New plants use rather multi-effect distillation or reverse osmosis.

Desalination technologies: Multi-effect distillation (MED)

Multi-effect distillation is a complex set of interconnected distillation units, in a functioning principle quite close to MSF.

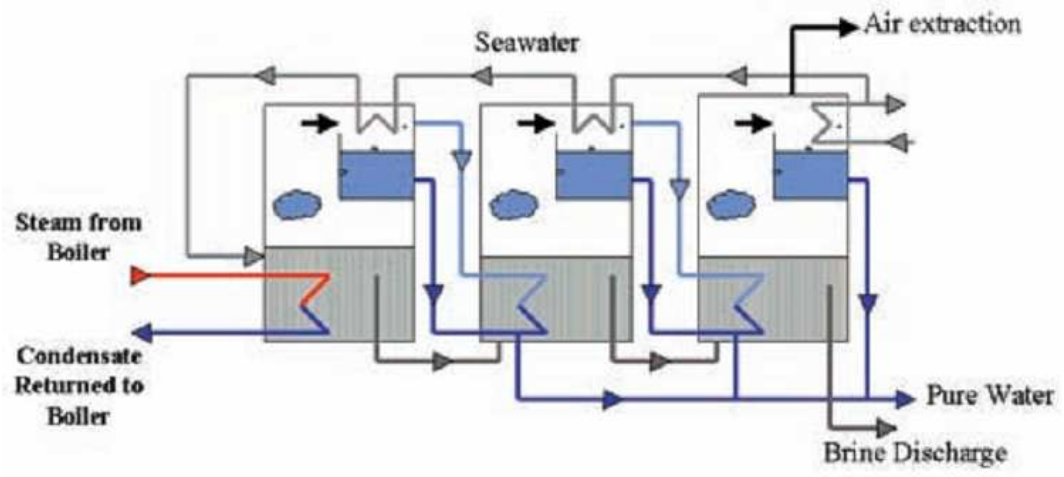


Figure 3.1-10 Schematic diagram of multi-effect distilation system (Source: IAEA 2007b)

Desalination technologies: Reverse osmosis (RO)

Reverse osmosis uses semi-permeable membranes to water molecules but not salts. The saline feed is forced into a set of membranes to produce potable water. Some pumping energy may be recovered in a back-end turbine.

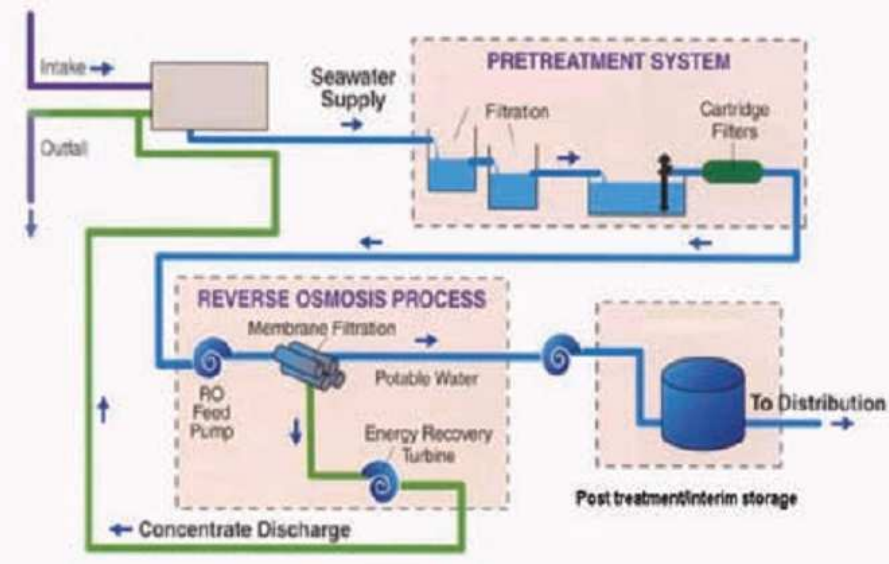


Figure 3.1-11 Schematic illustration of an operating reverse osmosis plant (Source: IAEA 2007b)

Energy consumptions

Indicative energy consumptions of the different technologies are reported in the table below (IAEA 2007b):

Process	Specific heat consumption (kWh/m3)	Specific electricity consumption (kWh/m3)
MSF	100	3
MED	50	2
RO	-	4,5

Table 3.1-7 Specific heat and electricity consumption by desalination technology (Source: IAEA 2007b)

For a large desalting plant of 290 000 m3/d, MSF would require 1 208 MWth and 36 MWe, MED 604 MWth and 24 MWe and RO 54 MWe only.

European energy market related to desalination

Market information on desalination is sparse. The European desalination market and its related energy consumption are therefore evaluated indirectly.

Assuming a current world desalination capacity of 40 Mm3/day (equivalent to 14,6 bnm3/year) and a European share of minimum 8% and maximum 10% (IAEA 2007), the European desalination capacity range from 1,2 to 1,5 bnm3/y. Finally, assuming the technology mix is similar to the world's one (IAEA 2007) and knowing the energy consumptions of each technology (other technologies are assumed to have similar energy consumption than reverse osmosis), the following European heat and electricity market can be estimated:

	Technology mix (IAEA 2000)	Min (8% share of world's market)		Max (10% share of world's market)	
		Electricity (GWh/y)	Heat (GWh/y)	Electricity (GWh/y)	Heat (GWh/y)
Multistage flash	69%	2 418	80 592	3 022	100 740
Reverse osmosis	23%	1 209	-	1 511	-
Multi-effect distilation	3%	70	1 752	88	2 190
Other	5%	263	-	329	-
TOTAL	**100%**	**3 960**	**82 344**	**4 949**	**102 930**

Table 3.1-8 Estimated heat market for nuclear desalination in Europe

The European desalination industry may represent a non-negligible heat market of around 80 to 100 TWh/y, corresponding to 21 to 26 nuclear reactors of 500 MWth, operating 8 000 h/y.

Potential of nuclear heat

Nuclear reactors were already coupled with commercial desalting plants, especially in Kazakhstan which accumulated 26 reactor-years of experience in a large-scale desalting plant of 80 000 m3/d. Japan operates several power plants with smaller-scale desalting plants and has accumulated 150 reactor-years of experience (IAEA 20007 and 2007b)

The coupling with a reverse osmosis plant is weak because this process consumes electricity that may be taken from the grid if the nuclear plant stops or transferred to the grid if the desalting plant stops.

On the contrary, thermal processes require a strong coupling. The coupling schemes have been widely studied worldwide and the technology can be considered as proven. The International Atomic Energy Agency is especially active in this field.

3.1.4. Nuclear process heat

Nuclear energy has a lower experience of coupling with industrial heat end-users; interesting experiences are reported in this section.

Canada's Bruce Nuclear Power Development (BNPD)

Canada has certainly the best experience in coupling a nuclear power plant with an industrial park. BNPD is the largest nuclear steam and electricity generating complex worldwide (IAEA 2007).

The power plant is made of eight CANDU reactors with a total output of 7 200 MWe and the Bruce Bulk Steam System amounts to 5 350 MWth of medium pressure steam. The normal steam capacity is 1 680 kg/s of medium pressure steam with 315 kg/s emergency back-up from oil fired boilers.

Bruce Eco Industrial Park is an example of industrial ecosystem. It gathers a heavy water production unit (supplying the CANDU reactors), a plastic film manufacturer, a 30 000 m2 greenhouse, a 12 000 m3/y ethanol plant, a 200 000 t/y alfalfa dehydration, cubing and pelletising plant, an apple juice concentration plant and an agricultural research facility.

Figure 3.1-12 Bruce nuclear power development (Source: IAEA 2007)

The utility system consists of the nuclear power plant, supplemented by biomass commercial facilities and other electricity producers from processes in the park. The utility company gathers and distributes the energy in the form of electricity, steam, water utilities and hydrogen and oxygen, via a joint venture.

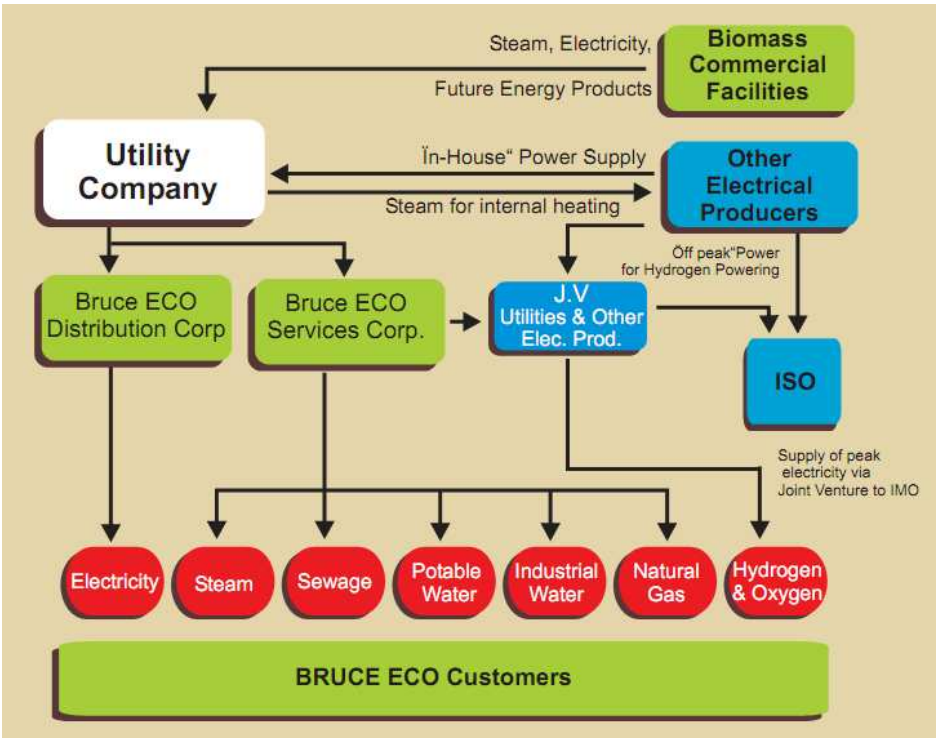


Figure 3.1-13 Bruce Eco Industrial Park utility system (Source: Bruce 2010)

Germany's Stade nuclear power plant coupled to a salt refinery

Other experiences include Germany's nuclear power plant Stade (1892 MWth, 640 MWe), which supplied steam for a salt refinery located 1,5 km away. The salt refinery required 45 t/h of process steam (equivalent to around 35 MWth) at around 190°C and 10,5 bars.

Stade was commissioned in 1972 by Nordwestdeutsche Kraftwerke AG (now E.ON Kernkraft GmbH). The coupling with the salt refinery was operated from 1983 with an excellent track record until the decommissioning in 2003.

Switzerland's Gösgen nuclear power plant coupled with a cardboard mill

Gösgen is a 970 MWe nuclear power plant designed by German KWU (now Areva NP GmbH) and commissioned in 1979. The plant is operated with an excellent track record in terms of availability (8000 – 8200 h/y operation). It produces 17% of the country's electricity demand.

Gösgen has been supplying process steam to a cardboard paper mill situated 2 km away. The mil recycles used paper to manufacture base paper for corrugated cardboard and consumes steam for heating the drying cylinders (see paragraph on papermaking).

Two heavy-oil boilers which first supplied the mill with steam are not in standby status but a warm-up line maintains them ready for immediate start-up to compensate within 15-30 minutes the process steam if the supply from KKG is interrupted for any reason.

KWU designed the plant so it may deliver from 0 to 60 MWth of steam. The current steam consumption from the mill is 10 kWh/s (25-30 MWth).

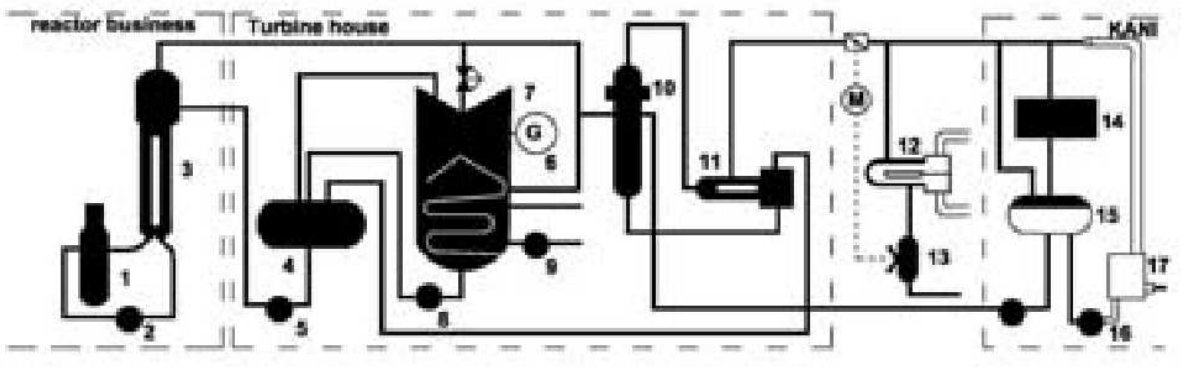


Figure 3.1-14 Gösgen-mill plant and coupling schematic layout (Source: IAEA 2007)

The steam is extracted between the steam generator and the turbine so the steam and the electricity production processes are de-coupled and the evaporater keep on operating even in case of a turbine trip.

3.1.5. Synthesis and recommendations

- Low temperature nuclear cogeneration was already demonstrated at industrial scale, especially for district heating, desalination and process heat.

- The most experimented countries worldwide are Russia, Ukraine and Japan; 13 European reactors in 6 Central and Eastern European countries and Switzerland are currently co-generating heat, mostly for district heating but also for process heat and have accumulated a valuable experience.

- District heating represents a significant heat market at 100-150°C. It concerns mostly cold countries (Northern and Eastern Europe) and is seasonal. It requires heating plants to be located close to densely populated consuming zones. Nuclear acceptability may challenge the siting of the plant. A high temperature reactor may supply more numerous and distant consumers so the required thermal capacity could be high. The economics must yet be proven.

- Desalination is a growing market worldwide, in particular in desert regions like the Middle East. Although Europe is not a desert region (except some parts of Spain in particular), Europe operates desalination capacities in order to decrease the pressure on water resources. Up to now, desalination was not perceived as a competitive option but dramatic production costs decrease makes it a real competitor to water treatment processes. The related energy market may therefore be non-negligible. It could be a back-end use of high temperature steam.

- Nuclear process heat production was demonstrated in a few sites. The leading site is the Bruce Eco Industrial Park in Canada consuming heat from the Bruce nuclear power plant. Several companies are gathered in an industrial cluster with significant heat consumption. Other experiences include German plant Stade coupled to a salt refinery and Swiss Gösgen coupled to a cardboard mill.

- It is recommended to:
    - Liaise with companies having operational experience with nuclear cogeneration in Central and Eastern Europe for district heating, in Canada, Switzerland and Germany for process heat and in Kazakhstan and Japan for desalination.
    - Liaise with the European technology platform for water (Water Supply and Sanitation Technology Platform) to possibly develop nuclear coupled desalination plants
    - Liaise with the International Atomic Energy Agency which has accumulated an important knowledge on nuclear cogeneration, especially nuclear desalination
    - Launch an analysis on the economic potential of district heating using high temperature nuclear cogeneration

3.2. Oil refining and chemical sectors

3.2.1. Oil refining sector

Summary

Refining is the largest heat consuming industry with large average thermal consumption per individual site. Most processes (with the notable exception of hydrogen production, see dedicated part below) are operated at temperatures between 350-550°C. Refineries have very different structures, products and are specific to selected crude oils. The degrading quality of crude oils, due to the depletion of light resources, will require new energy-intensive equipments. Some refineries are supplied partially by cogeneration power plants. However, it is difficult to draw any general scheme on the potential for plugging in a nuclear reactor, because of the balance of consumption and production of the refinery gas produced by some processes; the design duty required; and the safety issues. Although the market could be potentially very large and technically compatible with the operational conditions of a nuclear reactor, only several sites (typically large refineries) may be supplied with nuclear steam and this possibility can only be verified by site-by-site detailed analysis.

3.2.1.1. Purpose and structure of refineries

Refineries aim at processing crude oil extracted from oil-rich regions and transform it into:

- Fuels for cars, trucks, aeroplanes, ships
- Combustion fuels for the generation of heat and power
- Raw materials for the petrochemical and chemical industry
- Speciality products such as lubricating oils, paraffins/waxes and bitumen
- Energy as a by-product

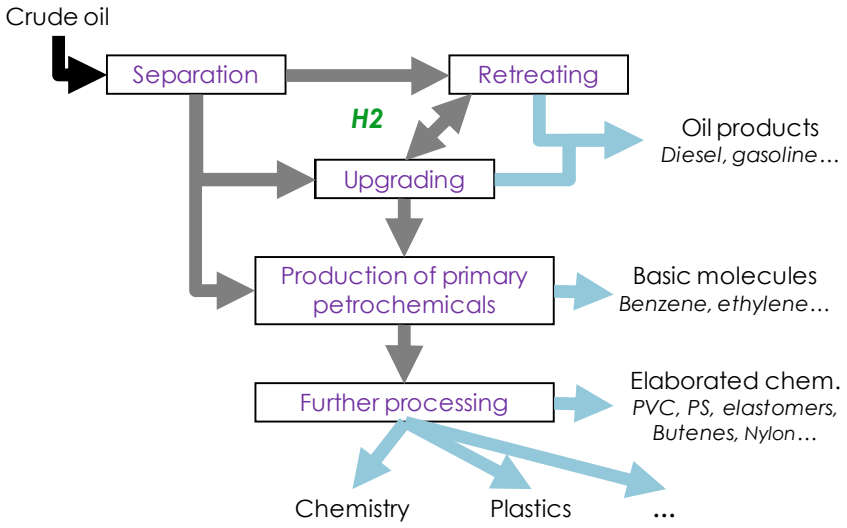


Figure 3.2.1-1 Schematic graph of the main functions of a refinery

All refineries operate an atmospheric distillation tower separating the different hydrocarbon chains constituting crude oil. Additional equipment is required for purifying crude oil (desalting, desulphurisation) and converting low value distillates into high value molecules. This conversion

requires significant amounts of H2, which makes of the refining sector one of the biggest consumer of H2.

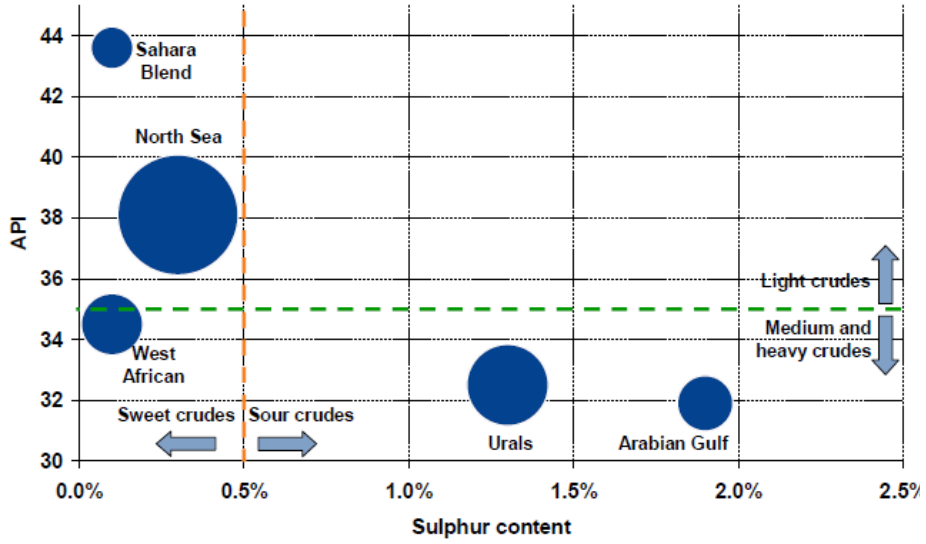
The characteristics of crude oil differ depending on the region. The main parameters are:

- sulphur content: the higher the content, the higher the need for desulphurisation capacities
- API gravity index: this index represent the density of the crude oil and is inversely correlated to the density (20 relates to very heavy oil, 60 to very light oil); the lower the index, the larger the need for energy to pre-heat, distillate, break long-chain molecules, convert them into higher value, shorter chain molecules.

The supply of oil depends greatly on the importing country. Indeed, each country has specific relations with certain oil exporting countries, which insert the refinery sector in a broader scope of geopolitics and international relations.

The supply of oil is depicted by region (Purvin&Getz 2008) in the following graphs:

- Northwest Europe (Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, Sweden, and UK) uses mostly North Sea good quality crude oil with low sulphur content and light density
- Mediterranean countries (Cyprus, Greece, Italy, Malta, Portugal, Slovenia and Spain) use mostly Arabian Gulf crude oil with large sulphur content and heavy density
- CEE countries (Bulgaria, Czech Republic, Estonia, Finland, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia) use mostly Urals crude oil with medium sulphur content.



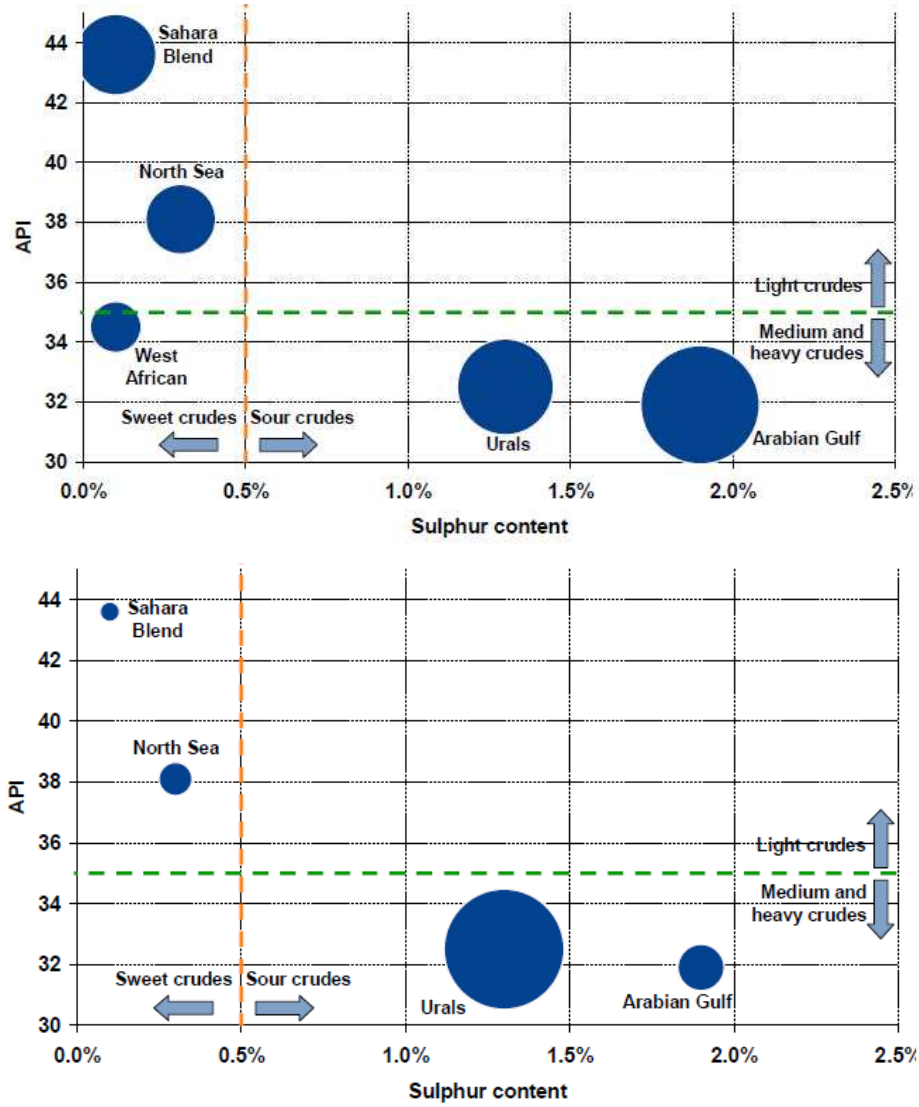


Figure 3.2.1-2 Supply distribution by European region (Northwest Europe, upper graph, Meditarrenaen countries, medium and Central and Eastern Europe, lower; source: Pöyry 2009)

Each refinery is designed to process the crude oil from a specific region and to produce a specific set of oil products at a defined quality. The above graphs indicate that Mediterranean and Central and Eastern European countries operate comparably more energy-consuming refineries in order to process an heavier and more sulphured crude oil.

3.2.1.2. Main equipments of refineries

The main equipments of a refinery can be listed as follows:

Table 3.2.1-1 Description of the main equipments in a refinery

General activity	Equipment name	Exact action	Technical data
Separation of	Atmospheric	Separate the molecules	Crude oil heating at 300-400°C

molecules	distillation tower	constituting the crude oil to be processed	
	Vacuum distillation tower	Separation of heavy components of crude oil	Atmospheric distillates heated up to 400°C Steam is further consumed to create vacuum and injected into the tower to vaporize the feedstock
Retreating	Hydrotreating	This encompasses several processes for desulphurisation, deniitrification, saturation of olefins and aromatics or removing lowe levels of metals from different feeds (naphtha, diesel)	Naphtha hydrotreater: 30-40 bar, 320-380°C Distillate desulphurisation: 40-70 bars, 330-390°C All hydrotreating processes consume H2
	Desalting	Water soluble salts, sand, silt, rust and other solids are removed from the crude oil, before it is fed into the atmospheric distillation column	Crude oil pre0heating: 115-150°C Demulsifier chemicals and/or electric fields are applied to separate salts
Cracking of long chains	Catalytic cracking	Heavier hydrocarbons are broken up by heating and using a catalyst. Most common technology: Fluid Catalytic Cracking	Oil is pre-heated to 250-425°C The catalyst is heated at about 680-730°C Steam is consumed to atomise the chains and to strip catalysts polluted with the remaining oil
	Coking	Coking is a severe thermal cracking process Coking produces in particular refinery gas, LPG, naphtha, light and heavy gas oils and pet coke.	Temperature in the coke drum: 450°C Pressure: 1,5-7 bars Steam is consumed to remove hydrocarbon vapours and cutting coke solid settle
	Hydrocracking	This very versatile process convert any fraction from atmospheric distillates into lower molecular weight molecules	35-200 bar 280-475°C The process consume H2
	Visbreaking	Visbreaking is a noncatalytic thermal process converting residues into lighter molecules	Operating conditions in the soaking drum: 450°C and 10 bar Steam is abundantly used in the fractionators and the stripper.
Conversion	Catalytic reforming	Heavy naphtha is converted into gasoline	Process temperature: 500-550°C The process produces H2 through the endothermic dehydrogenation phase

A number of further processes occur after the above processes, mostly to manufacture specific products, like alkylation, etherification, isomerisation, polymerisation, product treatments, base oil production and bitumen production but they consume less energy and are not described further.

The distribution of technologies by application above is reported in annex II.

3.2.1.3. Industrial context of the refining sector

The European refinery sector faces major challenges that will require corrective measures. This will tend to re-deploy the capacities and increase energy consumption.

Mapping of European refineries

Figure 3.2.1-3 Map of European refineries in Europe (source BREF 2003b)

The four principal refining countries were in 2003 Germany (17 refineries), Italy (17), France (15) and UK (13) (BREF 2003b). The density of refineries is high in Northern Italy and Benelux countries.

Trade imbalance

Europe faces a major imbalance in the consumption/supply of oil products. It exports its overproduction of gasoline to the US and Africa and imports its overconsumption of diesel from the Former Soviet Union countries.

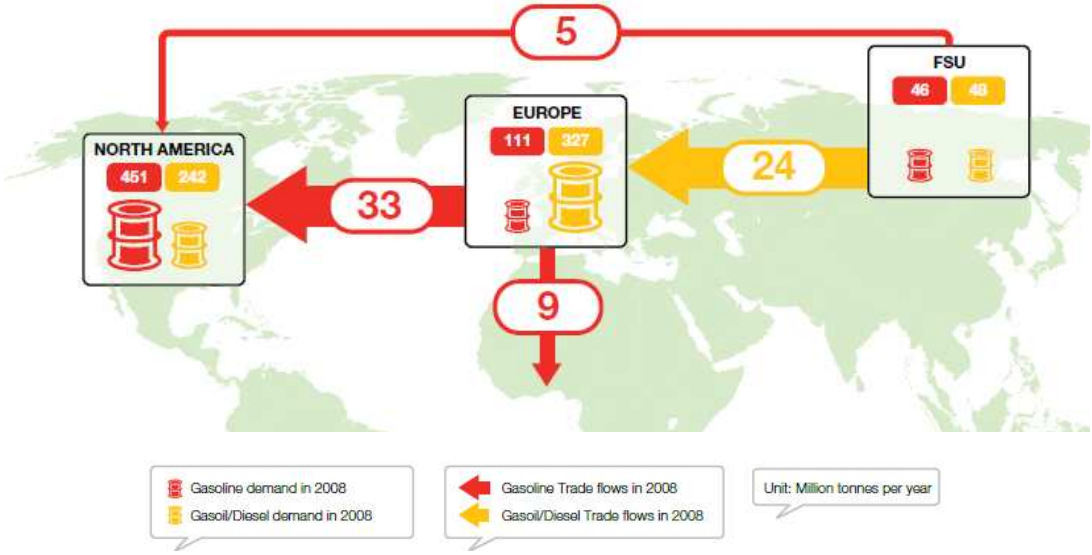


Figure 3.2.1-4 Trade imbalance between the consumption and supply of gasoil and gasoline in 2007 (source: EUROPIA 2009)

Degrading crude oil quality

Furthermore, the crude oil produced in the world is expected to be heavier and to have increasing sulphur contents, requiring additional re-treating capacities. The new market for heavy crude oils will demand even specialised refineries to be transformed into a useable crude oil by normal refineries.

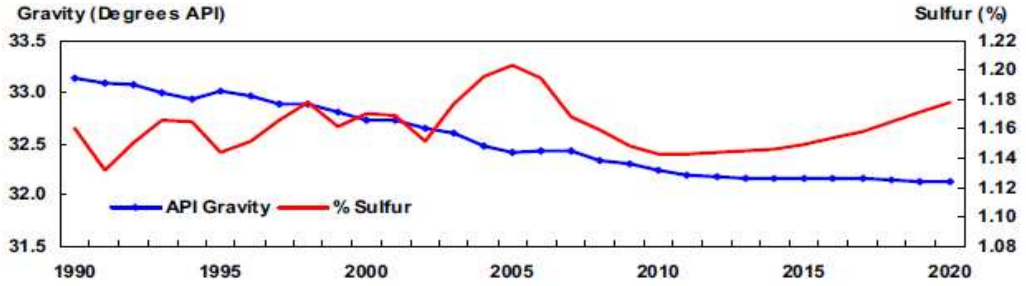


Figure 3.2.1-5 Crude oil quality (API gravity, Sulphur content, source: Purvin & Getz 2009)

Increasingly stringent regulatory requirements on product quality

The European Community and the carmakers are pushing for increasing level of quality of oil products (content in sulphur, aromatics, olefins, benzene, evaporation temperatures, oxygen, cetane, density, viscosity, octane number, etc.), which will demand additional retreating capacities and therefore energy.

Regulatory constraints on emission reductions

The EU Emission Trading Scheme as well as most EU climate policy directives are putting a regulatory pressure on refiners to decrease their CO2 intensity, which drives them to seek energy efficiency measures and low-carbon alternatives to current energy sources (see next paragraph).

Type of refineries

Refineries can be classified into 5 main categories, following the installed capacities; the larger the number of equipments, the higher the level of complexity and the energy consumption by ton of final product (BREF 2003b):

Configuration		Processes	Number in EU27+CH+NO
0	Base oil and bitumen	This is the base scheme distillates the crude oil without post-processing. It produces fuels in a ratio determines by the crude oil composition.	10
1	Hydroskimming + isomerisation	This type of refinery can refine further the fuels than the base scheme; vacuum distillation unit may be added	26
2	Catcracker configuration	This configuration is the most common. The catalytic cracker enables to produce a wider variety of products with higher yields. Etherification and alkylation unit may be added, as well as a thermal cracker and a visbreaker.	42
3	Hydrocracker configuration	This configuration adds to the basic scheme an hydrocracking unit, possibly with a coker	14
4	Complex refinery with catcracking	This last configuration operates catalytic and hydro crackers, hydroconversion units and possibly an Integrated Gasification Combined Cycle Unit	12

Table 3.2.1-2 Distribution of refineries by main configurations in Europe (Source: BREF 2003b)

It must be noted that a refinery is a site rather than a facility. The installed equipments can be adapted or replaced as necessary and new equipments can be installed at any time. A refinery has therefore no real lifetime.

The simplest categories of refineries tend to disappear due to the rigidity of their production, their low yields and their low economic margins compared to more complex refineries. The evolving demand for oil products makes necessary for refineries to upgrade their capacities with conversion equipments, demanding more energy.

Refining capacities are widely spread from small capacities of less than 0,5 Mt/y up to 20 Mt/y.

Economic margins of refineries

Refineries are under great economic pressure. The margins of refining are very variable following the market price of crude oil and of the final products, which themselves depend on complex parameters such as world geopolitics, economic situation, supply/demand balance, speculation, refining over- or under-capacities, oil stocks. regulatory constraints, taxes, or accidents. Simple refineries (hydroskimming refineries in blue) have in particular consistently low or even negative margins, as depicted below.

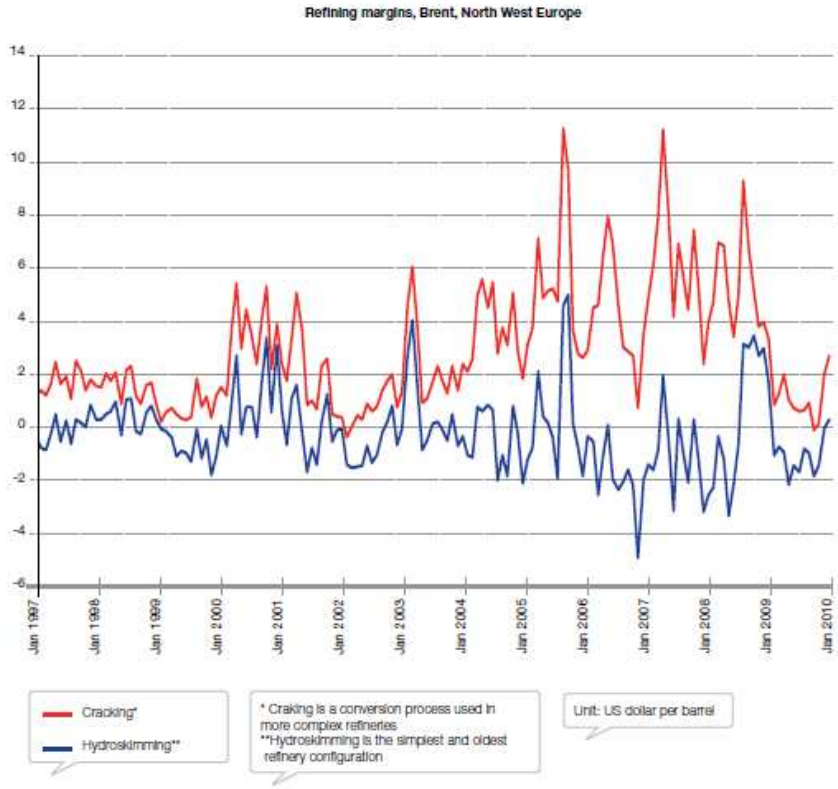


Figure 3.2.1-6 Economic margin of refining Brent in North West Europe (source: EUROPIA 2009)

3.2.1.4. Energy requirements and energy supply of the refinery applications

In light of the context above and considering that refining is an energy-intensive process, refiners attach a great importance to energy supply. The range of energy consumption is 1,7 – 5,4 GJ per ton of process crude, with most refineries ranging from 2,5 to 3,3 GJ/t. This depends from the autoconsumption rate (3% to 10% with most refineries in the range 6%-8%).

In general, 3% to 10% (depending on the complexity of the refinery, with an average of 6% - 8%) of the energy content of the processed crude oil is used to supply 90% of the refinery energy consumption, the rest being mostly electricity imported from the grid.

Refinery fuels

Refinery gas	This is the main fuel for refinery (approximately 80% of the fuel consumed). This is one major constraint in the energy management of refineries (see below)
Natural gas or Liquefied Petrol Gas	Both gases are back-up fuels of refinery fuel gas as necessary. They are injected in the refinery gas system with the refinery gas.
Heavy fuel oil	These are residues from atmospheric or vacuum distillation units but more expensive to use because of their high viscosity which require pre-heating and large pumping capacities (20% of the fuels consumed).

Solid fuels	They are mainly pet coke which may be gasified. Solid fuels are not burnt anymore due to the enforcement of more stringent regulations on nitrogen and sulphur oxides emissions. An exception may be the coke originated from the fluid catalytic crackers which is burnt directly in the catalyser regeneration phase, the combustion energy being used to heat the cracker.

Table 3.2.1-3 List of refinery fuels (Source: BREF 2003b)

Refinery heating sources

Energy is produced by fired heaters (heating the feedstock) and boilers (producing steam), gas and steam turbines, cogeneration power plants and integrated gasification combined cycles. Refiners try to take benefit as much as possible from process integration (heat exchanges from process inputs and outputs and between neighbouring processes).

Here are some ranges of capacities (BREF 2003b):

Capacity of combustion plants in a refinery	10 – 200 MWth *The largest furnaces are for the atmospheric and vacuum distillation*
Total installed capacity in a refinery	100 – 1 500 MWth

Steam use and supply

Steam is used at 10% as mechanical energy for electricity production, driving pumps and compressors, vacuum makers (in steam ejectors), stripping medium, atomiser of heavy fuel and as 90% as heating source. Steam is also a security fluid (with a marginal consumption of 1-10 t/h).

The steam supply system usually operates 3 parallel networks following the steam quality:

- High pressure steam (>30 bar, 350-500°C): HP steam is mostly used to generate electricity and medium pressure steam
- Medium pressure steam (7-20 bar, 200-350°C) is generated by pressure reduction of HP steam. It is used for stripping, atomisation, vacuum generation and heating
- Low pressures steam (3,5-5 bar, 150-200°C) generated mostly in heat exchangers by cooling of hot products and by pressure reduction of MP steam. LP steam is used for heating, stripping and tracing.

Refineries are equipped with steam boilers in virtually all process units.

A major constraint in energy management of refineries: the balance of refinery fuel gas and liquid

Refinery fuel gas is a mixture of different compounds like methane, ethane, butane, ethylene, hydrogen. It may also have sulphur, metal and chemical pollutants and other flue gases, depending on the emitting process.

Refinery liquid fuels gather heavy fuel oil, distillate residues and other such liquid by-product.

The composition of these by-products varies greatly depending on the process. Retreating and separating the compounds has therefore no economic rationale and such by-products are usually considered as having no commercial value.

The use of refinery fuel gas is one major constraint. As it is forbidden by law to burn refinery gas in a torch (which are allowed only for security purposes) and the storage of gases is difficult and costly, refiners have no choice but to burn it in internal boilers and furnaces.

The refinery gas is injected in a fuel gas network (either one or two networks of 4 and 10 bars). Natural gas and LPG may be injected in this network as complement.

Balancing in energy and mass the production and consumption of refinery gas is therefore one of the most important parameter in the operation of refineries. This is absolutely specific to each refinery and no general rue can be drawn.

3.2.1.5. General energy consumption in Europe

Using the installed capacities, fuel, electricity, steam, H2 consumption and steam production by process provided in BREF (2003b) and reported in annex II of this report, the following figures for energy consumption of the refineries in Europe are calculated:

	EU+ capacity in 2003 (Mt/y)	Fuel consumption (GWh/y)	Electricity consumption (GWh/y)	Steam consumption (GWh/y)	Steam production (GWh/y)	H2 consumption (Mt/y)	Comment
Crude distillation	804	120 645	4 022	18 432	-	-	
Vacuum distillation	284	47 400	853	9 480	-	-	
Coking	19	5 250	473	866	1 378	-	Exothermic
Thermal operations	87	14 450	1 084	1 264	-	-	
Catalytic cracking	123	36 276	3 573	6 160	5 133	-	
Catalytic reforming	124	73 936	4 643	-	-	-	
Catalytic hydrocracking	39	8 689	2 542	-	5 376	1,21	Exothermic
Catalytic hydrorefining	138	15 322	2 758	12 066	-	0,87	
Catalytic hydrotreating	318	35 278	6 350	27 781	-	1,73	
Alkylation	13	7 278	557	6 004	-	-	
Polymerisation	3	-	73	2	-	-	
Aromatics	11	2 562	54	71	-	-	
Isomerisation	25	-	615	9 225	-	-	
Base oil	8	1 187	496	3 687	-	-	
Etherification	3	-	51	4 000	-	-	
Bitumen	21	-	525	-	2 625	-	Exothermic
Hydrogen production	2	31 387	983	-	8 188	-	
TOTAL		**399 659**	**29 649**	**99 039**	**22 701**	**3,81**	

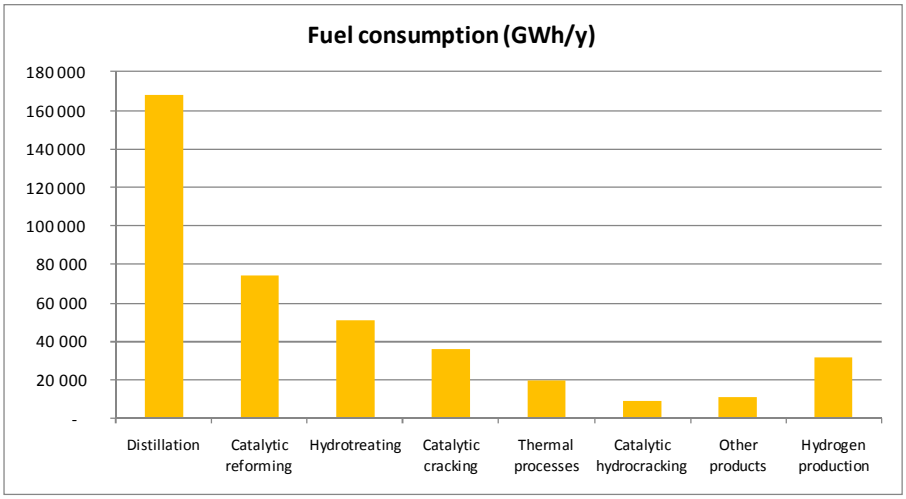
Table 3.2.1-4 General European energy consumption for the European refining sector by equipment

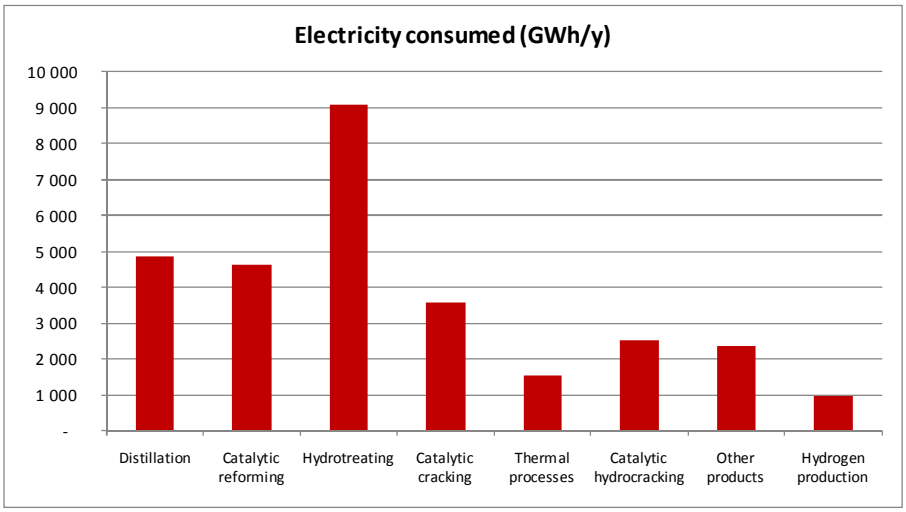
The total energy consumption in 2003 is 528 347 GWh / year. This is in accordance with the total energy consumption of 564 946 GWh/y calculated by the ETS (part 9).

Electricity consumption represents 6% of the total energy consumption (29 649 GWh/y) and heating and direct steam consumption represents 94% (498 698 GWh/y), including 31 387 GWh/y for hydrogen production.

22 701 GWh/y of steam is produced from heat recovery.

It was impossible to calculate the amount of refinery gas used as fuel for heating and steam production. Taking the 80% figure stated in the previous section with a margin (70%-90%), refinery gas may produce 349 089 to 448 829 GWh/y, so the external heat supply may range from 49 870 to 149 610 GWh/y.





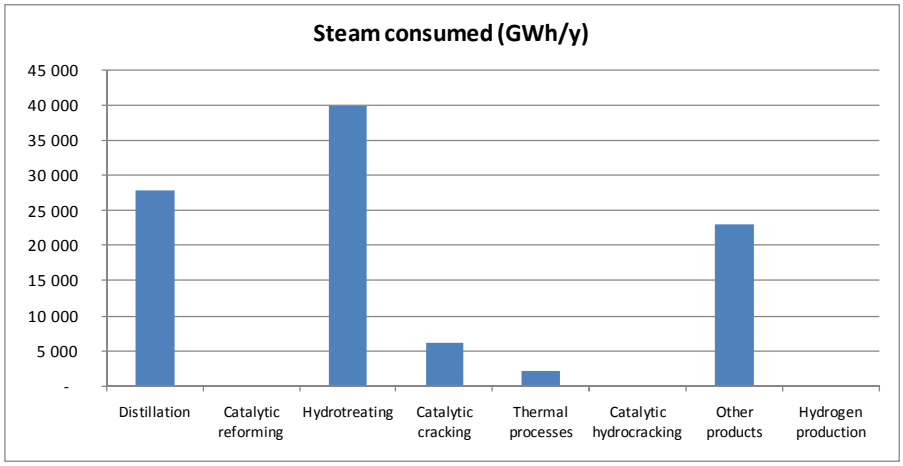


Figure 3.2.1-7 Distribution of fuel, electricity and steam consumption over the main process classes

Distillation is the largest source of energy consumption, being the first consumer of fuel, second of electricity and steam. Catalytic reforming is second for fuel and third for electricity consumption. Hydrotreating is the principal consumer of steam in a refinery. Hydrogen production is set apart and is a non-negligible energy consumer.

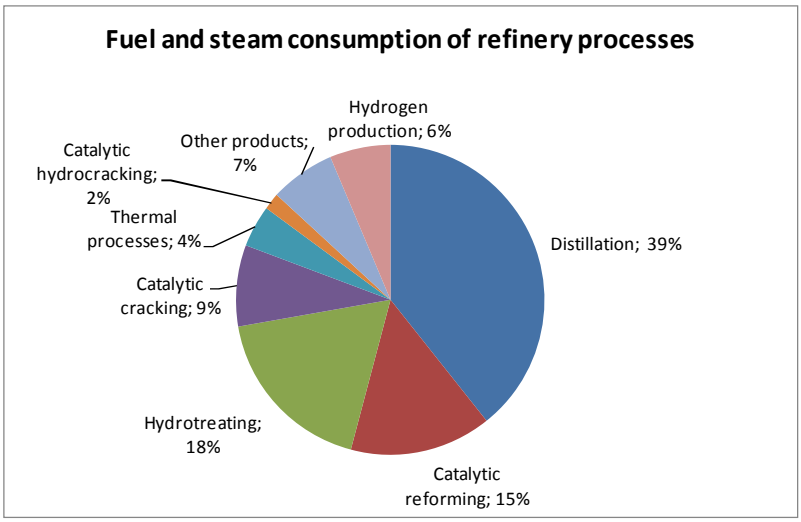


Figure 3.2.1-8 Distribution of fuel and steam consumption by type of process

Looking at fuel and steam consumption altogether, distillation appears as the greatest post, followed by hydrotreating and catalytic reforming.

All processes operate in the temperature class 250 – 500°C except hydrogen production (temperature class 700 – 1000°C), which accounts for a minor part of the heat consumption (8%).

Hydrogen production by steam methane reforming consumes fresh water (and not steam); this fresh water is heated by heat exchange with the cooling flue gas. This explains that in this case no steam is consumed (see schematic figure on steam methane reformer in Annex III).

Taking into consideration the expected evolution in the quality of the crude oil to be supplied and the European unbalance of consumption and production, it may be expected that hydrotreating capacities will increase (in particular to desulphurise crude oil) as well as hydrocracking capacities (to produce more diesel). Catalytic cracking and reforming are rather in overcapacities.

The case of distillation is less clear. Lower quality crude oils will be processed in the future, requiring more heat and steam to separate heavier compounds. Yet, the concern with the security of energy supply, in particular oil supply, may tend to decrease the final consumption for oil products and so the need for installed distillation capacity.

The opposing trends of increasing energy intensity of processes and decreasing quantities of oil products to be produced makes difficult any extrapolation; yet, considering the time scales (short for the need for upgrading capacities and long for oil demand decrease), an increase of the total energy consumption of the sector is very likely in the short term.

Hydrogen consumption and production

The calculated hydrogen consumption in EU+ refineries is coherent, although higher, with other calculations (Roads2HyCom 2007) which come to 2,75 Mt H2 consumed in Western European refineries (and not EU27). The calculation in the mentioned study may have used a slightly different methodology. As it is not mentioned, it is not possible to verify this.

It appears also a gap between the hydrogen production by steam methane or naphtha reforming which may be explained by 1/ some conversion discrepancies and 2/ by the hydrogen which is produced by some processes (like catalytic cracking), which are not accounted for in the line “hydrogen production” and 3/ by the external supply of H2 from industrial gas producers which may not be accounted as on-site production.

Average refinery energy consumption

Considering the 104 refineries which were in operation in 2003 (BREF 2003b), we come to the following average figures by refinery:

Type	Amount (GWh/y)	Equivalent to
Heat (fuel consumption)	3 843 GWh/y	439 MWth installed capacity *assuming an all-year-round flat heat consumption*
Steam (direct consumption)	1 031 GWh/y	An additional 109 MWth (equivalent to 141 t/h) of steam *assuming an energy content of 3 000 MJ/t*
Electricity	285 GWh/y	33 MWe installed capacity *assuming an all-year-round flat electricity consumption*

Table 3.2.1-5 Average heat, steam and electricity consumption by refinery (Source: BREF 2003b)

3.2.1.6. Real case example

This part was written following the kind contribution from a company active in refining; due to confidentiality reasons, the level of detail is kept low.

As a preliminary remark, it must be noted that the situation of each refinery is very specific due to the type of crude oil to which it is dedicated, the balance of production and consumption of refinery gas, the siting, the proximity of other chemical and petrochemical industries, the installed equipments, etc.

Introduction

The case of a typical large West European refinery is reported in this section. This refinery has a capacity of 15Mt/y and ranks among the largest in Europe. It may therefore not be representative of the average refineries.

Steam supply

The refinery produces 200-250 t/h of steam from waste heat boilers integrated within the processes, completed by 520 t/h from a cogeneration plant, industrial boilers and/or steam from over the fence.

The steam is usually superheated because it is more easily used as mechanical medium and can be transported over longer distance, with less corrosion and risks of droplets formation. Typical steam classes may be:

- 35 bars and 400°C
- 14 bars and 300°C
- 7 bars and 250°C
- 1,5 bars and 200°C

Steam at 65 bars and 495°C is also produced but only for electricity generation.

Energy consumption

The energy consumption of the refinery is as follows:

Type	Energy (GWh/y)	Equivalent thermal capacity
Heat (fuel consumption)	8197 (64 %)	936 MWth installed capacity assuming an all-round flat heat consumption
Steam (From CHP, industrial boilers and from over the fence)	4109 (32 %)	469 MWth equivalent to 521 t/h) of steam assuming steam at 35 bar / 400 °C (0,9 MWh / t
Electricity (from the grid)	430 (4 %)	49 MW (this figure does not take into account the power self-produced by the refinery through steam turbines)

Table 3.2.1-6 Energy consumption of a real case refinery (Source: private contribution)

Atmospheric and vacuum distillation units are large heat and steam consumers, with 41% of total heat and 11% of total steam consumed in the refinery.

The energy consumption profile of the refinery is rather flat since it operates generally at 100%. One maintenance turnaround occurs every 5 to 6 years and one or several short interim breaks may be scheduled for maintenance reasons.

There are no particular cycles in the energy consumption with week-ends, days or night but the steam consumption increases during winters.

The production has yet to be adapted following the demand.

Cogeneration power plant specifications

The installed cogeneration plant operates turbines and heat recovery steam generators

The fuel consumed in the cogeneration plant is natural gas (sometimes mixed with refinery off-gases). The electricity generation may be higher than the needs of the refinery, making it a net electricity exporter.

In case of trip of one of the lines of cogeneration, each boiler is able to produce more steam thanks to post-combustion (as a security capacity).

The power plant needs to be flexible. The design steam production uptake limit is +35 $t/h.min^{-1}$.

Although the demand is usually rather constant, it may evolve very rapidly. For instance, a thunderstorm cools the facility components and may require an additional 40 t/h for a few tens of minutes. In case of the trip of a naphtha cracker the steam generators have to produce a supplement of 100-120 t/h as soon as possible.

Installation of the cogeneration power plant and the constraint of refinery gas balance

The design and construction of the cogeneration power plant required a detailed technical and economic analysis of the advantages and disadvantages of the project. The main issues were:

- The balance of refinery fuels consumed and produced (in mass and energy)

If a cogeneration plant is to supply heat and steam to the refinery, then this implies a shift from the heating source consuming the refinery fuels (gas and liquid) towards an external source of heat using natural gas. The sources of consumption of refinery gas will be sparser while the production of refinery fuels remains constant (and refinery gas cannot be burnt except for safety reasons).

The refining liquid fuels may be taken care of so that the refinery fuel gas balance is the main issue to address. Replacing the combustion of liquid refinery fuel by refinery gas is one option to stabilise the consumption of refinery gas, although it requires changing the related furnaces and boilers.

Furthermore, the steam network has to be expanded to integrate the steam produced by the CHP plant and distribute it to heat exchangers replacing boilers and furnaces using refinery gas

- The cost and benefits of the project

The costs and benefits are therefore as follows:

Costs	Technical: • Reengineering of the refinery energy system (including the redistribution of refinery gas uses) • Replacement of boilers and burners • Extension of the steam network and refinery gas network Economic: • Construction and operation of the CHP plant • Cost of fuel • Cost of reengineering
Benefits	Technical: • Energy efficiency of cogenerating electricity and heat better than separate generation Economic: • Electricity export in case electricity is produced in excess • Regulatory and legal incentives to cogeneration in general • Regulatory and legal incentives to environmental performance (natural gas emitting less CO2 than fuel for instance)

Table 3.2.1-7 Cost and benefits of installing a cogeneration plant for a refinery (Source: private contribution)

The energy efficiency offered by cogeneration may not be a sufficient advantage for supporting the installation of a cogeneration plant, making the economic rationale the key driver of the decision.

The economic rationale depends on several factors, in particular the costs related to building and operating the plant itself and the necessary reengineering of the refinery to host the cogeneration plant.

To balance these costs, the regulatory incentives may bring a decisive economic advantage for cogeneration. The regulatory and legal frameworks depend on each Member State and are therefore to be analysed nationally.

The balance of costs and benefits provide an estimate of the net cost of steam which is to be compared to the cost of steam in the “business as usual” scenario.

3.2.1.7. Short analysis of the potential of nuclear heat in the refining sector

This analysis reflects the author's opinion solely and is not attributable to any contributor to the study.

Nuclear heat could supply refineries with nuclear heat but there are major challenges to overpass, in addition to the usual issues concerning nuclear new-builds (siting, availability of water, safety, radiological issues, geological properties, etc.):

- The balance of refinery fuel gas
- The necessary reengineering of the refinery
- The costs and benefits (which depend on the situation of each refinery)

The example above demonstrates that supplying a refinery by a large cogeneration power plant is feasible and may have an economic rationale but also how this choice is complicated and the numerous consequences it implies.

3.2.1.8. Conclusions and recommendations for the refining sector

- Europe has almost 100 refineries in operation today; the industrially denser areas can be found in Benelux countries, in the Rhein region in Germany, in France and in Northern Italy.

- Refineries are usually designed to process one or two specific types of crude oils; the products depend on the installed equipments. The industry is capital intensive so the process structure and design is subject to a certain inertia.

- The degrading quality of imported crude oils and the structural unbalance of production will make it necessary to install new energy intensive equipments.

- Refining is in general an energy intensive industry, even more so for larger and more complex refineries; the main fuel is the refinery fuel gas, a process by-product which has to be burnt immediately.

- The refining sector may be a suitable heat market for nuclear cogeneration
  - Most of the processes operate at steam conditions compatible with a nuclear high temperature reactor: maximum 550°C (except for H2 production), 30-40 bars, several hundreds of MWth, 100 or more tons/hour of steam as feedstock
  - Refining is the main consumer of hydrogen and a competitive H2 supply from a nuclear reactor would have every chance to be welcome.

- The related heat market is yet difficult to evaluate and no universal conclusion can be drawn. The case of every refinery is unique by its historical structure, the crude oil processed, its siting, its balance of consumption and production of refinery fuel gas.

- Considering this large market, a detailed analysis is required in order to identify refineries where nuclear cogeneration would be technically and economically most feasible.

3.2.2. Chemical clusters

Summary:

The chemical industry represents a great potential for nuclear cogeneration. Large clusters are of special interest: they integrate different companies and production units and are already equipped with large gas- or coal-fired cogeneration plants. Nuclear energy could further benefit from the pipeline infrastructures connecting chemical clusters, thus forming regional mega-clusters (like the Antwerp Rotterdam Rhine Ruhr mega-cluster) to supply distant customers with base raw materials like hydrogen and oxygen.

This part uses information from BREF on Large Volume Inorganic Chemicals (BREF 2007b) and from a utility management company for a medium-scale European chemical cluster.

3.2.2.1. Chemical industry and market

Specificity of the chemical industry

The chemical industry produces an outstandingly large number of chemicals; this variety is a specific feature of this sector and makes difficult to approach it product by product.

Each chemical is a molecule made of different atoms and different bonding types. The main atoms for chemicals are carbon, hydrogen, oxygen and nitrogen. Other atoms may be used, such as chlorine (e.g. in PVC), bromine (e.g. in PBDE), fluorine (e.g. in all PFCs) and iodine.

Crude oil, once processed by refineries, and gas are the principal sources of carbon and hydrogen for the chemical industry. Air is the main source of oxygen and nitrogen, and for some processes is separated into both compounds. This separation is mainly done by industrial gas producers.

Chemical bonds can be simple, double or triple; molecules forms can be linear, in Y form or cyclical with all possible atom and bonds arrangements. The assembly possibilities are therefore almost infinite.

Chemicals families

Base chemicals

Refineries produce in addition to oil products for energy purposes (e.g. diesel, jet fuel) different distillates (e.g. naphtha, ethane or petroleum gas). Industrial gas companies produce almost pure oxygen and nitrogen from air distillation (see paragraph on air gases); such companies are generally locating their production facilities near refineries and chemical production sites and act as service providers (like utilities).

Petrochemicals

Refinery base chemicals can be further processed in a petrochemical production facility into olefins (e.g. ethylene, propylene, C4 stream), using in particular a naphtha cracker and into aromatics (e.g. benzene, toluene, xylene). These base molecules can further be processed into monomers (for polymerisation) like styrene, esters, acrylate or vinyl chloride.

Polymers and plastics

Petrochemical monomers have the property to polymerise, i.e. to liaise with each other forming very long chains, so called plastics, in the form of pellets.

Fertilisers

Fertilisers are chemicals bringing important nutrient to plant crops like nitrogen, phosphorous and potassium, nitrogen being the principal nutrient. Nitrogenous fertilisers are derived from ammonia (NH3) produced currently from air derived N2 and fossil fuel derived H2.

Pharmaceuticals and life sciences

Pharmaceuticals and life science chemicals are a special chemical family since these chemicals are produced in a highly selective, highly specified and highly regulated frame. These chemicals are produced in much lower quantities and have considerably higher price in comparison to other chemicals.

Other specialty products and consumer goods

A wide range of specialty chemicals are produced using a fine mixture of chemical molecules like paintings, inks, perfumes, soaps, detergents, surfactants, explosives, pigments, resins, turpentine, adhesives, cleaning chemicals, catalysts...

All chemicals are interrelated and base chemicals serve as feedstock for all more advanced ones. A flowchart giving the example of petrochemicals and the different transformation up to their consumption in final products is reported in annex V and illustrates the complexity and versatility of the industry (although only petrochemicals are reported).

General sales structure and trends

The chemical industry is a versatile sector. Many products are manufactured, with various quality grades for almost all other non-chemical industries and households.

Base chemicals represent the largest share of the sales of chemicals (these are bulky products), followed by pharmaceuticals and specialty chemicals (low production, very high added value). Consumer chemicals are the lowest share of sales.

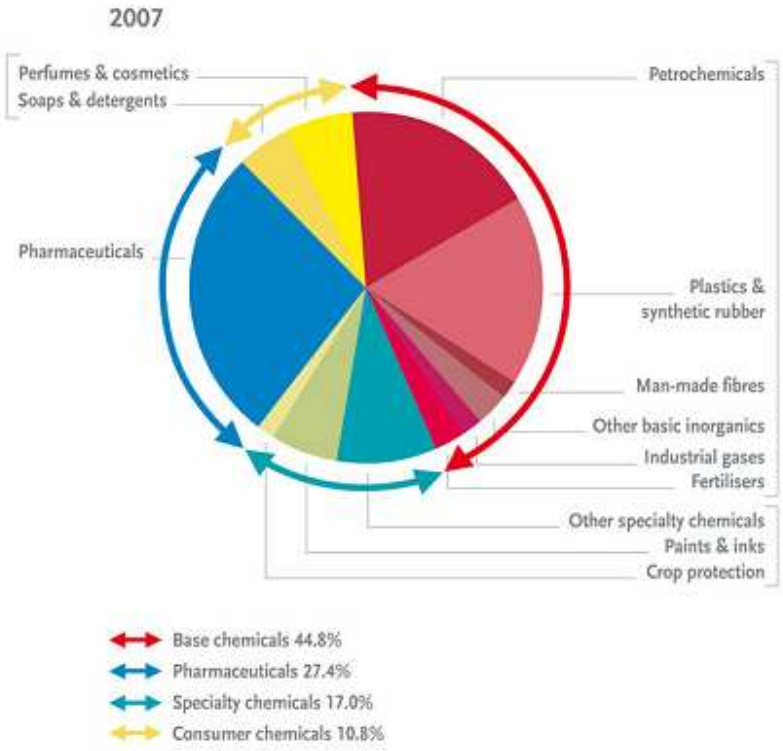


Figure 3.2.2-1 Sectoral breakdown of EU chemicals industry sales (Source: CEFIC 2009b)

The world chemical market is a growing market and the European Union chemical industry is a world leader: it is the largest chemical producer and the largest chemical exporter worldwide. Asian countries have increased their market share dramatically from 1997 to 2007. The production has been steadily growing over the last decades.

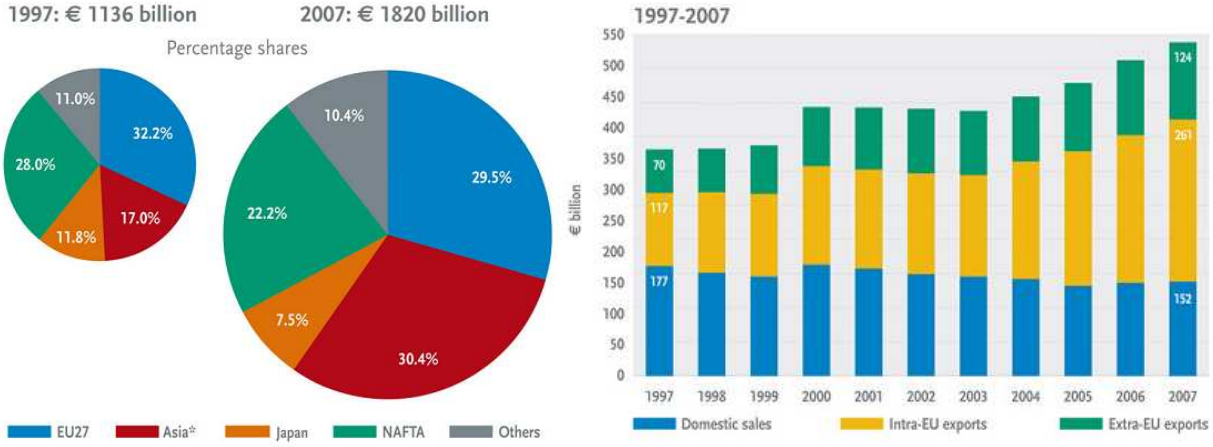


Figure 3.2.2-2 World chemicals sales by region: 1997 versus 2007 (left) and EU chemical sales structure by destination 1997-2007 (right) (Source: CEFIC 2009b)

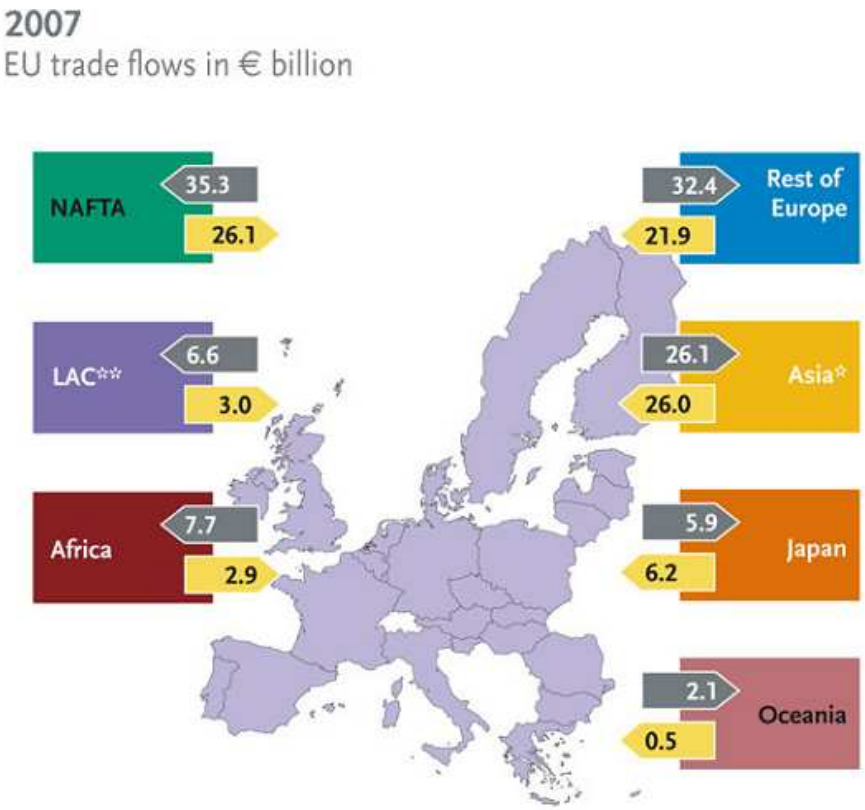


Figure 3.2.2-3 EU chemical industry trade flows in 2007 (Source: CEFIC 2009b)

The EU industry is trading with all world regions and is net importer only with Japan, the trade flow with Asia being almost equilibrated.

Germany is the European leader (25% of the European sales), followed by France (14%), Italy (12%) and Great Britain and Netherlands (10% each). 12 of 30 world chemicals majors had headquarter in EU, in particular, German BASF, Dutch Shell and French Ineos which are ranking respectively first, fourth and sixth among the largest petrochemical companies in the world.

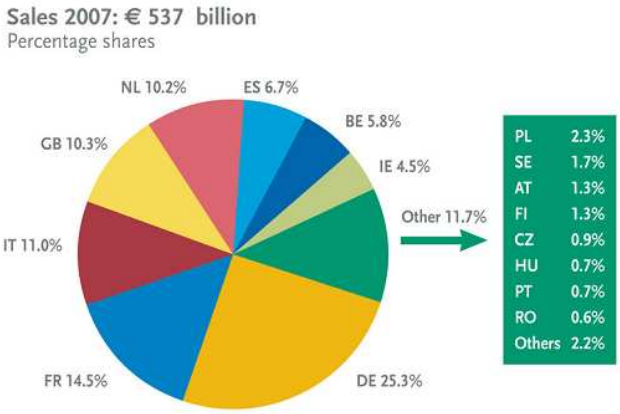


Figure 3.2.2-4 Geographic breakdown of EU chemicals industry sales (Source: CEFIC 2009b)

EU chemicals consumers

There are three main consumer groups of chemicals:

- The largest consumers group is end-users, i.e. households + government + non-profit organisations (30%) and services, which include cleaning companies, water treatment and other environmental services companies (16%) for a total of 46%
- Industry group include construction (5%), automatic (5%), paper and printing products (4,5%) and other industries for a total of 26% of the sales.
- Manufacturing ranks third with a total of 22% for metal products, industrial machinery, office machines, electrical goods as the main consumers
- Agriculture is the last sector with 6% of the sales.

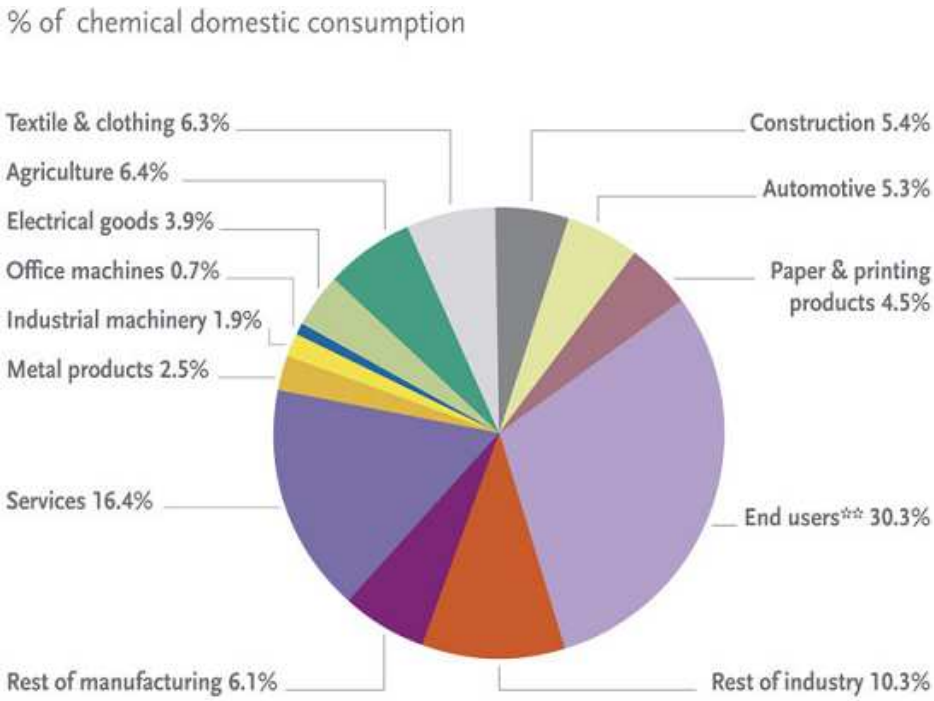


Figure 3.2.2-5 EU chemicals industry consumption structure (source: CEFIC 2009b)

Cost structure

Energy accounts for 8% of the EU chemical industry costs. Other costs include purchase of raw material and equipment, trading, labour costs and gross operating surplus and account for more than half of the cost structure (57%).

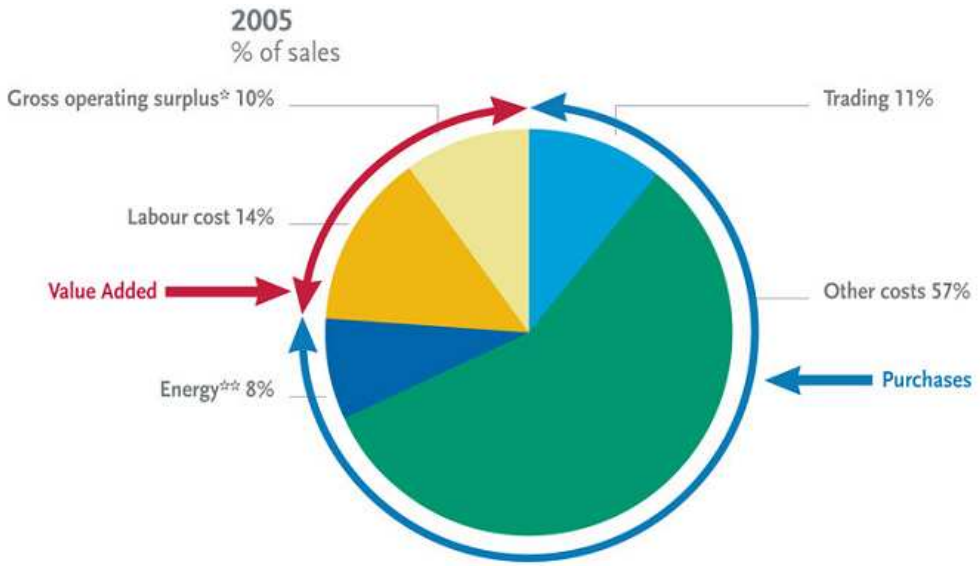


Figure 3.2.2-6 Cost structure of the EU chemicals industry (source: CEFIC 2009b)

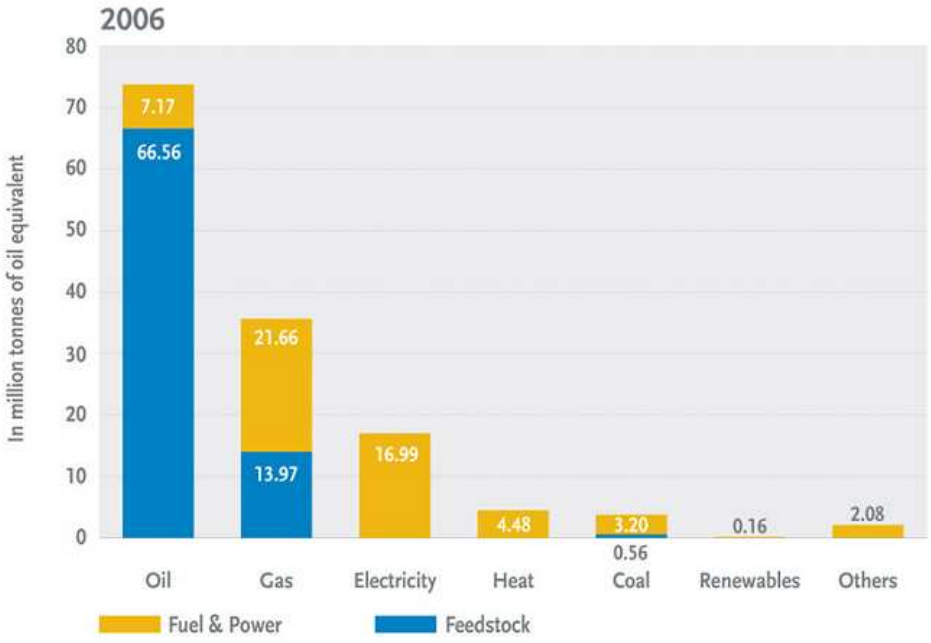


Figure 3.2.2-7 EU chemicals industry energy consumption by source (Source: CEFIC 2009b)

The chemical industry differs from normal energy consumer in the sense that fossil fuels serve as energy fuel and feedstock.

Whereas oil is the largest feedstock followed by gas and to a marginal extent coal, gas is the most important fossil fuel consumed followed by oil and coal. The industry is also electricity intensive. The column heat refers to heat purchased externally only.

The energy market in the chemical industry is therefore as follows:

Energy consumption in chemical industry in 2006	Fuel and power (GWh)	Feedstock (GWh)
Oil	83 387	774 093
Gas	251 906	162 471
Electricity	197 594	-
Heat	52 102	-
Coal	37 216	6 513
Renewables	1 861	-
Others	24 190	-
TOTAL	**648 256**	**943 077**

Table 3.2.2-1 Energy consumption in the European chemical industry by fuel and feedstock (CEFIC 2009b)

The energy market of the chemical industry is the outstandingly large when considering all energy sources and amounted to 648 256 GWh/y in 2006. Yet, most heating sources are embedded in processes through boilers burning fossil fuels mainly (oil, gas, coal).

The external energy consumption is in the form of electricity mainly (197 594 GWh/y) and heat (52 102 GWh/y).

The total fuel consumption except electricity is 450 TWh/y. This is much higher than the indirect calculation (74 TWh/y). This may be due to the facts that 1/ some fuel is used to generate electricity and not heat and 2/ that the declared emissions by the chemical industry do not cover all emissions (the ETS covers only production units with capacities higher than 100 t/d).

The heat purchased is lower than the plug-in market estimated via the indirect calculation (119 TWh/y). This is logical since the plug-in market estimates the heat produced at cogeneration plants, whatever their ownership (see section 2.1.4). It can therefore be concluded that many cogeneration plants may be still owned and/or operated by chemical companies.

3.2.2.2. Clustering in the chemical industry

Description and interest of clusters

The chemical industry operates a wide range of production units, which are mostly intermediary products for other units. Inter-relations inside the chemical industry are therefore natural.

Clustering is an integration which originates from the natural internal relations occurring in this industry. Due to European competition laws, integration in chemical clusters:

- is rather vertical than horizontal
- is restricted to commercial relations rather than extended industrial cooperation
- avoids involving large players with important market power or numerous smaller players which together could have a market power.

An example of clustering is reported below for the C4-cut interactions within the German Rhine/Ruhr cluster; C4 relates to carbon chains derived from crude oil with 4 atoms of carbon which are processed into different molecules having different shapes (simple bonds, double bonds, etc.), different compounds (hydrogen, oxygen, etc.).

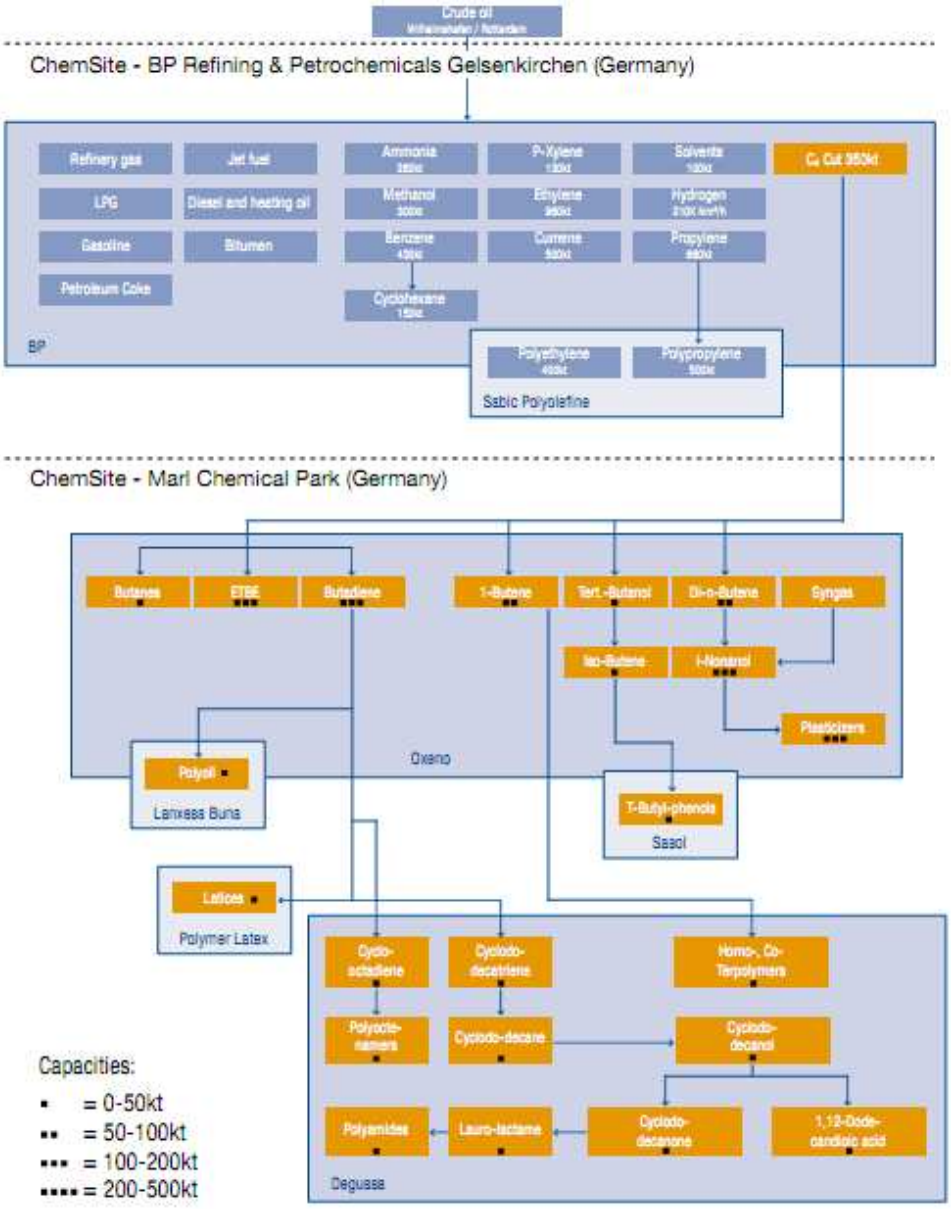


Figure 3.2.2-8 C4-Cut interactions within the Rhine/Ruhr cluster (Source: EPCA 2007)

Clusters have different sizes. They can be only an isolated cluster gathering different chemical companies and service providers (industrial gases, energy, water treatment, logistics…). They can also have a regional reach with integration between several isolated clusters.

Chemical cluster mapping

Chemical clusters are spread all over Europe. Denser regions with major clusters are Benelux countries with German Ruhr region, Northern Italy and Southern France. Spain has a major cluster, although isolated, of Tarragona near Barcelona. The UK has several smaller clusters spread over the country.

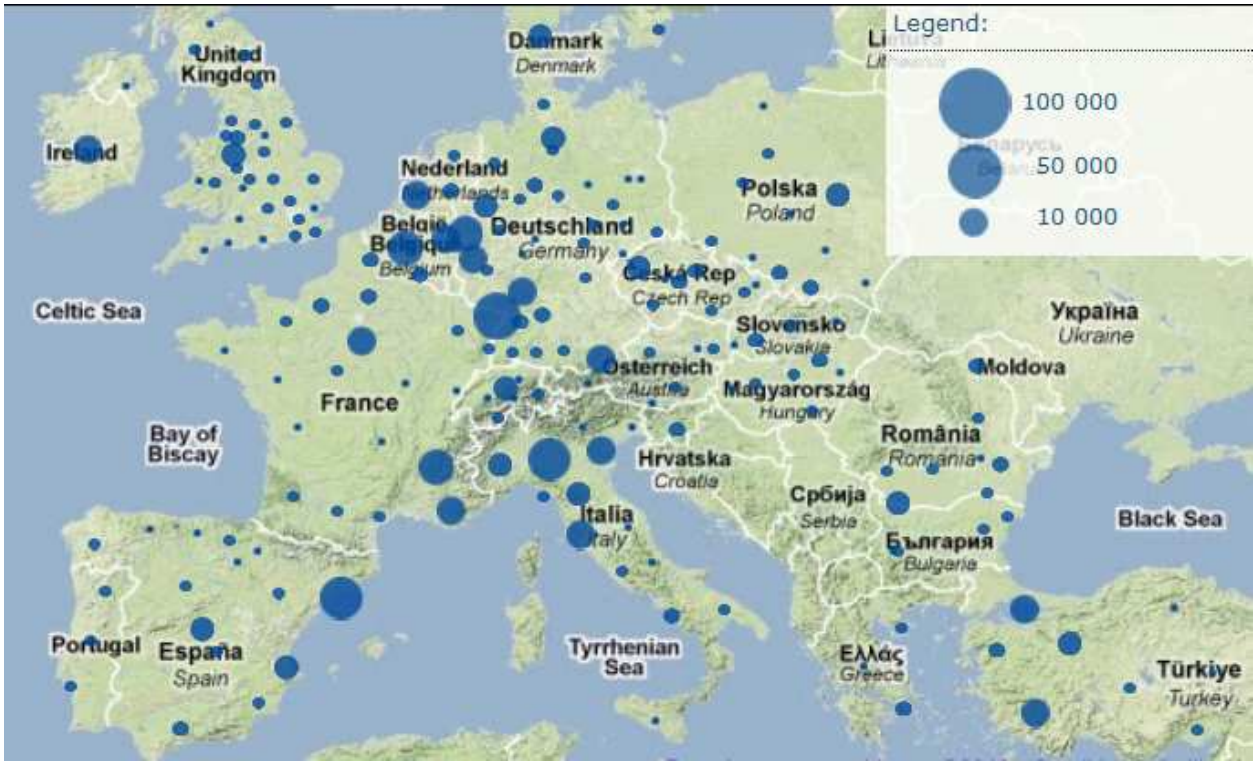


Figure 3.2.2-9 Number of employees by chemical regional clusters in Europe and neighbouring countries (Source: European Cluster Observatory, released in August 2010)

Chemical clusters are naturally related to the oil and petrochemical industry and the mappings of both industries overlap rather well.

Mapping of large clusters

Not all chemical clusters are large energy demanding sites. Production output, site sales or employment are not representative of energy consumption because the energy intensity related to all these parameters is too different depending on the chemical processes.

Very large chemical clusters may be identified by the existence of an on-site naphtha cracker. A naphtha cracker is a capital intensive process and produces hydrogen. Building a naphtha cracker has an economic rationale only if it is co-located with other processes, especially consuming ethylene.

In such cases, the steam demand may be of several hundreds of ton per hour (200-500 t/h) at 400-500 °C. Most such clusters operate a dedicated cogeneration plant. Processes requiring higher temperature are supplied by dedicated gas burners. Such large clusters could therefore well accommodate a small nuclear reactor.

The list of naphtha crackers in Europe is reported in annex V. The main clusters (with naphtha cracker capacities higher than 100 kt/y of ethylene) appear to be:

Country	Cluster site
Austria	Schwechat
Belgium	Antwerp
Bulgaria	Burgas
Czech Republic	Litvinov
Finland	Porvoo
France	Berre, Carling, Dunkerque, Feyzin, Gonfreville, Lavera, NDG
Germany	Burghausen, Gelsenkirchen, Heide, K-Worringen, Ludwigshafen, Munchmunster, Wesseling
Hungary	Tiszaujvaros
Italy	Brindisi, Gela, Priolo, Porto Torres, Porto Parghera
Netherlands	Geleen (Chemelot), Moerdijk, Terneuzen
Norway	Rafnes
Poland	Plock
Portugal	Sines
Romania	Pitesti
Slovaka	Bratislava
Spain	Puertollano, Taragona
Sweden	Stenungsund
UK	Fwaley, Grangemouth, Fife, Wilton

Table 3.2.2-2 Mapping of the main chemical clusters in Europe (based on the existence of a naphtha cracker)

Again, most sites are located in Benelux, France, Germany, Italy and the UK.

Pipeline infrastructures and mega-clusters

Individual clusters are geographically restricted industrial areas (several hundreds of hectares) integrating different chemical companies and service providers. Individual clusters may further be connected by pipelines to other clusters so all chemical companies and service providers may be organised at regional level and manage risk and investment efficiently. The Benelux region is an illustrative example and is reported in next sub-section.

Chemicals pipelines serve to transport especially ethylene and propylene, two very important olefin petrochemicals with many chemical applications. Ethylene is produced in Europe mainly by naphtha steam crackers, a capital intensive equipment. Naphtha crackers must be differentiated from steam methane reformers (which produce syngas, an hydrogen rich gas).

The map below reports the existing ethylene, propylene and crude oil pipelines, together with the steam crackers (to produce olefins) and refineries (which process crude oil):

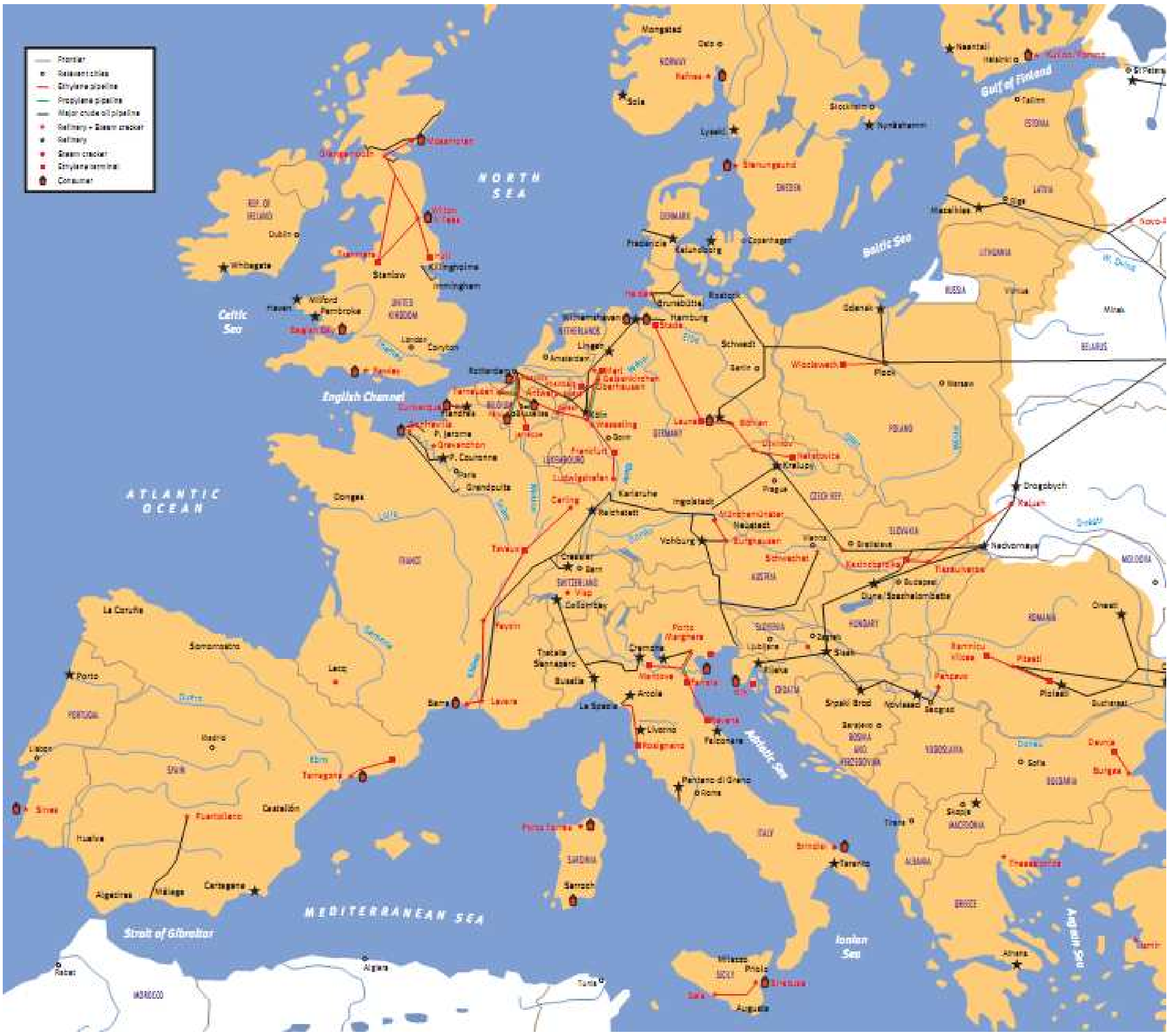


Figure 3.2.2-10 Map of refineries, pipelines and crackers in Europe (Source: APPE 2004)

Ethylene pipelines are common all over Europe whereas there are only two propylene pipelines located in Benelux and Germany (a region also rich in industrial gases pipelines, see related chapters).

Pipeline infrastructures are regional and disconnected. The main regional infrastructures are Benelux and Western Germany, Eastern Germany, German Bayern, Northern Italy, Western France.

There are plans to interconnect at least ethylene pipelines in order to link up all chemical facilities in Europe, creating a large area for chemical production, coupling world leading chemical clusters and offering a buffering system to accommodate short-term fluctuations.

The first interconnected region could be Great Britain, Belgium, the Netherlands, Germany, France, Spain, Austria, Italy, Hungary, Czech Republic, Slovenia and Croatia.

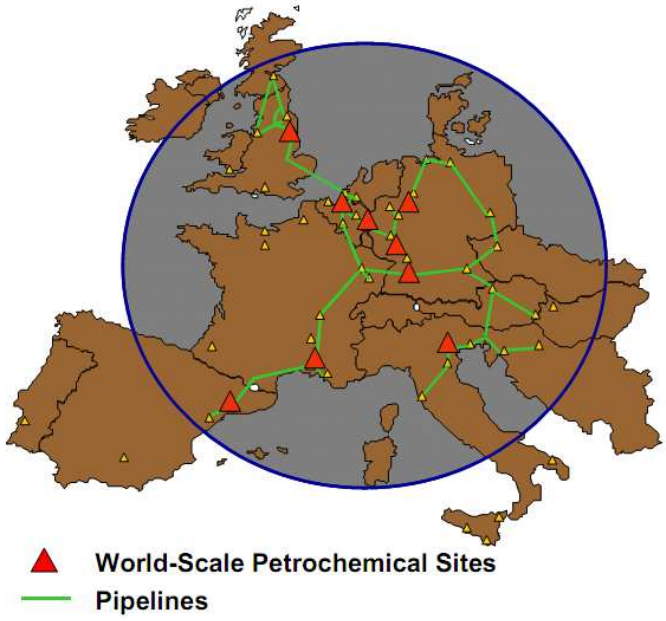


Figure 3.2.2-11 Vision of the future petrochemical landscape in Europe (Source: APPE 2008)

Presentation of the Antwerp, Rotterdam and Rhine/Ruhr inter-regional mega-cluster (ARRR)

ARRR takes place in one of the densest industrial regions in Europe. It is the largest interconnected chemical production cluster in the world in terms of production throughput.

The mega-cluster comprises the two port areas of Antwerp, Belgium and of Rotterdam, Netherlands and the two major inland areas in Germany of North-Rhine-Westphalia (Cheimsite and ChemCologne clusters) and of Ludwigshafen-Mannheim-Karlsruhe.

Several smaller clusters are interconnected to these major regions, including Terneuzen, Geleen (Chemelot), Feluy and Frankfurt.

Interrelationships between clusters take advantage of this density by building capital intensive inter-clusters infrastructures such as industrial gases, ethylene, propylene, naphtha and crude oil pipelines. These infrastructures enable to share the production capacities and trade commodities as necessary.

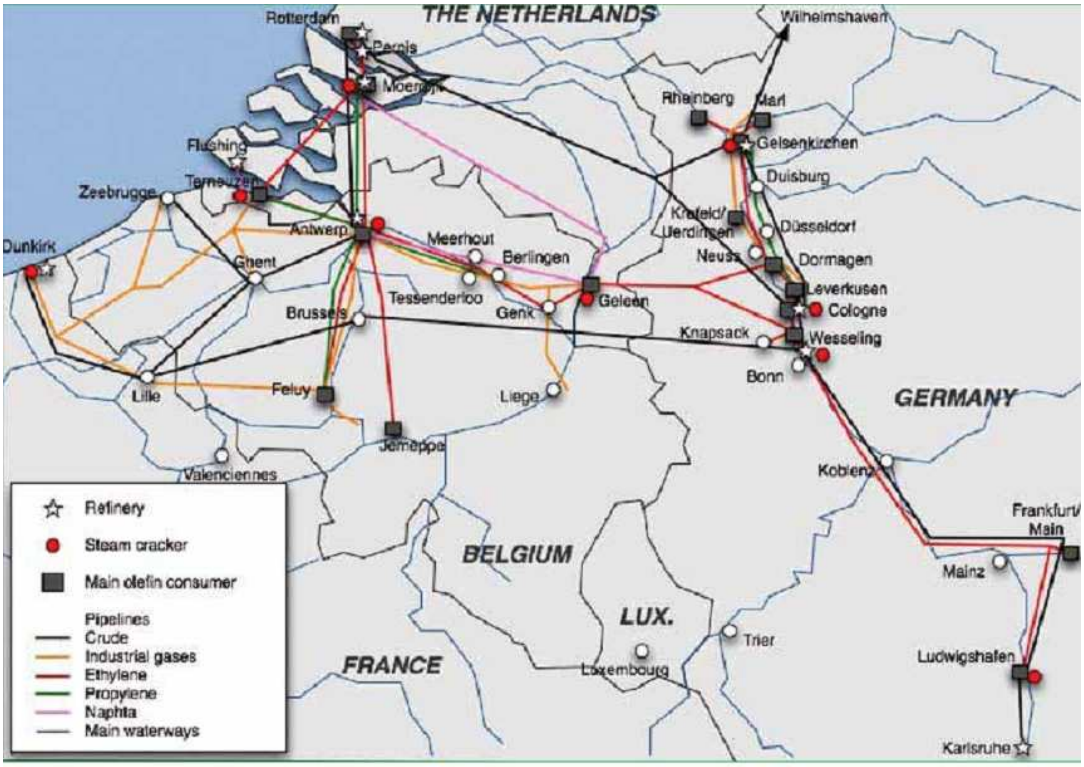


Figure 3.2.2-12 Overview of cluster interrelationships in the region ARRR (Source: EPCA 2007)

Innovations in clustering

Clustering is an ongoing trend in the European chemical industry. Mega-clusters may not be set up everywhere. For instance, interconnecting Northern Italy and Southern France would have to pass through the Alpes mountains, requiring either costly infrastructures or using road tunnels with the risk of transporting inflammable products.

Despite this macroscopic remark, integrating technically companies inside specific clusters offers significant added value. Several examples can be found in EPCA (2007); the case of INEOS Oxide Antwerp sub-cluster can be reported as representative situation.

INEOS Oxide manufactures ethylene oxide, a highly hazardous product unsuitable for transportation. In its production site, it managed to attract Japanese Kuraray to build an ethylene vinyl alcohol copolymer resin. Nippon Shokubai joined in turn with producing super-absorbent polymer, followed by GE Plastics, Fow, Seppic, Specialty Polymers Antwerp, Borealis and Praxair.

The integration is therefore as depicted below:

- INEOS Oxide supplies 7 customer companies with ethylene oxide
- All chemical companies benefit from Praxair produced oxygen and nitrogen
- All site stakeholders benefit from a common energy infrastructure and power by INEOS / Essent Energy.

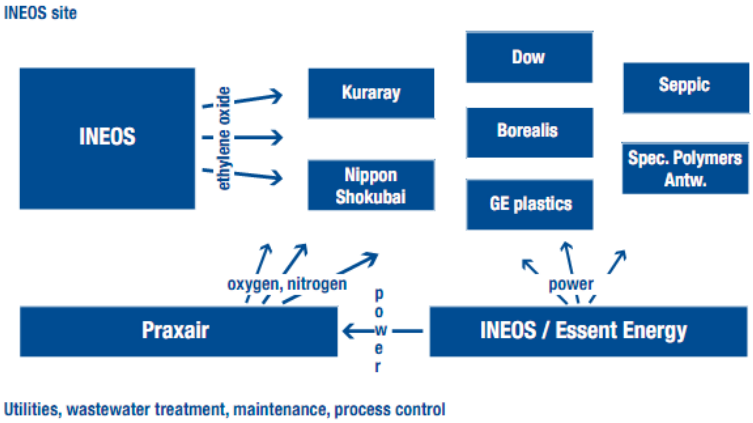


Figure 3.2.2-13 INEOS Oxide co-siting concept (Source: EPCA 2007)

Characteristics of clusters

Since a cluster gathers different companies, it tends to have very long lifetime since all member companies should leave at the same time to make it close.

The lifetime of chemical production site has therefore no fixed limit. Some European clusters are operated for more than 80 years. The process units can be replaced, upgraded, closed, installed but the site remains active in any case.

The technical lifetime of individual chemical process units may range from 30 to 40+ years. They may be upgraded or maintained so that the unit may be operated even longer. Units may be shutdown before the technical lifetime for economic reasons.

Despite the increasing production trend, new clusters will probably not be established.

Clustering and energy consumption

Although the production of chemicals is increasing, the energy consumption of the chemical sector remains stable. The industry has achieved significant improvements in the energy efficiency so that both trends equilibrate.

Clustering has several impacts on energy consumption:

- Process are energetically integrated: exothermic reactions supply heat to endothermic ones, steam being a common heat carrier
- Chemicals exchanged within the cluster may not require a specific energy-consuming preparation for transport
- The energy producer supplies a portfolio of companies/processes, which tends to flatten the energy demand but yet demands to produce all-year round energy, as necessary by back-up boilers
- Energy systems are a key feature for attracting new chemical companies in the cluster and retaining existing chemical activities; energy prices are a key parameter but also the flexibility, availability, security of supply and the general efficiency of the cluster energy system are key parameters as well.

- The security of supply is vital to all clusters so they pay attention to the redundancy of back-up systems, even more so in larger clusters.

Cogeneration is widely spread and energy systems are commonly shared in a cluster, on a specific area. All points on the map in the ARRR mega-cluster are relatively important clusters.

3.2.2.3. Case study of a European medium scale cluster

The information from this section originates from a kind private contribution. Due to confidentiality reasons, this section is restricted to a light summary. The full version will be made available only to EUROPAIRS partners in the final version of the study.

Introduction of the cluster industrial park

The cluster covers 800 hectares. It gathers R&D companies, start-ups, large chemical companies and around 70 service providers (energy production and distribution, water treatment, logistics, temporary work, legal support, engineering, etc.).

Service providers are an important feature of the site and contribute largely to its industrial attractiveness.

General overview of the energy flows in the cluster

Natural gas is purchased externally. 200 MW is used as fuel in embedded burners directly in chemical processes, 450 MW is used for the large cogeneration plant of the site and 175 MW in the several boilers dispersed all over the site.

The cogeneration plant produces 180 MW electricity and 220 MW steam. Electricity may be sold or purchased to the grid, depending on the economic rationale of doing so.

An important feature is the energy recovery in the site which takes two forms:

- Exothermic reactions produce steam from cooling water which is fed into the steam network and sent back to heat demanding processes (around 400 MW or twice the heat cogenerated)
- Some reactions produce high-calorific off-gases which are mixed with natural gas and burnt in dedicated boilers to produce steam for the site (around 300 MW or once and a half the heat cogenerated).

Steam network

The energy system consists of both a gas system supplying boilers and a steam grid carrying heat to demanding processes.

The steam network is made of a complex set of sub-networks. The highest steam pressure and temperature is 110-140 bars and around 500°C, which could be technically produced with a high temperature nuclear reactor.

Gas network and high-calorific off-gases

The gas network supplies internal dedicated boilers for energy use only (natural gas as feedstock is supplied by another network to keep a high purity).

Like in refineries (see dedicated paragraph), some chemical processes produce high-calorific off-gases in quantity and composition which vary significantly, depending on the portfolio of processes operated in the cluster. As the composition cannot be fixed, these off-gases cannot be sold on the gas market.

These off-gases (around 140 MW) are mixed with natural gas into the gas network of the chemical site and burnt into dedicated boilers (producing the above mentioned 300 MW), because of the obvious economic rationale of using a calorific gas which has no commercial value and because of environmental regulations which forbid the release of such gases. They may indeed contain methane, a much more powerful greenhouse gas than CO2.

High-calorific off-gases are specific to the production mix of each cluster. It is exactly similar to refinery gas and the energy and mass balance of the cluster must be analysed in depth in order to understand exactly the potential for cogeneration.

Cogeneration plant

The cogeneration plant operates a usual combined cycle gas turbine (1 gas turbine, 2 boilers and 1 condensing steam turbine)

For economic reasons, the cogeneration plants usually operate at full load with a small operational margin (e.g. 95%) in order to cope with sudden load uptake.

Load follow (and back-up capacities) is carried out via three main options:

1. increase the share of HP steam directly fed in the steam grid (the easiest option). Electricity production from the steam turbine will consequently decrease.
2. increase the plant load as it usually operates at 90%-95% with some operational margin
3. burn gas directly in the pipes exiting the gas turbine (also in case it trips or it needs a maintenance break) and heat directly the two boilers (which have each 100% capacity).

Each cogeneration scheme is specific to the cluster. Some clusters have up to 3 gas turbines, some have no steam turbine and/or possibilities for firing the boilers directly.

Boilers

In addition to the cogeneration plant, several boilers are operated at different locations at the site. They produce steam at different pressures (115 or 80 bars) and have different capacities. Some boilers are dedicated to burning specific off-gases (low calorific value, toxic pollutants...).

The design duty of these boilers is around twice the expected operation capacity in order to cope with strong variations (start-up, sudden stops of processes, disruption or maintenance of other boilers).

This redundancy achieves to secure the total availability of utilities for the site.

Heat demand

40%-50% of the steam supplied is consumed directly by chemical processes so only 50%-60% of the steam returns back to the cogeneration plant as condensate, the make-up water is taken from a river and demineralised on-site.

The yearly heat load curve is generally rather flat although significant fluctuation may occur:

- The yearly average depends on the year and the chemical activity.
- The peak load can be significant: during 2% of the year, the load can increase by up to 150% the yearly average.
- The normal daily fluctuations can reach up to 15% of the load (increase or decrease over one day).

3.2.2.4. Heat market of the chemical industry in Europe

There are around 40 chemical clusters operating a naphtha cracker in Europe, which is a sign the consumption of energy of these sites is large and the sites are very probably supplied by a cogeneration plant.

Considering that the cogeneration plant of the case study cluster has an average thermal capacity of 220 MWth, and that it is medium to large cluster, the plug-in market represented by the chemical clusters in Europe can be estimated considering different average thermal capacities:

Number of large clusters (est.)	40	40	40
Considered average thermal capacity on site (MWth)	150	200	220
Total thermal capacity of large chemical clusters (MWth)	6 000	8 000	8 800
Equivalent yearly consumption (GWh/y)	52 560	70 080	77 088

Table 3.2.2-3 Estimated heat market of the largest European chemical clusters

It must be noted that this estimate was done in absence of detailed data site by site.

This estimate compares well with:

- the CEFIC data heat purchased externally only (52 102 GWh/y); since the direct calculation is higher, it may be expected that some companies operate their own cogeneration plants and do not buy heat over the fence.
- the indirect calculation from emissions declared in ETS from the chemical industry (118 621 GWh/y); the difference can then be explained by the fact that the direct calculation above considers large clusters only whereas all chemical facilities are represented in ETS.

Due to the impossibility to consider detailed information site by site, the range of heat consumption estimated in this paragraph can be assumed as representative of the “plug-in” market for the chemical industry as a whole (including e.g. fertilisers).

The other chemical clusters may still consume some energy but they will tend to have no cogeneration plant on-site, a sign that their individual site consumption is lower.

3.2.2.5. Potential for nuclear heat

Nuclear energy may have several applications in the chemical industry heat market.

First, it may directly replace a cogeneration plant, supplying a chemical cluster with nuclear steam and electricity. This is favoured by:

- Individual site heat consumptions sufficiently large to accommodate a medium-large nuclear high temperature reactor
- Operational conditions compatible with a nuclear reactor (in particular cluster lifetime, relative flatness of the heat load curve)
- Already built infrastructures (boilers and possibly existing cogeneration gas plant, energy networks) to accommodate 1/ sudden time variations in the heat load of the site, 2/ peak load and 3/ the heat that cannot be supplied by the nuclear reactor during a maintenance break.

Second, a nuclear reactor may also benefit from the existing and planned pipeline infrastructures to poly-generate basic raw materials like hydrogen, oxygen, nitrogen, ammonia, syngas, ethylene, etc.) through co-located production units. This would have two consequences:

- A nuclear reactor supplying a dedicated chemical cluster with heat and electricity could supply it also with raw materials and could supply other distant clusters with surplus via pipelines.
- A nuclear reactor could be built distantly from chemical clusters and focus on poly-generating basic raw materials to be fed in the pipelines for distant clusters.

The main issues to be considered for a nuclear reactor to supply a chemical cluster or a chemical production unit in general would include:

- The steam purity, in particular the contamination by tritium
- The safety of the coupling
- The nuclear acceptability by neighbouring communities; the regions with the highest desnity of chemical clusters are also the most densely populated regions in Europe (Benelux and Germany)
- The availability of a full-load redundant back-up infrastructure on-site to accommodate unexpected load variations and to supply the cluster during the yearly maintenance break of the nuclear reactor; in case there are no sufficient back-up capacities, it would be necessary to build new ones, which would incur higher costs.

Back-up capacities should be made of conventional boilers rather than a cogeneration unit because the latter has the best technical and economic efficiency when operating at full load over long durations.

The load follow should not be an issue for nuclear, provided that a scheme like the one used for the medium scale cluster cogeneration plant is applied (unused steam serves is re-directed to electricity generation).

3.2.2.6. Conclusions and recommendations

- The chemical industry is a key sector in the European heat market. It is a versatile industry producing an outstandingly large number of products and supplying numerous consumer sectors mostly with intermediate chemical products.

- The EU chemical industry is a world leader and on an upward trend; it resists well to the growth of Asian players up to now.

- Energy is a key question for the competitiveness of European chemical companies which tend to gather into chemical clusters integrating different production units and sharing infrastructures, in particular energy production and integration (exchange between exo- and endothermic reactions, burning of high-calorific off-gases)

- There are possibly around 40 large clusters all over Europe and the densest regions are Benelux countries, Germany, Eastern France, Northern Italy, North-East Spain and Central Great Britain.

- European clusters tend to connect with neighbouring ones by pipelines which improve the operational efficiency of each company, as demonstrates the Antwerp Rotterdam Rhine Ruhr mega-cluster; there are plans to inter-connect all pipelines in Europe, creating an axis of pipeline infrastructures from Spain to Germany in the medium term.

- Nuclear energy could well supply existing clusters. They tend to have long lifetimes, flat energy consumption and existing back-up capacities which may take over unexpected load variations and supply the cluster during the yearly maintenance breaks of the reactor.

- A nuclear reactor could further benefit from poly-generating basic raw materials and supply distant clusters through the network of pipelines. In case it concentrates on this option, it may benefit from easier siting conditions, including nuclear acceptability.

- Considering the potential of the chemical industry, it is recommended to launch a study site by site to look at the energy and production balances of each site (especially the mass and energy balance of the high-calorific off-gases)

- It is also recommended to approach the European Technology Platform for Sustainable Chemistry to research and develop the coupling between a nuclear cogeneration plant and a chemical cluster and to customise a nuclear reactor to the operation of cluster energy systems as well as to partner with cogeneration plant operators and cluster legal organisations to discuss and develop nuclear cogeneration.

3.2.3. Ammonia, urea and fertilizers industry

Summary:

Ammonia and urea are the main heat demanding processes in the fertilisers industry, the former principally for the production of hydrogen and the second principally to compress CO2. Fertiliser producers usually operate within chemical clusters (see dedicated part). The particularity of the fertiliser industry is that ammonia consumes hydrogen and nitrogen, two basic raw materials that could be co-produced at a nuclear facility (so-called polygeneration), replacing a rather dispersed heat market by a more centralised direct raw material market.

This part uses information from BREF on Large Volume Inorganic Chemicals (BREF 2007b) and the contribution from a fertiliser producer.

3.2.3.1. Ammonia applications, industry and market

General introduction to fertilisers

Fertilisers are chemicals that are to bring essential nutrients to plants. The most important nutrients are nitrogen (N), phosphor (P) and potassium (K). The fertilisers industry is therefore based on important raw materials that are ammonia (bringing nitrogen), phosphoric acid and sulphuric acid, as depicted below:

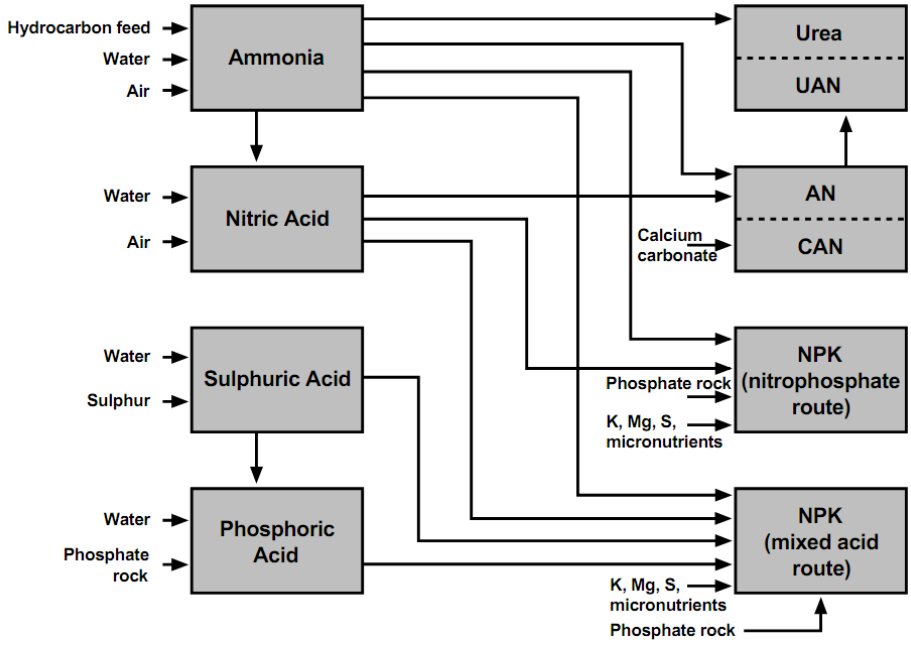


Figure 3.2.3-1 Relations between ammonia and its derivatives fertilizers products (adapted from EFMA 2000)

UAN = Urea Ammonium Nitrate, AN = Ammonium Nitrate, CAN = Calcium Ammonium Nitrate

Fertilisers applications

The table below summarises the main applications of each product (BREF 2007b):

Table 3.2.3-1 Main applications by product (Source: BREF 2007b)

Product	Raw materials	Main markets
Ammonia (NH3)	Hydrocarbons, air	80% production of nitrogenous fertilizers, 20% manufacture of plastics, fibres, explosives, hydrazine, amines, nitriles and other nitrogenous chemicals
Urea (CO(NH2)2)	Ammonia and CO2	Urea is mainly used as fertiliser in flooded rice cultures It is also a feedstock for melamine, resins and cattle feed supplement production
Ammonium nitrate (NH4NO3)	Nitric acid, ammonia	AN is used as nitrogenous fertiliser; it is a raw material for the production of Calcium Ammonium Nitrate
Calcium Ammonium Nitrate	AN, dolomite or limestone	CAN is the most applied fertiliser in Europe
Nitric acid (HNO3)	Ammonia, oxygen	Nitric acid is mostly used to form ammonium nitrate, other uses include production of explosives, caprolactam, adipic acid, dinitrotoluen or nitrobenzene
Sulphuric acid (H2SO4)	Sulphur, water	Sulphuric acid is used for in the fertilisers production, waste water treatment, manufacture of titanium dioxide, metal processing and batteries production.
Phosphoric acid (H3PO4)	Phosphate rock, water, sulphuric acid	Phosphate acid is mainly used for the production of fertilisers (80%) and animal feed supplement (8%); it can be also used for producing sodium, potassium, ammonium and calcium salts and for treating metal surfaces.

Fertilisers consumption in the world and in Europe

The global consumption of nitrogenous fertilisers has been steadily increasing, driven by the agricultural growth in Asia whereas the European consumption has decreased until stabilising in the 1990s.

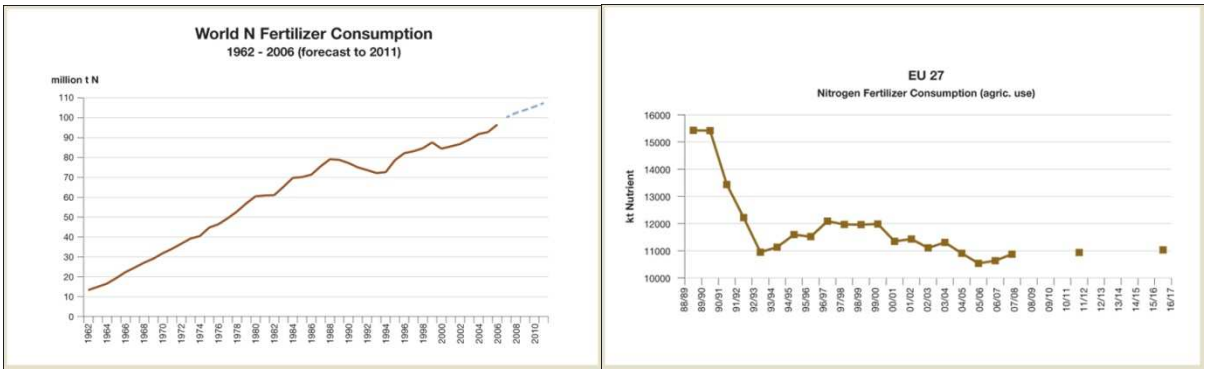


Figure 3.2.3-2 Consumption of nitrogenous fertilisers in the world (left) and in EU27 (right) (source: EFMA 2010)

Due to the transport costs and the availability of cheap natural gas in Asia, the growing Asian demand will not trigger the construction of new capacities in Europe.

In Europe, three very important European policies impact the industry, namely:

- the Common Agriculture Policy which encouraged the consumption of fertilisers in Europe, increased the land productivity (and therefore decreased the land used for agriculture)
- the biofuel policy which creates a new market and will expand the agricultural production
- the EU Emissions Trading Scheme which will increase the production costs of fertilisers and agriculture

Energy profiles and market trends

The table below summarises the energy profile, yearly European production, market trends, number of EU plants and the typical plant capacities for the fertiliser products.

Table 3.2.3-2 Energy profile, EU production, trends, number of plants and typical plant capacity by fertiliser product (Source: BREF 2007b)

Product	Energy profile	EU production (Mt/y)	Market trends	Number of EU plants	Typical plant capacities (t/d)
Ammonia	Heat intensive	11 (in 2001, 109 Mt/y worldwide)	Rising feedstock prices and hard market competition has pushed producers to revamp projects and locate new projects where conditions are competitive	50	1 000 – 2 200
Urea	Heat intensive	5.14 in 1999 in EU	Urea consumption has been steadily increasing, mainly driven by the Asian demand for domestic rice culture	16	1 000 - 3 500
UAN	Limited	3,72 in 1998 in EU	UAN follows urea market	19	200 - 2 000

Ammonium nitrate	Highly exothermic	4 in EU 40-45 Mt/y worldwide (estimate)	The European consumption of nitrogenous fertilisers has been decreasing in 1990s and then stabilising; the world consumption has been steadily growing since the last decades	28 (AN/CAN)	100 – 3 600
Calcium Ammonium Nitrate	Highly exothermic	7 in EU in 2006	Like AN	16 (CAN) + 28 (AN/CAN)	100 – 3 600
Nitric acid	Exothermic	16,6 in EU in 2003	Like AN	100	150 – 2 500
Sulphuric acid	Exothermic	22 in EU in 2004	Market trend is partially correlated to fertilisers consumption.	95	<250 – >1 000
Phosphoric acid	Exothermic	41,6 Mt/y worldwide in 2004	The consumption of phosphoric acid strongly decreased in Europe	≈20	500 (average)

Ammonia and urea are key commodities and the economic pressure pushes producers to find any way to optimise their processes. This part focuses on these two materials as they are the key raw material for the whole industry and are endothermic processes.

Localisation factors and mapping

Fertilisers are bulk materials with relatively low added value so transporting them on long distances has no economic rationale. Plants are therefore located close to the consumers, typically large countries with significant agricultural activities.

Localisation will depend on the expected production costs and focuses mainly on access to feedstock, the most important one being natural gas. A fertiliser production unit is therefore connected to the gas grid. Another localisation factor relates to the availability of logistical infrastructures.

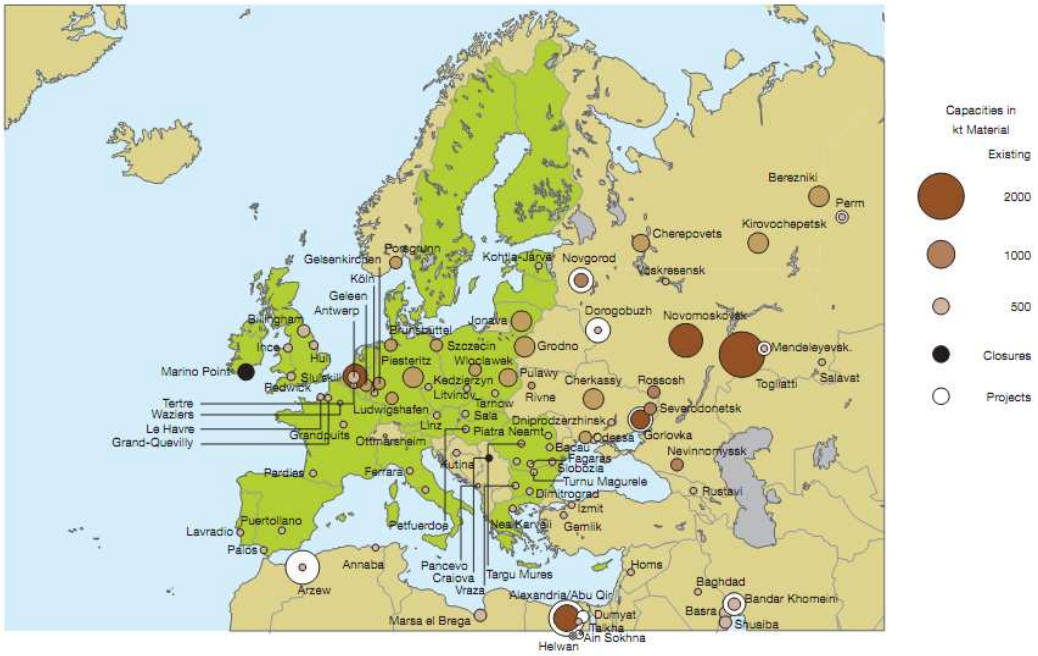


Figure 3.2.3-3 Ammonia production capacities in Europe and neighbouring countries in 2007 (Source: EMA 2010)

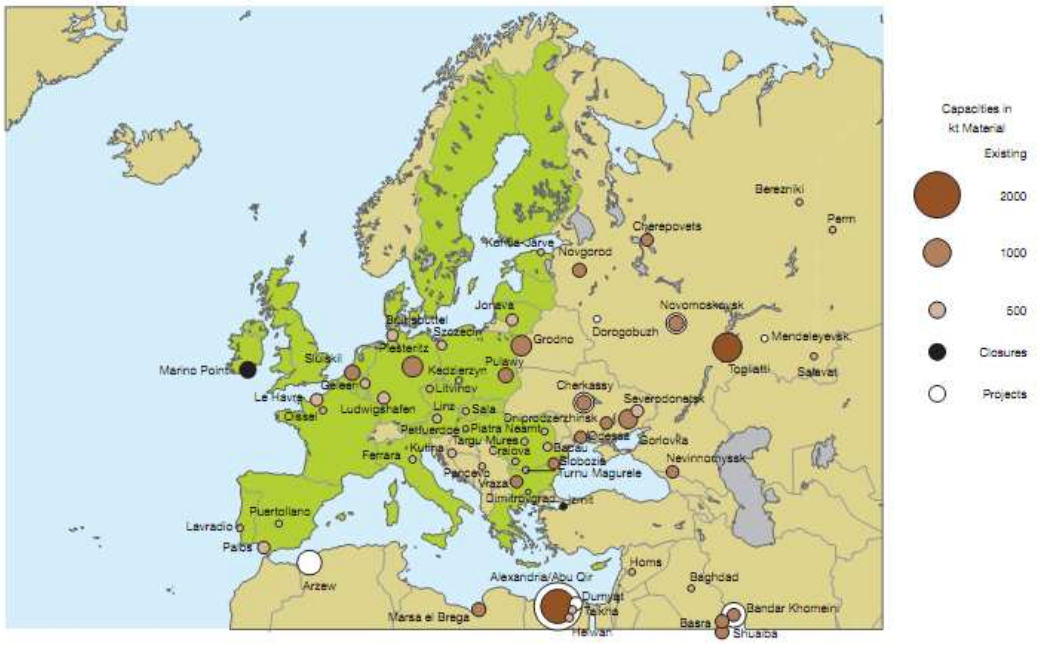


Figure 3.2.3-4 Urea production capacities in Europe and neighbouring countries in 2007 (Source: EMA 2010)

Figure 3.2.3-5 AN/CAN production capacities in Europe and neighbouring countries in 2007 (Source: EMA 2010)

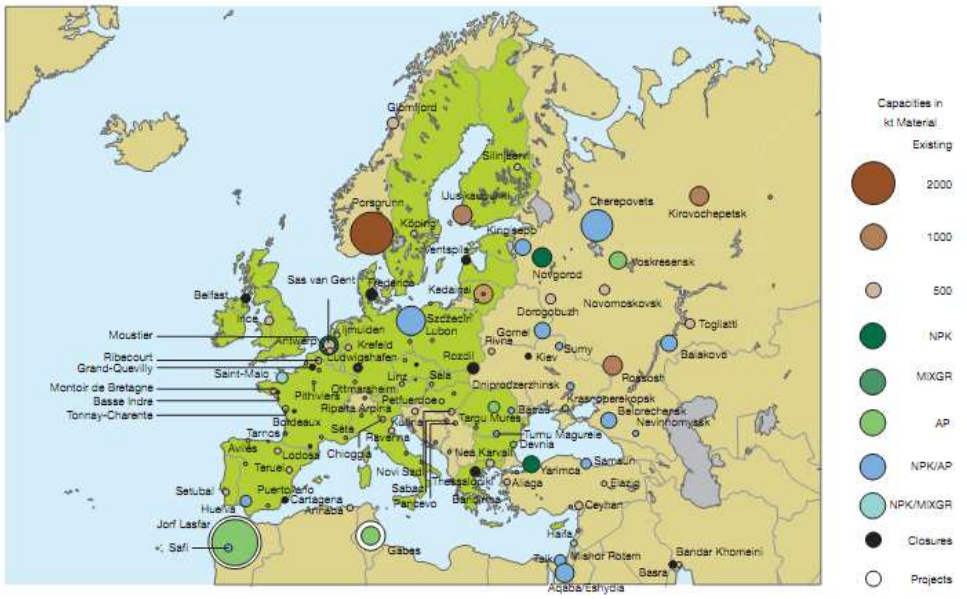


Figure 3.2.3-6 NPK fertilizers production capacities in Europe and neighbouring countries in 2007 (Source: EMA 2010)

Fertilisers industry

The fertiliser industry is widely spread in Europe with Benelux, Germany and Poland being the largest producing countries.

The main producers are: Norwegian Yara, German BASF, German SKW Plesteritz. French GPN, Dutch DSM and Spanish Fertiberia. Several smaller producers are also active and operate usually only one production site. Many of such producers can be found in Poland.

Fertilisers companies are usually active beyond the sole fertilisers production. For instance, in Poland, ZAK produces fertilisers and oxo-products, ZAP produces fertilisers, caprolactam, peroxo compounds and melamine, ZAT produces fertilisers, caprolactam and plastics, etc.

Fertilisers tend therefore to be produced within chemical clusters, benefitting from the energy integration and scale economies for infrastructures (see part on the chemical industry). There are very few standalone plants in the world and these plants are usually located close to very cheap natural gas reserves, where producing ammonia offers an economic interest.

Ammonia plants have a lifetime of around 50 years, most units in operation today are more than 30 years old.

3.2.3.2. Ammonia production route

There are two main production routes for ammonia, depending on how hydrogen is produced, as depicted below:

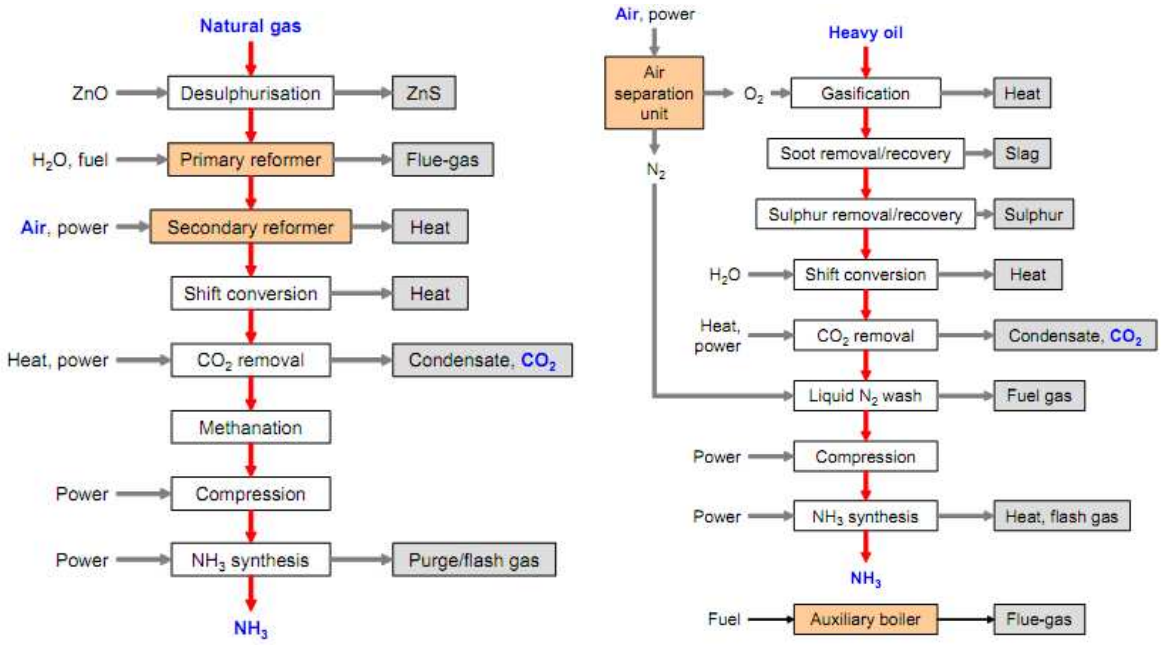


Figure 3.2.3-7 Main ammonia production routes using steam reforming (left) and partial oxidation (right) (Source BREF 2007b)

Steam reforming is the most common process for hydrogen production in the world (BREF 2007b); there are only few partial oxidation plants in Europe and autothermal reforming is used only in Poland. Electrolysis is not used in Europe.

Table 3.2.3-3 Hydrogen production processes and world capacities (Source: BREF 2007b)

Feedstock	Process	% of world capacity
Natural gas	Steam reforming	77
Naphtha, LPG, refinery gas	Steam reforming	6
Heavy hydrocarbon fractions	Partial oxidation	3
Coke, coal	Partial oxidation	13.5
Water	Water electrolysis	0.5

The production route using steam reforming is presented in details in the table below and the main differences with partial oxidation route are then presented.

Table 3.2.3-4 Description of the ammonia production route using steam methane reforming (Source: BREF 2007b)

Process step		Input	Output	Description	Temperature	Energy
1	Sulphur removal	ZnO, methane	ZnS, low-sulphur methane	Sulphur is hydrogenated into H2S which in turn produces ZnS	350-400°C	Heat demand
2	Primary reformer	Low S methane, H20	CO, H2	Technologies are the same than in refineries (steam reforming, partial oxidation or water electrolysis). The objective is to produce syngas, a mixture of CO and H2.	400-600°C	Heat intensive but half heat is recovered for other process steps
3	Secondary reformer	Air, syngas	Nitrogen enriched syngas	The objective is to add nitrogen to the syngas. The process air is compressed and heated following an adiabatic reaction (outlet gas are at 1 000°C)	500-600°C (air pre-heating)	Heat demanding but heat is also recovered
4	Shift conversion	N2 enriched syngas	N2, CO2, H2 mainly	The objective is to remove the remaining CO of the syngas in order to get a pure H2; this is achieved by the water gas shift conversion (CO+H2O -> CO2+H2)	350-380°C	Exothermic
5	CO2 removal	N2, CO2, H2	N, H2 mainly	CO2 is removed from the gas mixture by either chemical (using solvents) or physical absorption processes		Heat and power required
6	Methanation	N2, H2	N2, H2 pure	The small remaining amounts of CO and CO2 can poison the ammonia synthesis catalyst and must be removed in this step.	300°C	Exothermic
7	Compression	N2, H2	N2, H2	The mixture is compressed up to 100-250 bars, 350-550°C. Compressors are usually driven by steam turbines, using steam from the excess process heat	350-550°C	Power demand only
8	NH3 synthesis	N2, H2	NH3	The reaction is exothermic but unfavourable conditions makes necessary to increase pressure and control the catalyst temperature	350-550°C	Exothermic, power demand only

The main differences with the partial oxidation production route are:

- An air separation unit provides oxygen to the gasification of heavy hydrocarbons and nitrogen is used as a raw carbon
- The gasification step is carried at very high temperatures (1 400-1 500°C)

Process energy and cost comparison

There is a very wide diversity of processes for ammonia production and it is difficult to compare and classify them. The generic average values are reported below (BREF 2007b):

Table 3.2.3-5 Specific energy consumption by production route for ammonia (Source: BREF 2007b)

Process	Feedstock (GJ/t NH3)	Fuel (GJ/t NH3)	Steam (GJ/t NH3)	Relative investment depending on process and feedstock (SMR = 1)
Steam reforming route	22 – 25	4 – 9	4,5 – 4,8 *1,8 - 2,1 at stoichiometric ratio*	1 (natural gas only)
Partial oxidation route	28,8 – 34	5,4 – 9	3,6	1,5 (heavy hydrocarbons) 2 – 3 (coal)

Partial oxidation is the most costly option as regards investment and feedstock consumption, although steam consumption is lower.

Alternative routes

Alternative routes are related to hydrogen production routes. Nuclear assisted steam methane reforming would lower the CO2 emissions and the natural gas consumption.

Electrolysis represents an even simpler ammonia production route: producing hydrogen (and oxygen) from water electrolysis and nitrogen from air separation would skip all preliminary production steps related to natural gas reforming and would resume the ammonia production to compressing N2 and H2 (power or steam as mechanical medium demanding process) and ammonia synthesis (an exothermic, power demanding process).

The economic viability of this production route depends on the hydrogen production cost. Collateral advantages of this route like the rather pure quality of hydrogen produced by electrolysis (requiring no post-treatment) and the related CO2 emissions should also be taken into consideration.

3.2.3.3. Urea production route

Urea (CO(NH2)2) is produced by reacting ammonia (NH3) with carbon dioxide (CO2), with ammonium carbamate as intermediary product (NH2COONH4), as follows (BREF 2007b):

$$2\ NH_3 + CO_2 <-> NH_2COONH_4 <-> CO(NH_2)_2 + H_2O$$

Both reactions take place in liquid phase in the same reactor. Reaction 1 is fast and exothermic and goes to completion. Reaction 2 is slower and endothermic and does not go to completion.

For an economic conversion rate, urea producers tend to remove urea to create a chemical unbalance and favour reaction 2 and to decompose excess ammonia carbamate in NH3 and CO2 to recycle them into the process ("total recycling processes").

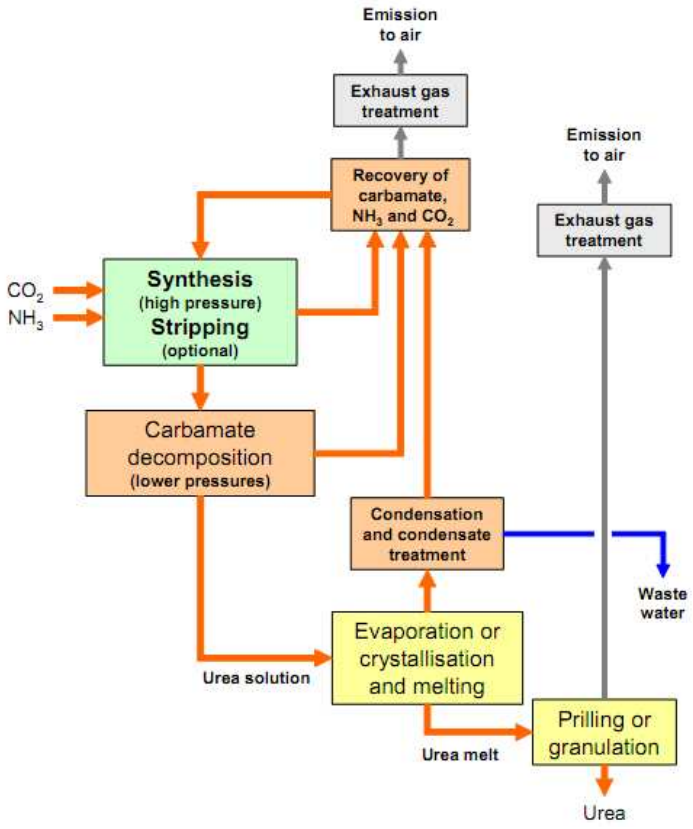


Figure 3.2.3-8 Overview of the production of urea by tota recycling processes (Source: BREF 2007b)

The urea synthesis takes place in a reactor at high pressure (140-250 bars) and temperature (180-210°C). Various strategies for recycling CO2 and/or NH3 and/or ammonium carbamate have been developed using CO2 and/or NH3 stripping processes with high pressure steam.

Energy consumption

The main consumption source in urea production is the CO2 compressor (which used to be electrical but now replaced by more efficient steam driven compressors) and steam for evaporation, vacuum making and prilling. The consumptions are as follows:

Table 3.2.3-6 Specific electricity and steam consumption for urea production (Source: BREF @007b)

	Process except compressor	Compressor	Total
Electricity (MJ/t urea)	54 – 108	*400 (if electrical)*	Steam driven: 54 – 108 Electricity driven: 454 - 508
Steam (MJ/t urea)	2,1 – 4,5	*400 (if steam driven)*	Steam driven: 402 – 405 Electricity driven: 2,1 – 4,5

3.2.3.4. Energy systems based on a real case example

This part uses information from a fertiliser company.

The facility is a chemical cluster where part of the production is made of fertilisers.

The site operates 5 boilers producing steam at 100 bars and 500°C which is first used to produce electricity and then sent to the chemical cluster.

2-3 boilers are operating which 2-3 are back-up capacities. Each boiler can produce 100 t/h steam, which is equivalent to a total installed capacity of 417 MWth (considering a steam energy content of 3 GJ/t).

The steam network includes two grids with operating pressures of 15 and 6 bars.

In normal operation, the fertiliser production plant does not require high amount of steam but plant start-ups (happening several times a year) require high pressure steam (70 bars for the ammonia plant).

Exothermic and endothermic systems are relatively but not completely integrated. Energy integration offers advantages (energy efficiency, service optimisation) but also disadvantages (interdependencies, lack of flexibility). Energy integration is therefore a trade-off between flexibility and energy efficiency.

The main energy consuming process is the syngas production plant (used for hydrogen production) and the urea production plant (in particular for CO2 compression).

The sole explosive product in the fertiliser chain is ammonium nitrate. The conditions for explosion are yet very restricted and the risk is very low.

3.2.3.5. Related energy market and potential for nuclear heat

Energy market

The energy market of ammonia and urea production is not representative of the fertiliser industry since they are usually integrated into chemical clusters with energy integration to some extent.

The overall calculated heat market for ammonia and urea production (considering that all urea production uses steam driven compressor, i.e. a maximum assumption) is reported below:

Table 3.2.3-7 Estimated energy market and site average thermal capacity for ammonia and urea production

Process	Production Mt/y	Number of sites	Energy market				Site average capacity (MW/site)	
			Heat (GWh/y)		Steam (GWh/y)			
			Min	Max	Min	Max	Min	Max
Ammonia SMR	10	46	11 111	25 000	12 500	16 111	31	40
Ammonia POx	*1*	*2*	1 500	2 500	333	333	19	19
Urea (steam driven only)	5,14	16	-	-	571	571	4	4

For ammonia production, steam methane reforming being the largest production route, represents the largest heat market for both heating and steam direct consumption. Partial oxidation is a marginal process with low market share. Urea production is a small heat market. The market is rather dispersed with low average site capacities.

It must be noted that ammonia and urea production units are mostly located in chemical clusters whose consumption are higher (see dedicated part).

Potential for nuclear heat

The heat market represented by ammonia production relates mainly to hydrogen production (nitrogen is produced by industrial gas producers independently). Supplying hydrogen and nitrogen produced via nuclear energy directly to the fertiliser producers would replace this rather dispersed heat market by a centralised market for raw materials.

Should hydrogen and nitrogen be competitively supplied, the ammonia production would be very much simplified to ammonia synthesis (N2 and H2 compression and NH3 synthesis in the reactor).

Even if hydrogen produced from water electrolysis or thermochemical cycles have slightly higher production costs than steam methane reforming (see part on hydrogen production), they could well be overall competitive considering the following points:

- The fertiliser industry would avoid investment costs related to the integrated hydrogen production units
- The hydrogen supplied would be of sufficient good purity to avoid any gas pre-treatment and reducing operating costs even further
- The nuclear polygenerated hydrogen would have very low CO2 emission so there would not be any over cost.
- Large production units centralised close to the nuclear facility would replace rather dispersed hydrogen production units and offer scale economies.

According to BREF 2007b, two plants produce ammonia from directly supplied H2 and N2 with small capacities: Sabinanigo in Spain (15 kt/y, operated by Energia e Industrias Aragonesas) and Hull in the United Kingdom (298 t/y, operated by Kemira GrowHow). In addition to the obvious environmental advantage of producing hydrogen from CO2 lean energy, this scheme looks therefore also technically and economically feasible.

An ammonia plant could however not be co-located at a nuclear facility, due to the transport costs and the impossibility to integrate with other production units (especially urea taking currently CO2 and NH3 as raw materials from the ammonia unit).

Considering the molar masses of ammonia (17 g/mol) and dihydrogen (2 g/mol), and the total ammonia production in Europe (around 11 Mt/y), the related hydrogen consumption would be a significant 51 bnm3/y. This estimate is in line but slightly higher than Roads2HyComm (2007, see next sub-chapter on hydrogen).

Replacing steam reforming in ammonia plant would further impact urea production which usually consumes ammonia and CO2 from ammonia production in the corresponding ratio for urea production. An alternative source of CO2 could yet well be found, e.g. a neighbouring fossil fuel power plant.

3.2.3.6. Conclusions and recommendations

- The fertiliser industry is integrated in the wider chemical industry; companies operate into clusters (see section 3.3).

- In the fertiliser industry, the heat market is represented by ammonia and urea production, all other fertilisers being produced mostly through exothermic processes.

- Ammonia represents a significant but dispersed heat market. Heat is mainly used for hydrogen production using steam methane reformers or partial oxidation units integrated directly into the ammonia plant.

- Ammonia production could well be simplified to ammonia synthesis if hydrogen and nitrogen were supplied directly to the unit, as it is already the case in two ammonia plants in Europe (Sabinanigo in Spain and Hull in the UK).

- Ammonia is therefore an example where a nuclear cogeneration plant could advantageously poly-generate hydrogen and nitrogen and replace an existing dispersed heat market by a centralised direct production of raw materials.

- Ammonia is the second largest hydrogen consumer in Europe. It is recommended to
    - liaise with the operators of the two European sites consuming N2 and H2 directly (Energia e Industrias Aragonesas for Sabinanigo and Kemira GrowHow for Hull) to benefit from their experience
    - liaise with European fertiliser companies to investigate the potential of replacing current embedded hydrogen production capacities by nuclear hydrogen and possibly jointly develop nuclear hydrogen production routes.

3.2.4. Soda ash production

Summary

Soda ash is a small but very attractive heat market for nuclear heat. Cogeneration is widely used, the operational conditions are compatible with nuclear energy and the existence of cogeneration power plants and boilers would hinder the necessary construction of back-up capacities.

This part uses information from the BREF report on Large Volume Inorganic Chemicals – Solids and Others industry (BREF 2007d), and from the contribution from a major European producer of soda ash.

3.2.4.1. Soda ash applications and market

Soda ash is a fundamental raw material for (BREF 2007d):

- Glass making: chemical reactant for flat and container glass manufacturing which decreases the melting temperature, and consequently the energy consumption.
- Detergents: raw material of a large number of prepared domestic products (soaps, scouring powders, soaking, washing powders) in which it acts mainly as water softener.
- Steel making: used as a flux, a desulphuriser, a dephosphoriser and a denitrider
- Non-ferrous metallurgy: treatment of uranium ores, oxidising calcinations of chrome ore, and lead, zinc and aluminium recycling
- Chemicals: soda ash and its derivatives are used in a large number of chemical applications
    - Refined sodium bicarbonate: animal feeds, paper industry, plastic foarming, water treatment, leather treatment, flue-gas treatment, drilling mud, fire extinguisher powder, human food products
    - Sodium sesquicarbonate: bath salts, water softener
    - Chemically pure sodium carbonate: pharmaceuticals, cosmetics, food and fine chemicals
    - Sodium percarbonate: used as bleaching agent
- Other applications include: synthetic fertilizers, production of artificial sodium or activated bentonites, colouring industry, enamelling industry, petroleum, fats and gelatine industries, etc.

It is consumed either as light soda ash (500kg/m3) or dense soda ash (1 000 kg/m3), the latter being the preferred for glass making and transportation over long distances.

Soda ash is a commodity traded worldwide. The price is based on the cost of manufacturing and delivery, which is an incentive to locate industrial sites as close as possible of their consumers. The world market is around 40Mt.

The sector has experienced a very low production growth in Europe (around 0,2%/y), although its consumers, in particular the chemical industry may have experienced a stronger growth.

There are 16 production sites in Europe with capacities ranging from 200 to 1200 kt/y. Soda ash manufacturing is very capital intensive:

Different process routes exist depending on the locally available raw material, which in turn influences the energy intensity of producing soda ash.

Region	Process used	Raw materials	Total capacity (2007, Mt/y)	Total energy requirements (GJ/t soda ash)
Europe	Solvay process	Salt brine (NaCl) and limestone (CaCO3)	10 Mt/y in EU27	9,7 – 13,6
North America	Na minerals process	Trona (large deposits in the US) and nahcolite	12	6,1 – 7,7
Asia	Mainly Solvay process, followed by new Asahi process	Salt brine and limestone (Solvay) olid salt and limestone otherwise	14 (10 by Solvay process, 4 by other processes)	Solvay process: 12,6 GJ/t New Asahi 8.9 GJ/t

Table 3.2.4-1 Process used, total production capacity and specific energy requirements by regions in the world (Source: BREF 2007d)

This means that European producers face the largest energy intensity compared to their extra-European competitors, due to the less interesting raw materials available locally.

Solvay is the largest European producer of soda ash and produces also several other chemicals (peroxides, fluorised products, sodium bicarbonate, caustic soda, chlorinated products, etc.) and plastics (PVC and specialty polymers). These last sectors demand less energy, except the chlorine for PVC production which require significant amounts of electricity in the electrolysis of salt brine.

Other EU27 soda ash producers include Brunner Mond (UK), Clech (PL), Novacarb (FR), SC GHCL Upsim Romania (RO), Sodawerk Stassfurt & Co (DE).

3.2.4.2. General information on soda ash plants

Although it is difficult to draw any generality on a small sample of 14 European production sites, some common characteristics of the soda ash sector are reported below:

- Most soda ash plants are located relatively close to some cities of several thousands people (e.g. in France, Spain, Italy, Germany); there are still some exception.
- Soda ash plants are usually not integrated into chemical clusters. They mostly produce only soda ash; in some cases, chlorine sodium electrolysis plant may be also co-located in the plant (whose products are Dichhlorine gas Cl2 and caustic soda NaOH).
- Soda ash plants have outstandingly long onstream time of usually 8 500h/y or higher. Equipments are redundantly built so that one train can be maintained while the others are

operating. Therefore, maintenance breaks are generally not necessary. The maintenance of common parts may require some decrease in the production or even a stop, but this is rare. The shutdown of the plant for any reason may not last longer than 1 week.

- The sector has an important technical and market inertia: the chemical reactions taking place in the Solvay process have constant times larger than a day and the market consumption of this fundamental raw material is not fluctuant on the short. Yet, long term trend can be observed. For instance, the production of soda ash has constantly decreased since the economic crisis in 2008 down to 50% of the capacities.
- Soda ash plants have very long "lifetime" because all equipments can be replaced. Some sites are therefore older than 100 years.
- The soda ash sector is very capital intensive so that delocalisation is generally not an option and the plant decommissioning is a last resort option.
- Soda ash production is also very energy intensive and emits CO2 (part from the process itself, the rest from the energy supply system) so producers are very keen to find low-carbon competitive energy sources.

The list of production sites in EU27 in 2007 was as follows (adapted from BREF 2007d); the site in Austria of producer A is not closed.

Producers		Country - location	Capacity (kt/year)	Plant start-up year
Producer A	1	France – Dombasle	700	1874
	2	Germany – Rheinberg	600	1903
	3	Germany – Bernburg	540	1883
	4	Spain – Torrelavega	950	1908
	5	Italy – Rosignano	1020	1917
	6	Portugal – Povoa	230	1934
		~~Austria – Ebensee~~	~~160~~	~~1885~~
Producer B	7	Bulgaria – Devnya	1200	1954
Producer C	8	United Kingdom – Northwich (Winnington/Lostock)	1000	1873
	9	The Netherlands – Delfzijl	375	1958
Producer D	10	France – La Madeleine	600	1884
Producer E	11	Germany – Stassfurt	450	1886
Producer F	12	Poland – Janikowo	550	1957
	13	Poland – Inowroclaw	550	1879
Producer G	14	Romania – Govora	400	1960
Producer H	15	Romania – Ocna Mures	310	1894
Producer I	16	Germany – Ludwigshafen	65	-
		Total EU-25 + 4 Countries	**9540**	**1873 – 1975**

Table 3.2.4-2 List of European soda ash production sites by Member State and producer (Source: BREF 2007d)

3.2.4.3. Energy consumption of soda ash plants

The Solvay process requires mostly thermal energy, whereas the electrolysis of chlorine sodium is an electricity intensive process.

The energy consumption is proportional to the installed production capacity of the plant. It varies from 60 MWth for a 200 kt/y soda ash plant to 300 MWth for a 1 000 kt/y plant and up to 350-400 for a 1 200 kt/y plant.

Steam is distributed via a steam network at low pressure (1-2 bars), medium pressure (12-15 bars) and possibly high pressure (30-40 bars), depending on each site.

Steam is mainly used as heat carrier, but 40% is consumed directly in the plant, mainly for the ammonia distillation unit. The heat contained in this consumed steam is yet taken off before it is consumed: this steam is produced at high pressure, passes into several heat exchangers, decreasing its pressure and finally fed in the low pressure steam network (1-2 bars). This means that in mass 40% of the steam is removed, but in energy almost all heat is taken.

The energy profile of soda ash plants is very flat since they have outstandingly long onstream time, up to 8 500 h/y or higher. The energy consumption is therefore very stable and no brusque time variations are to be observed.

3.2.4.4. Energy production at soda ash plant

All soda ash plants in Europe are supplied with captive cogeneration power plants. They are usually located no farer than 1km. There were no particular issues, in particular safety or process redesign to take into account while installing these cogeneration capacities.

There are two main technologies that can be found at each site:

- A boiler produces steam at 100-140 bars and 540°C which is injected in a steam turbine producing some electricity via a generator; the turbine outlet steam (300-400°C, 40 bars) is injected in the network; the form of energy produced may be 10% electricity and 90% steam.
- A gas turbine activates a generator producing electricity and the heat of the outlet exhaust gas is recovered in a heat recovery boiler producing steam which in turn activates a steam turbine generating electricity. The exiting steam (300-400°C, 40 bar) is fed in the plant steam network. The form of energy produced may be 55% electricity and 45% steam.

The electricity generated is usually sent to the electrical grid. The production of electricity usually depends on various parameters such as the national legislation (whether they favour cogeneration electricity or not), the arrangement with the grid operator, the need for steam and electricity from the plant, the price of electricity, etc.

Steam supply lower limit is 60% of the plant capacity, below this would trigger the shutdown from the soda ash plant. Redundant steam capacities are therefore built on-site.

The use of steam is already optimised in soda ash plant so no further extension can be expected. The lime kilns, which require a lot of heat, provided currently by coke, could possibly be supplied with nuclear steam but it would incur a major redesign and some technical research, which is not a priority for soda ash producers.

3.2.4.5. Example of a large soda ash plant

A large soda ash plant of 1 020 kt/y consumes around 300 MWth, equivalent to a steam supply of 400 t/h.

This large plant has both a CHP plant and two back-up boilers.

- The CHP plant specificities are
  - The plant comprises two gas turbines generating 2 x 150 MWe and one steam turbine generating 60 MWe (for a total of 360 MWe).
  - The thermal capacity is 300 MWth.
  - Steam is produced at 160 t/h, 400°C, 40 bar + 400 t/h, 300°C, 14 bars as a design duty and 115 t/h and 285 t/h in average. The design duty can accommodate a 20% peak.
  - The redundancy in the gas turbines enables to secure the steam supply in case of incident or shutdown of one turbine.
- The two back-up boilers are located in two separated buildings and produce respectively 145 t/h and 35 t/h at 400°C, 40 bars.

Electricity is generated in winter as an arrangement with the grid operator and provides a net income to the company.

3.2.4.6. Heat market of soda ash production and potential of nuclear energy

Heat market

Soda ash plants have the following energy consumption (BREF 2007d)

Energy and application	MWh / t of soda ash (dense)
Heat for lime kilns *(impossible to supply externally at the moment)*	0,61 – 0,78
Heat for soda ash plant *(supplied by cogeneration steam)*	2,03 – 2,87
Electricity consumed by soda ash plant	0,05 – 0,13

Table 3.2.4-3 Specific energy consumption in a soda ash plant by application and type (Source: BREF 2007d)

Considering only heat for the soda ash plant, which is already supplied by cogeneration and boiler plants, and applying the above figures to each production sites, we obtain:

Production sites	Capacity (kt/y)	Heat demand (GWh/y)		Equivalent thermal capacitiy (MWth)	
		Min	Max	Min	Max
1	700	1 423	2 009	167	236
2	600	1 220	1 722	144	203
3	540	1 098	1 550	129	182
4	950	1 932	2 726	227	321
5	1020	2 074	2 927	244	344
6	230	468	660	55	78
7	1200	2 440	3 443	287	405
8	1000	2 033	2 869	239	338
9	375	763	1 076	90	127
10	600	1 220	1 722	144	203
11	450	915	1 291	108	152
12	550	1 118	1 578	132	186
13	550	1 118	1 578	132	186
14	400	813	1 148	96	135
15	310	630	890	74	105
16	65	132	187	16	22
TOTAL	**9540**	**19 398**	**27 375**	**2 282**	**3 221**

Table 3.2.4-4 Heat demand and equivalent thermal capacity per European production site

The thermal capacities are calculated considering an onstream time of 8500 h/y.

The heat market related to soda ash is rather limited (19 to 27 TWh). If adding the lime heat consumption, the heat market would not be much larger (25 to 35 TWh).

The equivalent thermal capacity is equivalents to 5 to 6 nuclear reactors with capacity 500 MWth and 8000h/y availability, which is rather low.

Sites 5, 7 and 8 are particularly suitable for accommodating a large nuclear reactor.

Potential of nuclear heat in the soda ash sector

Nuclear reactors could well be plugged in a European soda ash production plant for the following reasons

- It is technically feasible. The steam network already exists, the steam consumption would be compatible with a nuclear high temperature reactor: 100-300 MWth, 400°C and 40 bars, with 40% of steam production take away for the closed steam loop.
- The co-location of a chlorine sodium electrolysis plant would provide an additional non-negligible demand for base load electricity.

- The soda ash plants do not have major safety issues to deal with. There are no explosive products, except ammonia.
- The lifetime of soda ash plant is compatible with the long lifetime of nuclear reactors (60-80 years)
- There would be no need for building back-up capacities, since the existing CHP and boilers may be kept.

Attention should yet be paid to the following points:

- The long maintenance breaks of nuclear reactors (3-5 weeks) are not compatible with long onstream time of soda ash plant and would require having a 100% back-up capacity (feasible as seen above).
- Since some soda ash plants are close to some cities, the nuclear acceptance may be an obstacle to plugging in a nuclear reactor. The isolated plant in Bulgaria, which has the largest installed capacity in Europe (1200kt/y), could be yet a good starting point.

3.2.4.7. Conclusions

- Soda ash producers are under economic pressure due to the capital intensity of the sector, the worldwide competition and the energy intensity of the Solvay process

- The industrial sector demonstrates therefore some stability: delocalisation and shutdown of plants are unusual; the market of this basic commodity is relatively stable and does not fluctuate much in the short term.

- European soda ash producers are keen to find low-carbon alternatives to fossil fuels.

- Soda ash represents a relatively small heat market but is an example of a plug-in market, because of compatible operational conditions (temperature, pressure, lifetime, safety issues, onstream time, availability of back-up capacities). Yet some sites are close to cities and raise the issue of nuclear acceptance. The production site in Bulgaria is very promising from all respects and could be analysed in preference.

3.3. Industrial gases

3.3.1. Hydrogen production

Summary

Hydrogen production is a viable and potentially considerable market for nuclear heat. Nuclear reactors could produce competitive hydrogen by nuclear assisted steam reforming, high temperature electrolysis or thermo-chemical cycles. The competition with the numerous other production routes will yet be fierce. Hydrogen distribution by pipeline is a mature technology. In the denser consumer regions, pipelines are already in operation so a nuclear reactor could be built at any distance from its consumer, lifting the issue of siting.

This part uses data from the European project Road2HyCom (www.roads2hy.com) which produced valuable information on the hydrogen economy.

3.3.1.1. Hydrogen applications and market

Applications

Hydrogen has multiple applications.

- Refining: This is the largest single application is hydrodesulfurisation of crude oil, hydro cracking and other hydrotreatments
- Ammonia production**:** ammonia is made of nitrogen and hydrogen (NH3) and requires in the production process significant amounts of hydrogen
- Chemistry: for plastic production
- Glass making
- Electronics
- Metallurgy and metal fabrication (H2 is in particular a reducing gas)
- Aeronautics (as rocket fuel)

Consumption

Many industrial processes consume hydrogen. The first one is refining with almost 50% of the market, followed by ammonia (32%). The third and fourth sectors are methanol (5,5%) and metals (4,5%). The four sectors account altogether for more than 90% of the current hydrogen market.

	Consumption [bn m³]		Growth rate [%/year]	Share of total [%]	
	2003	2008 extrapolation		2003	2008 extrapolation
Refining	30.56	44.74	7.9	49.7	58.6
Ammonia	19.44	19.50	0.1	31.6	25.5
Methanol	3.36	3.10	-1.6	5.5	4.1
Metals	2.67	3.25	4.0	4.3	4.3
Cyclohexane	1.01	1.11	1.9	1.6	1.5
Aniline	0.95	1.05	2.0	1.5	1.4
Caprolactam	0.71	0.75	1.0	1.2	1.0
H_2 Peroxide	0.70	0.75	1.2	1.1	1.0
Oxo Alcohols C8	0.34	0.35	0.6	0.6	0.5
Oxo Alcohols C4	0.26	0.27	0.7	0.4	0.4
Toluene Diiscocyanate	0.38	0.35	-1.6	0.6	0.5
Hexamethylenediamine	0.31	0.33	1.6	0.5	0.4
Adipic Acid	0.15	0.16	0.8	0.3	0.2
Hydrochloric acid	0.10	0.10	-0.4	0.2	0.1
Tetrahydrofuran	0.21	0.22	1.6	0.3	0.3
Fats and oils	0.31	0.30	-0.3	0.5	0.4
Float glass	0.04	0.05	3.4	0.1	0.1
Electronics	0.03	0.04	2.3	0.1	0.0
Total	**61.53**	**76.41**	**4.4**	**100**	**100**

Figure 3.3.1-1 Hydrogen consumed by major production processes in Western Europe (source Road2HyCom 2007)

The potential uptake of hydrogen fuel cells would add an additional demand of 154 bn m3, following for instance IEA scenarios (IEA 2005).

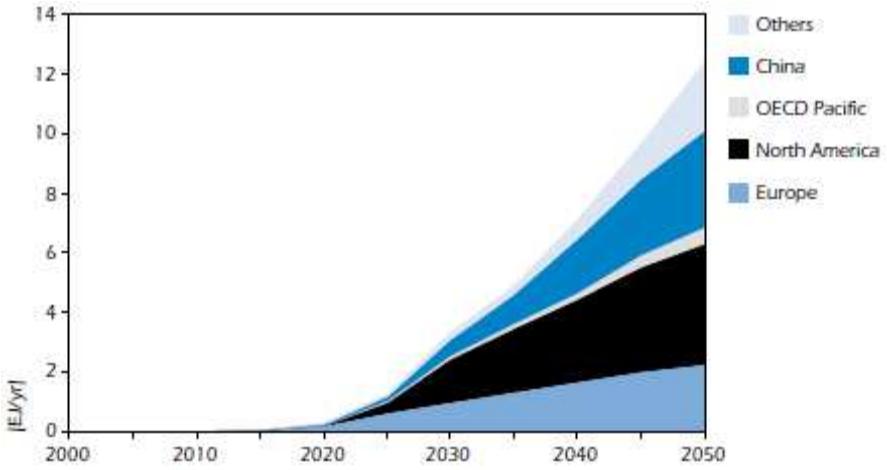


Figure 3.3.1-2Hydrogen demand for fuel cells by region (Source: IEA 2005)

In refineries industries, the consuming processes are hydro-cracking, hydrorefining and hydro-treating, that we have seen will tend to increase due to the re-equilibration of diesel/essence unbalance and the increasing sulphur content of the processed crude oil.

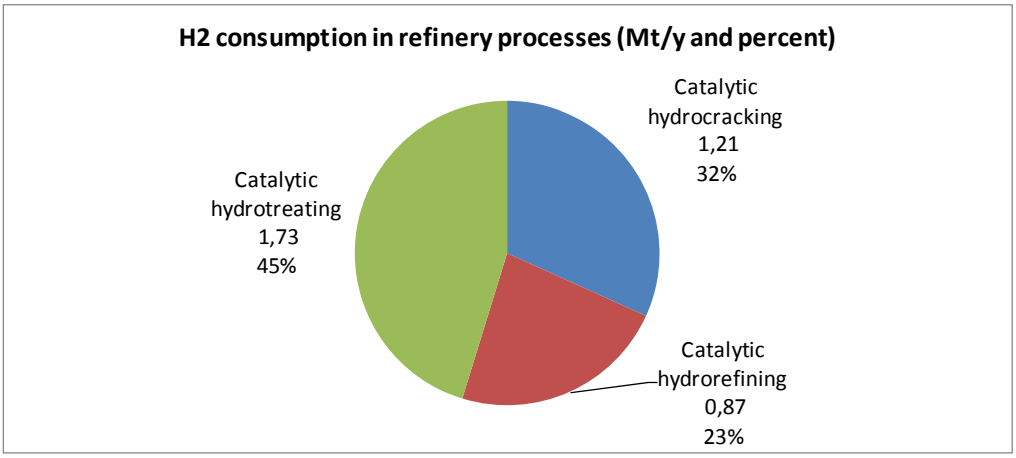


Figure 3.3.1-3 Hydrogen consumption in refinery processes (Mt/y and percent)

Production

The producers of hydrogen can be distributed into:

- Captive users: mostly industrial gas companies that produce on-site at a customer exclusively for him
- Merchants: companies that trade with hydrogen, sometimes producing the hydrogen themselves
- By-product producers: hydrogen that is produced inadvertently as a by-product of a process

The production of hydrogen production between these categories of players is estimated in Europe (and not only in Western Europe as the table above) as follows; the by-product category is an estimation that was expressly pointed to be indicative (Roads2HyCom 2007):

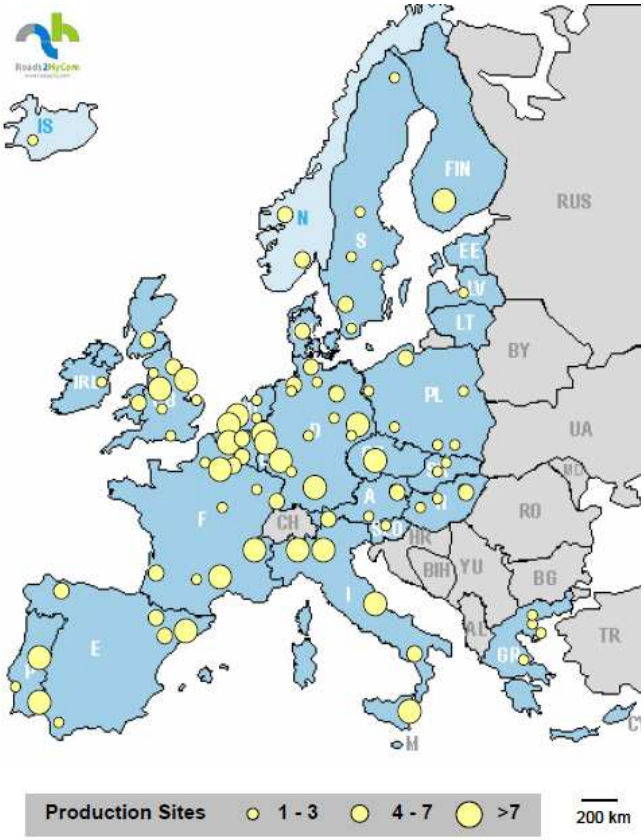
Market sector	H_2 production
By-Product	23
Captive	57
Merchant	8
Total	**88**

Figure 3.3.1-4 Hydrogen production by category in Europe (bn m3, source Roads2HyCom 2007)

As by-product hydrogen may not be automatically used in hydrogen demanding processes, the hydrogen market must be limited to its commercial part, i.e. 65 bn m3.

The uptake of fuel cells would therefore represent a +230% increase in the required production capacities, and a +150% considering the full use of by-product hydrogen.

The mapping of the production sites highlights several regions with denser production sites: Benelux, Rhein-Main in Germany, Northern and Southern France and Northern Italy.



Zone	Country	bn m³
EU 25	Austria - Österreich	1.9
	Belgium - Belgique - België	5.7
	Czech Republic -Ceska Republika	0.9
	Denmark - Danmark	0.2
	Finland - Suomi	1.8
	France	7.1
	Germany - Deutschland	21.5
	Greece - Ellada	0.8
	Hungary - Magyarorszag	1.0
	Ireland	0.9
	Italy - Italia	6.6
	Lithuania - Lietuva	0.6
	Netherlands - Nederland	10.1
	Poland - Polska	4.2
	Portugal	1.2
	Slovakia - Slovenska Republika	0.9
	Slovenia - Slovenija	0.0
	Spain - España	5.9
	Sweden - Sverige	1.3
	United Kingdom	7.6
	Total EU 25	80.3
CC	Bulgaria	1.8
	Croatia - Hrvatska	0.8
	Romania	5.5
	Turkey - Turkiye	2.2
	Total CC	10.2
EFTA	Iceland - Ísland	0.0
	Norway - Norge	1.0
	Switzerland - Schweiz - Suisse - Svizerra	0.6
	Total EFTA	1.6
Total		**92.1**

Figure 3.3.1-5 Geographic distribution of hydrogen production sites by region (number of sites, source: Road2HyCom 2007)

3.3.1.2. Hydrogen production routes

Technologies

There are an extraordinary large number of production routes for hydrogen which are either deployed at industrial scale or under development (US DoE 2003, Roads2HyCom 2009 and 2010, Ahmed et al 2002, plus all references in the part dedicated to hydrogen):

Table 3.3.1-1 List and description of hydrogen production routes and their development status (Sources: US DoE 2003, Roads2HyCom 2009 and 2010, Ahmed et al 2002)

Resource / approach	Production route	Short description	Development status
Fossil fuels	Steam reforming using natural gas or naphtha	Steam reforming steps are 1/ production of syngas (endothermic), 2/ conversion of CO into H2 (water-gas shift reaction, exothermic) and 3/ purification of H2 either by methanization of CO and CO2 (95-98% H2 purity) or by Pressure-Swing Adsorption (99,9% H2 purity). Steam reforming requires a lot of heat, which is usually provided by burning a part of the feedstock (gas) and	Industrial scale

		could also be supplied by an alternative source of heat, ideally low-carbon.	
	Steam reforming using other feedstocks	Such steam reforming may use heavy oils, coal or biomass. They emit however more CO2 than steam methane reforming because the H/C ratio is lower in liquid and solid fossil fuels.	Industrial scale
	Partial oxidation of coal	Partial oxidation follows the same principle as steam reforming although steam (H2O) is replaced by oxygen (O2); the reaction is exothermic.	Industrial scale
	Auto thermal reforming	Auto-thermal reforming is a combination of partial oxidation and steam reforming, in a balanced thermal way; outlet temperatures of syngas are as high as 1100°C. Using catalysts decrease the required process temperature.	Mature
	Combined cycle method for reforming coal using Ca(OH)2	No information available	Under development
	Coal or biomass gasification	Coal to Gas (CTG) or Biomass to Gas (BTG) is the reaction between the carbonaceous feedstock and oxygen and steam. This requires a significant supply of O2.	Industrial scale (South Africa)
	Pyrolysis	Biomass (or coal) pyrolysis thermally degrades the feedstock in a mixture of gases, char and an oxygen-rich liquid; it takes place at 500-800°C	Under development
Water	Water low temperature electrolysis	H2O molecule is broken into H2 and O2 by applying a rather important electrical field on water; this method coproduces very clean H2 and O2 but is very electro-intensive. The theoretical voltage to apply is 1,23V (equivalent to 237kJ/mole H2) but in practice, voltages of 1,55-1,65V must be applied. Electricity may be produced from any energy source.	Mature
	Water high temperature electrolysis	The water electrolysis is assisted by heat, increasing the overall efficiency	Under development
Solar energy	Photocatalytic water splitting	These cells use a catalyst cycle producing hydrogen using the energy of light for heat and for creating a DC voltage	Under development
	Grätzel cell	The Grätzel cell is an ameliorated photovoltaic water splitting process using a nanocristalline TiO2 dye film	Under development
Biological and biomimetic systems	Many processes based on natural examples	Such systems would use natural and modified organisms like bacteria or algae to produce hydrogen by photosynthesis, fermentation, digestion, photolysis, copying a natural production cycle. The energy performance are yet rather low, lower than PV cells	Research
Thermo-chemical cycles	Sulfur Iodine	This cycle mixes two sub-cycles using sulfur and iodine. The energy efficiency is high and only thermal energy would be required for operating the process (no electrolysis).	Under development Demonstrated
	Hybrid Sulfur	This is another sulfur cycle consuming both thermal energy and electricity for electrolysis. H2O is mixed with SO2 and electrolyzed (no use of iodine in a second sub-cycle)	Under development Demonstrated

	Sulfur Bromide Hybrid	This cycle resembles to the Sulfur Iodine except that Iodine is replaced by Bromide and that the Br sub-cycle necessitates electrolysis.	Under development Demonstrated
	Other cycles	Other cycles includes Ca-Br (not demonstrated), Ca-Br-Star, Copper-Chlorine hybrid, Iron-Chlorine. Copper Sulfur Hybrid, Vanadium chlorine	Research
Other methods	Al-Ga alloy (Woodall 2009)	Aluminum put into liquid Ga produces naturally H2, alumina and heat following the reaction: Al + H20 -> H2 + Al2O3 + heat Ga serves as catalyst removing the passivating alumina layer which tends to cover Al naturally and enable the reaction to be sustained.	Under development Demonstrated

It must be noted that

- Fossil fuels and biomass: The production routes from fossil fuel and biomass necessarily emit CO2. Furthermore, they produce syngas (a mixture of CO and H2) with a variable composition depending on the process; this syngas requires therefore a further treatment to obtain a H2 gas with a sufficient purity.
- Electrolysis: electrolysis co-produces a high purity H2 and O2 which can be sold directly with not much post-treatment processes. Both products need therefore to be valued in the business case of electrolysis.
- Biomimetic systems: such systems depend on the understanding of certain living organisms, which can have great level of complexity. The engineering of new organisms will require genetic modifications. The H2 produced is generally not absolutely pure and the yields are still rather poor, because many other processes necessary for life (absorption of nutriments, production of proteins, cell-repair, etc.) require energy.
- Thermochemical cycles: such cycles take benefit from specific elements decreasing the energy need. They emit no CO2 but may require significant engineering to accommodate safely the greater complexity of the internal cycles. Like electrolysis, they co-produce oxygen.

The current distribution of the European hydrogen production by production route is (adapted from the data of Roads2HyCom 2007, BREF 2007):

Table 3.3.1-2 Distribution of the European hydrogen production by production route (Source: adapted from Roads2HyCom 2007 and BREF 2007)

	Process	Total (km3/d)	Total (bn m3/y)	Percentage
On purpose	Steam Methane Reforming	127 311	46	51,6%
	Partial Oxydation	18 208	7	7,4%
	Steam Naphtha Reformer	16 799	6	6,8%
	Steam Reformer	2 122	1	0,9%
	Water electrolysis	528	0	0,2%
	Topsoe Convection Reformer	120	0	0,0%
	SUB TOTAL	***165 089***	***60***	***67,0%***
By-product	Ethylene	14 212	5	5,8%
	Chlorine sodium hydroxide electrolysis	12 535	5	5,1%
	Styrene	3 684	1	1,5%
	Acethylene	1 760	1	0,7%
	Sodium Chlorate	1 150	0	0,5%
	Coke oven gas	34 096	12	13,8%
	Other	13 962	5	5,7%
	SUB TOTAL	***81 399***	***30***	***33,0%***
TOTAL		**246 488**	**90**	**100,0%**

Steam Methane Reforming is the very first route with more than half of the total H2 produced and ¾ of the hydrogen produced on purpose. The second route, far behind, is partial oxidation, steam naphtha reformer. Water electrolysis is only marginal.

By-product hydrogen arises from mostly coke oven gas, ethylene and chlorine sodium hydroxide electrolysis.

Costs

The costs of several production routes are reported below from Roads2HyCom publications (2008e and 2009); some key parameters are summarised also.

It must be noted that the economic evaluation of the each production route depends greatly on the assumptions which are made following specific cases. It is for instance difficult to compare a centralised electrolysers with 72 kgH2/h and one with 5 400 kgH2/h as it is proposed in the Roads2HyCom document. They must therefore be considered with cautiousness and are reported as indicative figures.

Table 3.3.1-3 Main economic paramters and production costs for hydrogen production by steam methane reforming, electrolysis and S-I thermo-chemical cycle (Source: Roads2HyCom 2008e and 2009)

Technology	Steam Methane Reforming (with PSA)	Electrolysis				S-I thermo-chemical cycle
		Centralised		On-site		
		Using power from the grid	Using wind energy	Using power from the grid	Using wind energy	
Capacity *(kgH2/h)*	5392	72	5400	10,8	5,4	25424
Charge consumption *(GJ/h)*	900					
Eletricity consumption *(kWh/kWh H2)*	0,009	1,433	1,39	1,6	1,43	1,28E-05
Investiment *(M€)*	75	2,2	198	0,272	0,647	2344
Maintenance *(%invest/y)*	3,70	0,9	3,3	0,9	16,00	3,54
Lifetime *(years)*	15	20	10	20	10	30?
Capacity factor *(hours/y)*	8401	6000	6500	6000	4000	7500
Price of electricity *(€/kWh)*	0,066	0,066	0,091	0,066	0,091	0,07
Price of gas *(€/GJ)*	7,25					
Production costs *(€/kgH2)*	**1,6**	**3,4**	**5,33**	**3,73**	**18,33**	**2,33**

- Steam Methane Reforming is clearly the cheapest production route today, even if a Pressure Swing Adsorption unit must be installed to purify the hydrogen. Assigning a price to CO2 emissions adds a further 0,19 to 0,48 é/kgH2, assuming a CO2 intensity of 9,5 kgCO2 / kgH2 (EHFCTP 2005) and a CO2 cost of respectively 20 and 50 €/tCO2.
- The Sulphur Iodine thermochemical cycle, which would use a nuclear high temperature reactor looks very promising in terms of costs.
- Electrolysis is greatly sensitive to electricity prices and consequently on the source of electricity generation. Electrolysis using wind electricity is thus much more costly. Centralised large electrolysers are more competitive than small on-site ones.

The table below shows the sensitivity of the H2 production cost by electrolysis against the electricity price (Roads2HyCom 2008); blue figures are linear extrapolation of the Roads2HyCom figures:

Table 3.3.1-4 Sensitvity of H2 production cost by electrolysis against electricity price (Source: adapted from Roads2HyCom 2008)

Electricity price *(€/kWh)*	*0,02*	*0,03*	0,05	0,07	0,091	0,11	*0,2*	*0,7*
H2 production cost *(€/kgH2)*	*2,26*	*2,81*	3,91	5,01	6,15	7,20	*12,14*	*39,58*

0,02 €/kWh corresponds to a very competitive electricity generation cost from a current nuclear reactor,

0,03 €/kWh corresponds to a realistic production cost from a current nuclear reactor

0,05 €/kWh corresponds to a gas power plant

0,07-0,091 €/kWh corresponds to a the usual industrial price of electricity

0,091-011 €/kWh corresponds to very competitive wind electricity

0,2 and 0,7 €/kWh corresponds to usual electricity generation costs from wind and PV.

The European Hydrogen and Fuel Cell Technology Platform, which gathered all stakeholders of the future hydrogen economy and which has transformed into a more formal entity, the so-called Hydrogen and Fuel Cells Joint Technology Initiative, has therefore listed the following challenges to overcome for hydrogen production (EHFCTP 2005):

- Decabornise hydrogen production through the medium term deployment of carbon management and by increasing the share of carbon-free energy resources
- Improve electrolysis efficiency and electrolyser cost
- Increase the range of capacity of electrolysers and chemical conversion devices
- Improve pathway efficiency through systems integration.

Electrolysis and thermo-chemical cycles are two top priorities of the European research in hydrogen production, in particular as a viable output of renewable electricity.

3.3.1.3. Hydrogen distribution

Hydrogen can be distributed mainly by pipeline and by truck. The technology is mature although the costs remain high.

- Pipelines serve mostly large consumers from the refining, chemical, steel or glass making industries, as an alternative to large on-site hydrogen production plants.
- Transport by truck serve mostly smaller scale industrial sites (consumption smaller than 1 000 m3.

Pipelines may be more interesting over longer distances or denser regions whereas trucks are interesting over a few hundreds of kilometers and for regions with a low demand density.

Pipelines

Europe has the longest pipeline network in the world with almost 1 600 km of length. The network is split into small independent systems operated by three main companies (Roads2HyCom 2007c):

Table 3.3.1-5 List of hydrogen pipelines by operators and length (Source: Roads2HyCom 2007c)

Operator	Transit countries	Length (km)
Air Liquide	Netherlands	187
	Belgium	613
	France	303
	Germany	240
	Switzerland	2
	Italy	6
	Sub-total	***1 351***
Linde	Germany	135
	United Kingdom	35
	Sub-total	***170***
Air Products	Netherlands	50
	United Kingdom	5
	Italy	2
	Sub-total	***57***
Others	***Sweden***	***18***
TOTAL		**1 596**

Air Liquide network

AL operates pipelines for supplying hydrogen but also oxygen, nitrogen and carbon monoxide with a total length of 2 700 km. The diameter of most pipelines is 100 mm, with working pressure up to 100 bar. It usually connects a source of hydrogen (dedicated production sites or hydrogen as a by-product). The total capacity of these network systems is 1 200 Mm3/y.

Figure 3.3.1-6 Hydrogen pipeline networks of Air Liquide in Northern Europe (Source: Roads2HyCom 2007c)

Figure 3.3.1-7 Hydrogen pipeline network of Air Liquide in the Ruhr Area (Source Roads2HyCom 2007c)

Linde Group

Linde Gas AG owns and operates two hydrogen pipelines in Eastern Germany and in the United Kingdom to supply regional chemical clusters. The pressure of the British pipeline is up to 50 bars.

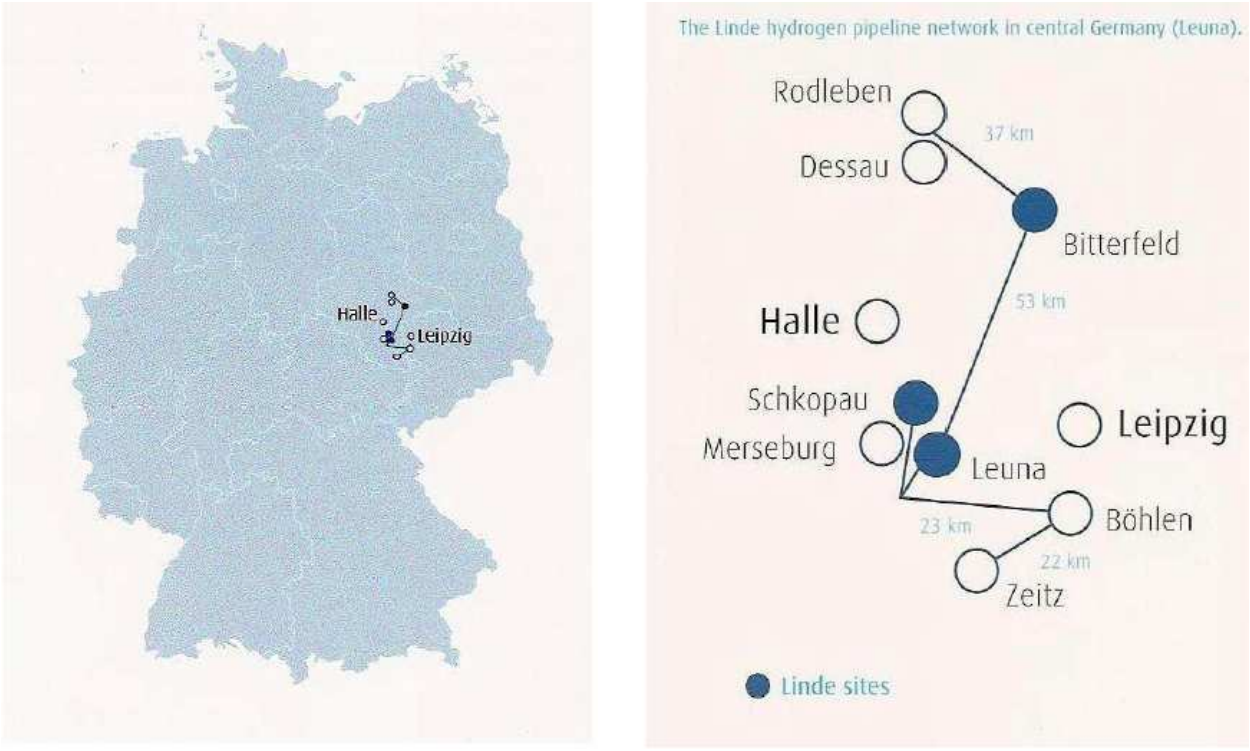


Figure 3.3.1-8 Hydrogen pipeline network operated by Linde in Germany (source: Roads2HyCom 2007c)

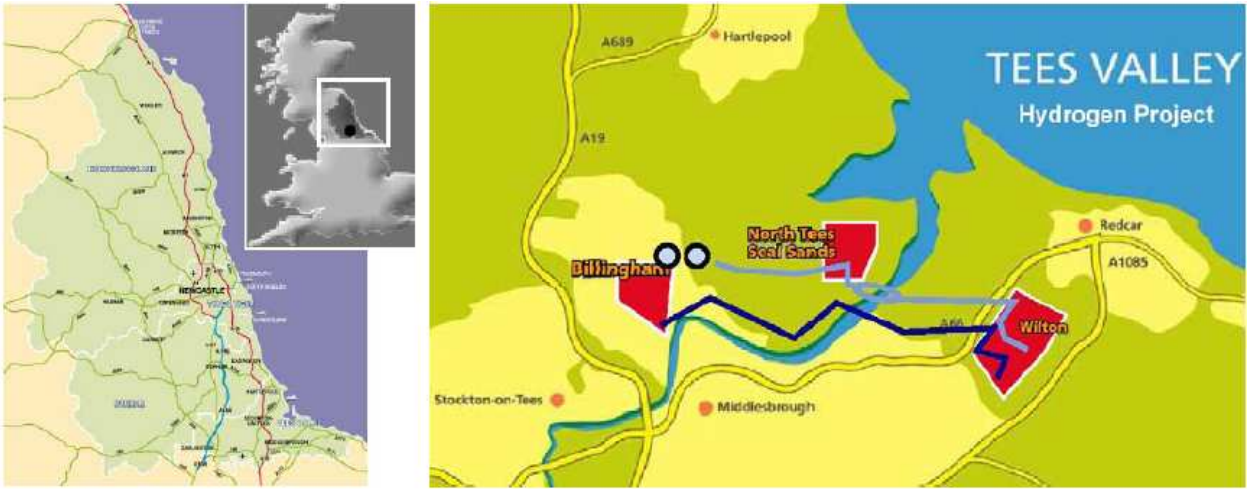


Figure 3.3.1-9 Hydrogen pipeline network operated by Linde in the UK (Source Roads2HyCom 2007c)

Air Products

Air Products operates several smaller networks. Below is the largest one with 50 km linking Europoort (where an ammonia plant was refurbished into a hydrogen production plant by Air Products) and Rotterdam, principally to supply an ExxomMobil refinery in Rotterdam. From Brielle to Pernis, it runs parallel to the Dutch part of Air Liquide's network.

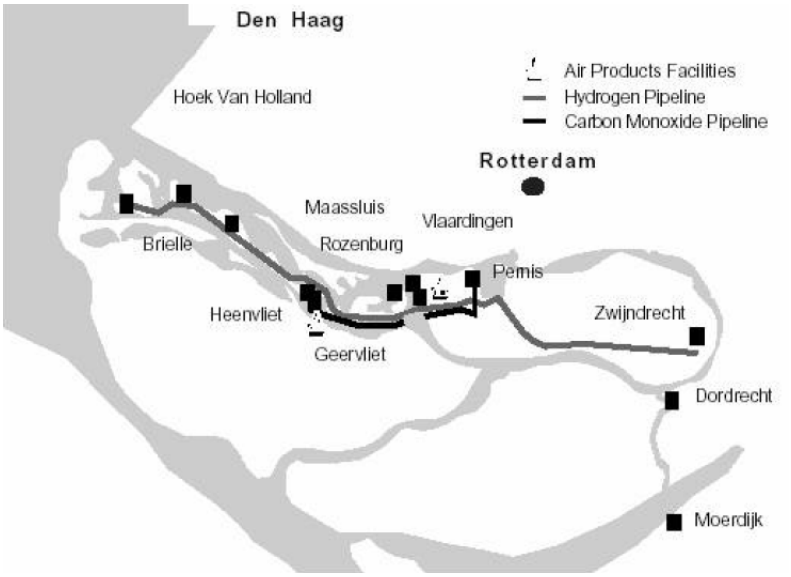


Figure 3.3.1-10 Hydrogen pipeline network of Air Products in the Rotterdam Area (Source: Roads2HyCom 2007c)

Transport by truck (trailers or cylinders)

The total capacity of trailers or cylinders is 425 Mm3 (which is a minor part of the hydrogen production capacity in Europe estimated to 90 Gm3).

The distribution route is as follows:

1) Gas filling centres purify and package the gas in first level stations from which trailers depart to serve customers or second level cylinder filling centres. These gas stations may have their own on-site production but more often use excess capacities of close production site or by-product hydrogen from a neighbouring chlorine0alkaline plant or naphtha cracker.

2) Hydrogen can further be liquefied in liquefaction units. There are only three such plants in Europe operated by Air Liquide, Air Products and Linde, with a total capacity of 20 t/d (equivalent to 84 Mm3/y).

3) Transport either by compressed gas or liquid hydrogen trailers
   a. All industrial gas companies have truck fleets to transport compressed gaseous hydrogen. Each trailers may carry 2 000 – 6 200 m3H2 at 200 or 300 bars, equivalent to 180 – 540 kgH2. The total European truck fleet may be 1 000 trucks.
   b. A super insulated liquid H2 truck may transport over 6 times more than a compressed gas trailer: 1 000 to 3 750 kg. The total fleet may not be higher than a few hundreds.

Costs of transport, including preparation for transport

Storage

Storage is used at the central production plant to accommodate time variations in demand. Storage in compressed gaseous form costs 0,45 €/kg and in liquid form 1,83 €/kg.

Preparation

Compression is required is hydrogen is to remain gaseous. This costs 0,93-1,71 €/kgH2 (Roads2HyCom 2009).

Liquefaction is more expensive and energy consuming. 30% to 40% of the thermal energy contained in the hydrogen is lost in liquefaction but it enables to multiply the transport capacity due to the higher density of hydrogen. The cost would be higher than 0,49-1,07 €/kgH2 (Roads2HyCom 2009).

Transport

The cost of a transport with a compressed gas trailer is estimated at 5,80 € / ton.km.

Large tankers with capacity from 400 – 4 000 kgH2 may cost around 1,30 € / ton.km

The cost of transport by pipeline greatly depends on its planned capacity. A 20 Gm3/y pipeline may cost 0,142 € / ton.km.

3.3.1.4. Heat market for H2 production and potential use of nuclear heat

Producing hydrogen represents an obvious market for nuclear energy. Nuclear energy may be used in different ways, of which the economic performance must be individually assessed:

- Nuclear assisted steam methane reforming: nuclear heat would be used to heat the steam reforming phase (endothermic), replacing the burning of natural gas (T=700-800°C). There would be however no need for supplying steam because the SMR process is a net exporter of steam and consume therefore only fresh water.
- High temperature electrolysis would use both nuclear heat and electricity
- Thermo-chemical cycles would use mostly nuclear heat but also some electricity, depending on the cycle.

The heat market related to hydrogen production depends greatly on the production route which is taken and the sub-part on hydrogen production routes above recalls how numerous they are. The heat and electricity requirements of steam methane reforming and electrolysis low and high temperature are reported below (BREF 2003, Roads2HyCom 2009, Py and Capitaine):

Table 3.3.1-6 Heat and electricity requirements for different hydrogen production routes (Sources: BREF 2003, Roads2HyCom 2009, Py and Capitaine)

Heat and electricity requirements for different hydrogen production routes						
	Steam Methane Reforming		Electrolysis Low Temperature		Electrolysis High Temperature	
	Min	Max	Min	Max	Min	Max
Heat (MWh / tH2)	9,72	22,22	0,0	0,0	17,4	14,3
Electricity (MWh / tH2)	0,2	0,8	46,3	47,7	28,9	33,4
TOTAL	**9,92**	**23,02**	**46,33**	**47,67**	**46,33**	**47,67**

Assuming a total market demand of 60 bn m3, as reported in Roads2HyCom (2007), which is equivalent to 5,4 MtH2 and assuming that partial oxidation and other steam reformer types have the same heat and electricity requirements than Steam Methane Reforming, we obtain:

Table 3.3.1-7 Evaluation of the heat market for hydrogen production

	Production (MtH2/y)	Heat (GWh/y)		Electricity (GWh/y)	
		Min	Max	Min	Max
SMR and assimilated	5,40	52 474	119 956	1 080	4 319
Electrolysis	0,02	-	-	802	827
TOTAL	**5,42**	**52 474**	**119 956**	**1 882**	**5 146**

If nuclear reactors were to assist Steam Methane Reforming by supplying the required heat, the equivalent number of nuclear reactors (500 MWth, availability 8 000 h/y) would be 13 to 30.

As a matter of comparison, if hydrogen was to be supplied by high temperature electrolysis only, the heat market would become as follows:

Table 3.3.1-8 Evaluation of the hypothetical heat market for H2 production by HT electrolysis only

HT Electrolysis	Min	Max
Heat (GWh/y)	94 237	77 448
Electricity (GWh/y)	156 520	180 891

Nuclear reactors would then produce principally electricity and the equivalent number of nuclear reactors (500 MWth, availability 8 000 h/y, efficiency 33%) would be 117 to 136 reactors.

When considering the possible uptake of the hydrogen economy (+154 bn m3/y of demand) and assuming an equivalent technology mix, we come to:

Table 3.3.1-9 Evaluation of the heat market in a future hydrogen economy

	Production (MtH2/y)	Heat (GWh/y)		Electricity (GWh/y)	
		Min	Max	Min	Max
SMR and assimilated	19,20	186 583	426 529	3 839	15 357
Electrolysis	0,06	-	-	2 853	2 939
TOTAL	**19,26**	**186 583**	**426 529**	**6 692**	**18 296**

The equivalent number of nuclear reactors (500 MWth, availability 8 000 h/y) would then be 47 to 107, which becomes very significant.

3.3.1.5. Conclusions and recommendations for the hydrogen sector

- Hydrogen production could be already today a viable market for nuclear heat, either as nuclear assisted steam reforming or as energy source for electrolysis and thermo-chemical cycles. The possible uptake of the so-called hydrogen economy would represent a considerable market on top of the existing demand.

- The competition with the numerous other production routes will be yet very fierce. Steam methane reforming is by far the most competitive technology at the moment, although environmental regulations may increase production costs.

- The consumer density is the greatest in the Benelux countries, Western Germany, Southern France and Northern Italy and the Midlands in the UK. This is coherent with the refining, petrochemical and chemical industry mapping.

- The European network of H2 pipelines could be conveniently used to feed H2 from a distant nuclear reactor. The interface with the processes of the final H2 consumer would then be less problematic from a technical and safety point of view. These networks are furthermore located in the densest consuming regions.

- In order to research and develop the coupling and the production route using nuclear energy, it is recommended to partner with industrial gas producers and liaise with the European Fuel Cells and Hydrogen Joint Technology Initiative. The FCH-JTI considers electrolysis and thermo-chemical cycles as priority technologies.

- Due to the uncertainty on the uptake of the hydrogen economy, this extended market should not be accounted for in the business cases for nuclear hydrogen.

3.3.2. Air gases production (oxygen, nitrogen, argon)

Summary:

Although the current production route for air gases is mainly cryogenic air separation, an electro-intensive process, this market has several interests for nuclear energy producers: 1/ it may become a future heat market with the implementation of high temperature air separation membranes and 2/ an air separation unit, whatever the technology, may in any case be valuably co-located near a nuclear reactor in order to participate in polygeneration and to benefit from the other processes which may consume nuclear heat and oxygen (H2, methanol...).

This part uses information from the contribution from the European Industrial Gas Association and from two producers of industrial gases.

3.3.2.1. Oxygen, nitrogen and argon applications and market

Air gas applications

Air is comprised of nitrogen (78%), oxygen (21%), argon (1%) and other gases in very low concentrations (CO2, H2O, xenon, neon, krypton, H2, radon...).

Air gases are used in almost all industrial sectors, making them a key raw material. Nitrogen is basically used for its properties of being inert, colourless, odourless and tasteless. Oxygen is used for its oxidising and combustion properties. Argon is an inert gas with low thermal conductivity.

Market information is difficult to find; only general market shares for oxygen, which could be found from public sources, are reported (Emsley (2001):

Gas	Industrial sector	Application
Oxygen	Steelmaking *(55% of oxygen market)*	Oxygen is used mainly in the blast furnace production route 1/ to remove excess carbon in cast iron by blowing air over the hot metal and 2/ to ameliorate the reactivity of coke by injecting enriched air (close to 24%). Pure or almost pure oxygen blowing could further improve energy efficiency and produce purer CO2 exhaust gases with a view to deploy Carbon Capture and Sequestration systems (CCS). In the electric arc furnace, oxygen allows a greater use of metal scrap.
	Chemicals, refining and energy *(25% of oxygen market)*	Oxygen is mainly used as a raw material in many oxidation processes, including the production of ethylene oxide and dichloride, propylene oxide, hydrogen peroxide, nitric acid, vinyl chloride (for PVC) and phthalic acid. Oxygen is notably used for producing synthesis gas (used for H2 production) via the partial oxidation route or coal gasification route. Oxygen is also used to enrich air feed for specific processes like catalytic cracking regenerators, sulphur recovery units and catalysis regeneration. Finally oxygen is used to ameliorate the combustion of wastes in incinerators.

	Other sectors: *(20% of oxygen market)*	
	Glassmaking	Oxygen is used in oxy-fuel combustion devices, more efficient than air-fuel ones.
	Pulp & paper	Oxygen is used as a bleaching chemical, as an alternative to chlorine to remove lignin, as a comburant in boilers and lime kilns and sulphur remover in black liquor.
	Metallurgy	Oxygen is used in gas cutting processes
	Medical	Oxygen is a key gas for hospitals.
	Petroleum	Improve flow conditions in oil and gas wells, reduce viscosity of heavy residues
Nitrogen	Chemicals	Nitrogen is a key raw material for ammonia production, which is at the basis of nitrogenous fertilizers and ammonia derivatives. Nitrogen is used to purge equipments or to maintain an inert and protective atmosphere.
	Metal manufacturing	Nitrogen is used as an inert gas to reduce carbonisation and nitriding, to limit oxidisation and to cut cast metals (by cooling them).
	Cooling and freezing	Nitrogen is used for cryogenic purposes in a wide variety of cool demanding industries, including the chemical industry (reactor coolant), rubber and plastics, food and beverages, health care, construction, glassmaking (electrode coolant)
	Preservation of oxidation	A nitrogen rich atmosphere protects against oxidation different products in particular food products, packaging of pharmaceuticals and food products, electronics.
Argon	Aluminium	Argon replaces air or nitrogen in an inert atmosphere and to assist in the removal of unwanted soluble gases and hydrogen and particulates
	Electronics	Argon provides a protective atmosphere and heat transfer medium for growing germanium and silicon crystals for ultra-pure semiconductors
	Glass	Argon is used to fill the double-pane insulated windows, due to its low thermal conductivity.
	Metal fabrication and steel	Argon provides a shielding oxygen- and nitrogen-free atmosphere for several processes (welding, annealing, rolling) and is further used to eliminate porosities in molten metals. In steelmaking, argon serves to displace gas or vapours and prevent oxidation, to control the temperature and metal composition, to remove soluble gases.

Table 3.3.2-1 Industrial applications of air gases (Source: adapted from Emsley 2001)

Quality of O2 and N2

All industrial gases consumers do not require the same level of gas purity. Here are the main purity levels:

Gas	Purity	Sectors
O2	93%-95%	Steel making, ferrous and non-ferrous metals production, glass manufacturing, pulp and paper, water treatment
	99%-99,5%	Chemical processing, refineries, oxy-fuel combustion, metal fabrication
	>99,5%	Health services
N2	>99,5%	Chemical processing, concrete cooling, electronics, food, glass manufacturing, metal production and fabrication, refining
Ar	>99,999%	Argon is only used at very high purity levels.

Table 3.3.2-2 Required quality of air gases by application

Industrial gas producers must therefore tailor their product qualities to the specific requirements of each of their individual consumers.

Potential market trends

Nitrogen and argon are used for their inert properties mainly in manufacturing processes so the market may not significantly change in the medium term. A notable exception for nitrogen, the market should be significantly correlated to the ammonia production market, as it is an important user of nitrogen. This will be analysed in the part dedicated to ammonia.

The oxygen market is however larger and upwards market trends may be anticipated. Two new technologies are especially pushing the oxygen market further (Shelley 2009):

1. Gasification systems

The gasification systems of carbonaceous feedstocks using partial oxydation (coal to gas, biomass to gas, etc.) require significant amounts of O2. The produced syngas may be burned in an Integrated Gasification Combined Cycle power plant (IGCC) or used to produce liquid fuels, chemicals and fertilizers. Current cryogenic ASU may represent 20% or more of the total capital requirements of the facility and puts a great pressure on offering competitive operating costs.

A 250-300 MW IGCC plant may require 2 000 t/d of O2 and a 600 MW plant, up to 5 000 t/d. Many CTL and GTL plants under development require up to 30 000 t/d (e.g. Pearl GTL project in Qatar). As a matter of comparison, 5 000 t/d is a current maximum for an individual air separation unit.

2. Oxyfuel combustion

Oxyfuel combustion is one of the clean coal technologies. The concept is to burn coal in an almost pure oxygen atmosphere so that the furnace produces almost pure CO2 that can be easily captured and

further sequestrated. This technology is expected to grow dramatically since it may be easily adapted on current coal power plants.

The technology is already used in steel making and glass manufacturing, although on a smaller scale.

Oxygen production cost is the main issue to make the technology competitive.

Context of the industrial gas sector

The sector of industrial gases is a competitive sector, with four major producers worldwide: Air Liquide, Air Products, Linde and Praxair. Other companies, like Messer and SOL, operate in Europe or in limited regions of the world.

Air gases production (O2, N2, Ar) through the current process of cryogenic air separation is electro-intensive and capital-intensive. The competitive context pushes producers to optimise this production route and to develop innovative and efficient new processes.

Industrial gases supply

The supply of gases is a key issue due to the cost of transportation. There are three main options to supply customers, depending on their consumption volume:

- Cylinders delivered to distribution centres by road: this applies only to very small volumes.
- Tankers transport by road: the economic limit of this mean is approximately 400 km.
- Pipelines: the high capital costs require to supply only large quantities of industrial gases and to limit the length of the pipeline as much as possible.

This distribution limitation explains that most industrial gases production plants are located close to regions gathering large consumers or even directly on-site in large facilities.

To overcome this difficulty, gas producers may also swap their products to supply distant customers; this implies sharing the production infrastructures, although this practice is very limited.

Oxygen and nitrogen pipelines are already in operation, Air Liquide being the operator of the largest network in Europe. The regions which are covered by these networks are basically the same than for hydrogen, i.e. Benelux countries and the Ruhr in Germany. To illustrate this, Air Liquide's pipeline network for H2, O2 and N2 is depicted below (its total length in Northern Europe is 3 500 km):

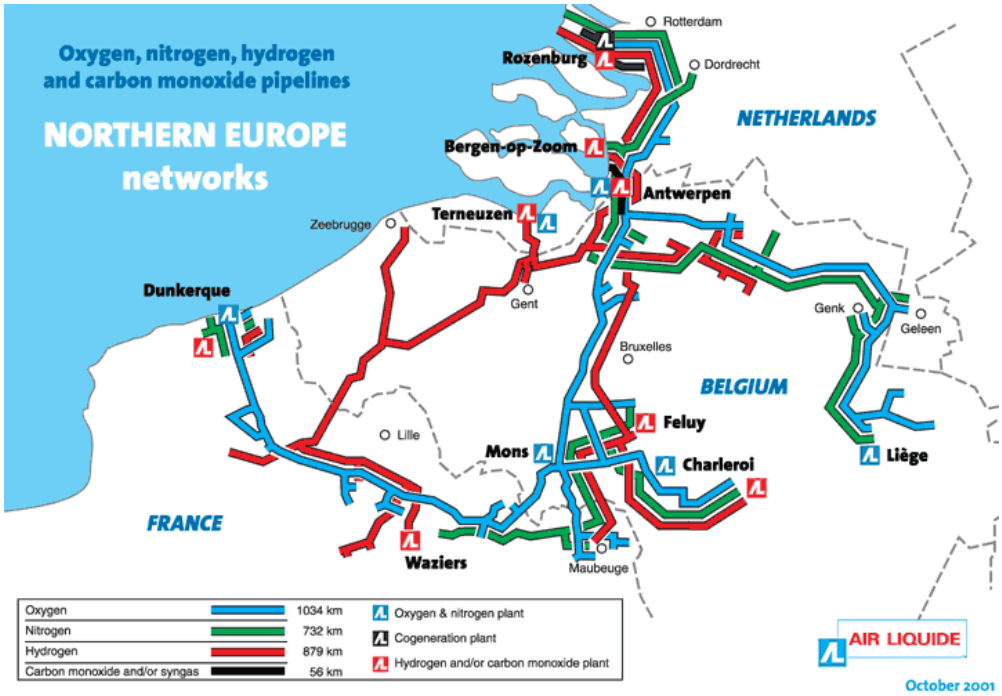


Figure 3.3.2-1 Air Liquide's oxygen, nitrogen hydrogen and carbon monoxide pipeline networks in Northern Europe (Source: Air Liquide)

3.3.2.2. Oxygen, nitrogen and argon production routes

All production routes for these gases use air as a raw material but differ significantly from the level of industrialisation and operating temperatures (Shelley 2009):

- Cryogenic air separation units (ASU) are the current reference and the sole industrial large-scale technology. The concept is to cool the air below the liquefaction temperatures of all components (most of them have very close boiling temperatures around -180°C) and then re-boil them in a coldbox schematically working as a distillation tower. Cryogenic ASU are the sole technology able to co-produce high purity nitrogen and argon.
- Adsorption technologies: they operate at near-ambient conditions following three main routes; the purity of the products remains low:
    - Pressure Swing Adsorption: air is pressurised on a vessel having selective adsorbents which capture nitrogen, leaving oxygen enriched air; when the adsorbents are saturated, the pressure is decreased and nitrogen is released and the process can cycle again.
    - Vacuum Swing Adsorption: this technology is close to PSA except that it runs under vacuum conditions in place of overpressure.
    - Hybrid Vacuum Pressure Swing Adsorption also exists combining PSA to separate gases and VSA to purge further the exiting gas.
- Membrane technologies encompass either ambient or high temperatures processes which promise lower capital costs, lower energy consumptions and higher yields and product qualities.
    - Ceramic membranes: air is pre-heated at 800-900°C, at which temperatures oxygen is ionized, and passed through a highly selective ceramic membrane selecting only oxygen

ions. This technology was demonstrated but large scale commercialisation will require a few years. Technology developer Air Products plans such an industrial facility by 2013.

- Polymeric membranes: this semi-mature process runs at ambient temperatures but the quality is low (93-95%). Such systems are limited to small scale facilities since economies of scale cannot be drawn from larger plants, which will require a proportional number of membranes.

It must be noted that all technologies produce air gases in the same proportion than they are found in air. This means in particular that oxygen can be considered the driving parameter for installing ASU capacities, nitrogen and argon being commercial by-products.

The cryogenic production process

Production step		**Process**
1	Air compression	Air is first compressed up to 6 bars The compressor requires most of the electricity of plant.
2	Pre-cooling	Compressed air is then pre-cooled at approx 8 °C using water
3	Air purification	CO2 and H2O (humidity) is then adsorbed in a batch of filters using specific molecular sieve adsorbents
4	Molsieve regeneraton by over-heated N2	The air purification systems are usually operated by more than two, enabling to run more than one filter while one is purged by over-heated N2. N2 is heated at 100°C and blown in the maintained filter, taking away the adsorbed CO2 and H2O. The heating of N2 is the sole process consuming heat.
5	Cooling to cryogenic temperatures	Purified air is then passed in a set of aluminium plates fin heat exchangers, cooled by several cycles of compression and decompression and by products or impure gases exiting from the cryogenic separation unit.
6	Cryogenic separation	The liquefied air is then separated in two distillation columns operating at different pressures (0,5 bar at the top, 5 bar at the bottom).The column produces liquid O2 and liquid and gaseous N2.
7	Argon isolation	Argon is taken away at a defined height in the distillation column, where the gas mixture contains the highest concentration of Ar. Ar consumers require a very high level of purity. The separation of argon is made in a separate dedicated unit. Two options exist: 1/ using H2 to take away the remaining O2 but this requires the management of small amounts of H2 and 2/ cryogenic rectification using pressure drop.

Table 3.3.2-3 Description of the cryogenic air separation process

The cryogenic ASU production plants units may range from small scale 100 m3/h to more than 50 000 m3/h, with typical single train capacities comprised between 500 and 3 000 t/d, and up to 5 000 t/d. Systems with capacities of 7 000 t/d are under development.

3.3.2.3. Example of a medium scale cryogenic ASU plant

This section uses information from a kind private contribution from an industrial gas producer.

The characteristics of a typical medium size cryogenic ASU are listed below:

Feedstocks

- Air:
  340 000 t/y
- Water at 25°C:
  16,5 m3/h

Products

- Liquid O2:
  87 600 t/y (or 240t/d) 1 t = 700 Nm^3
- Liquid N2:
  32 890 t/y (or 90 t/d) 1 t = 800 Nm^3
- Liquid Argon:
  4 560 t/y (or 12,5 t/d) 1 t = 561 Nm^3
- Gaseous N2:
  38 035 t/y (or 104 t/d)

Energy demand

- Steam:
  0,8 t/h at 18,1 bar and 210°C
- Electricity:
  10,5 MWe

The electricity requirements are proportional to the gas produced. The electricity consumption to produce 1 Nm3 of final air gas is as follows

- to produce 1 Nm3 of gaseous O2, 0,4 - 0,5 kWhe
- to further liquefy the gases, 0,6 - 0,7 kWhe are necessary for 1 Nm3 of final product (liquid).

Energy profile

The energy profile of such units is very flat. Maintenance breaks are carried out to:

- remove pollutants (CO2 and H2O) every 3 years. The plant is then warmed-up to melt the pollutants, such breaks usually last 2 days.
- Maintain the machinery every 3 to 5 years, these breaks are longer and last 3 weeks.

Consumption characteristics

The unit is however rather flexible. It can support a short electricity shortage of a several minutes to a couple of days, due to the inertia of the system. To restart a unit from cold condition takes few hours to re-establish the purity of the products.

Beyond a few days, the plant must be totally shut down and warmed-up. Start-up from ambient temperature condition takes about 2 days.

A production flexibility of 75% to 100% (and consequently of electricity consumption) is usual. 65% is a great minimum for the turn-down capability of the machineries. There is a slight difference of a few percent in electricity consumption between nights and days, due to the change in ambient temperature.

3.3.2.4. Current R&D in air gases separation technologies

Optimisation of cryogenic processes

All producers work on ameliorating the cryogenic process. The optimisation and re-engineering effort is focused on

- reducing energy consumption by higher efficiency heat exchangers, compressors, operating at higher pressure, new designs including energy re-use
- reducing capital costs by streamlined project management methodologies and reducing equipment cost, especially of the coldbox where liquefied O2, N2 and Ar are seperated.
- reducing operating costs by advanced plant control systems, dynamic simulations

High temperature oxygen production units

High temperature processes are dedicated to producing oxygen but not N2 since its purity is insufficient.

Technology	Principal developers	Short description	Main outcomes	Current achievements	Expected developments
Ion Transport Membrane	Air Products	Compressed and heated air (10-35 bars, 800-900°C) is passed through a stack of ceramic membranes that are selective with O2 ions	High purity O2 (99+%) 30-60% lower energy demand 30% lower capital costs	Test unit of 5 t/d by Air Products Ongoing project of test facility of 150 t/d by 2011	Small scale commercialised unit (800 t/d) by 2011 Test facility of 2 000 t/d by 2013
Ceramic Autothermal Recovery	Linde	CAR perovskite pellets absorbs and stores high temperature O2 (600-800°C) and releases it under specific partial pressure conditions.	Limited heat input due to the equilibrated exothermic sorption and endothermic release 20-30% lower O&M costs, 25% less power, 50% less capital costs	Pilot unit of 0,7 t/d operated by Linde Detailed analysis with Alstom on an oxyfuel combustion plant.	Challenges remain regarding the perovskite performance and costs

Integrated ceramic membrane	Praxair	Specific ceramic membrane is directly integrated in the furnace or boiler	No external production plant		

Table 3.3.2-4 Description and status of the main high temperature oxygen production processes (Source: Shelley 2009)

Ambient temperature air separation units

All producers work on these technologies. The concept is to use a set of several polymeric membranes or molecular sieve adsorbents. The purity of the oxygen produced is 93% - 95%.

The technology is yet competitive only at small scale. The number of membranes is indeed proportional to the quantity of products so that economies of scale are limited.

Other technologies include pressure swing adsorption (PSA) and vacuum swing adsorption (VSA).

PSA and VSA systems pass compressed air on adsorbents which adsorb nitrogen, water and carbon dioxide, while the oxygen can pass through. After becoming saturated, adsorbents are regenerated by reducing the pressure (PSA) or to vacuum conditions (VSA).

These technologies rely on

- activated carbon sieves which may produce O2 and N2 at purity levels of 95%-99,5%.
- or alumina combines with zeolite silicates, producing N2 and O2 at purity levels of 90%-95%
- or lithium based adsorbents with greater selectivity and higher mass transfer rates.

The current economic limit of these technologies is 200 t/d

Comparison of oxygen production routes

Technology	Status	Economic range (t/d)	By-product capability	Purity levels
Cryogenic	Mature	> 200	Excellent	> 99%
PSA	Mature	< 150	Poor	90% - 95%
VSA	Mature	< 300	Poor	90% - 95%
Polymeric membranes	Semi-mature	< 20	Poor	40%
ITM	Under development	N/A	Poor	> 99%

Table 3.3.2-5 Comparison of oxygen production routes

Considering the booming oxygen market, which will require large production capacities and high purity oxygen, the two technologies that may share this market would be cryogenic technologies and high temperature ceramic membranes, in particular ITM.

Since a cryogenic air separation unit has a lifetime of 20 years and is highly capital intensive so the amortisation time is long and the potential replacement of production capacities may require some time.

3.3.2.5. Potential heat market of high temperature oxygen production

Although current cryogenic process consumes electricity mainly, future technologies, especially the membrane technologies may consume heat. As the market may significantly increase, this represents a future potential and growing heat market for nuclear heat.

Market information for oxygen is very limited. A very indirect method was used to estimate the current production of oxygen in Europe but is must be noted that the figure is only indicative, since the exact figure is unknown.

The current total market production worldwide may be calculated indirectly from EPRI (2009). EPRI estimates that the US market for oxygen in 2040 will be of 3,3 Mt/d with a market share of 60% for the power sector against 4% today (the increase would be related to clean coal technologies using pure oxygen).

By re-calculating indirectly, we obtain a current production of 1,4 Mt/d in the US.

Assuming that the European market is equivalent to the United States', the European market is assumed to be of the order of 1,4 Mt/d, or 507 Mt/y.

The heat requirement for high-temperature ion transport membranes is confidential information due to the ongoing R&D but it can be estimated to be around 200 kWh/t O2.

According to Foy (2007), heat is required to heat air from ambient temperature (15°C) to high temperature (say 900°C). The temperature of the outlet gases (O2 and depleted air) is around 700 °¢. Assuming that:

- heat from exhaust gases is integrally recovered to pre-heat inlet air (exhaust gases come out at ambient temperature)
- the heat exchange efficiency is 100%
- oxygen is integrally removed from air (20% of air)

and considering the thermal capacities of air, oxygen and nitrogen, we calculate:

	Inlet air	Outlet oxygen	Outlet depleted air	Difference
Considered masses	1 kg (20% O2, 80% N2)	0,2 kg (100% O2)	0,8 kg (100% N2)	-
Temperatures	15°C -> 915°C	715°C -> 15°C	715°C -> 15°C	-
Thermal capacities (J/kg/K)	710	650	730	-
Heat released (+) or needed (-) (Wh)	- 178	+ 25	+ 114	- 39

Table 3.3.2-6 Estimation of the heat consumption of ion transport membranes

Therefore, following this theoretical calculation, the heat required to produce 1 kg of O2 is 39 / 0,2 kgO2 = 193 kWh/kgO2.

Considering that heat losses or efficiencies of heat exchangers are not taken into account in this theoretical calculation, the more realistic value of 200 kWh/kgO2 is considered below.

We come therefore to the following estimations of the heat market for oxygen production. ITM are assumed to be representative of the other high temperature technologies and ambient temperature technologies are considered as negligible due to their low capacity by plant. Today, only cryogenic ASU are used to supply the market. In the future, ITM technologies may diffuse and supply a growing market share. In this case, the potential heat market is as follows:

Distribution of production by technology	**Today**	**Future (ITM penetration)**					
		Low		**Medium**	**High**		**Maximum**
Cryogenic	100%	90%	75%	50%	25%	10%	0%
ITM	0%	10%	25%	50%	75%	90%	100%
Related heat market (GWh/y)	**6**	**10 144**	**25 352**	**50 697**	**76 043**	**91 251**	**101 389**
Equivalent number of 500MWth reactors (8000h/y)	**0**	**3**	**6**	**13**	**19**	**23**	**25**

Table 3.3.2-7 Evaluation of the heat market related to oxygen production following scenarios of market share

The current heat market of the cryogenic process is negligible. Yet, high temperature technologies may represent a non-negligible heat market for nuclear heat. It must be noted that the process temperatures are in the class 700-1000°C.

Following EPRI's estimation of the potential uptake of oxygen use in the power sector (clean coal technologies), which would increase from 4% to 60% of the oxygen market by 2040, the total market would then increase from currently 507 Mt/y to 1 216 Mt/y by 2040. The heat demand would then be as high as 243 333 GWh/y (assuming 100% ITM penetration), equivalent to 61 nuclear reactors (500MWth, 8000h/y).

Yet, it must be noted that the installed capacity per site would not necessitate a full 500 MWth nuclear reactor, even for very large consuming sites.

Illustrative example	Small demand		250 MW IGCC plant	600 MW IGCC plant		CTL or GTL plant
Daily demand (t/d)	500	1 000	2 000	5 000	10 000	30 000
Equivalent heat requirement if supplied by ITM (GWh/y/site)	37	73	146	365	730	2 190
Equivalent number of reactors (500MW, 8000h/y)	0,01	0,02	0,04	0,09	0,18	0,55

Table 3.3.2-8 Typical production capacities by type of site and equivalent heat consumption if supplied by ion transport membranes

A high-temperature oxygen production unit may therefore not use the entire nuclear heat from a 500 MWth reactor so other heat demanding processes should be co=located and the possible surplus oxygen should be fed into a pipeline.

3.3.2.6. Conclusions and recommendations

- Air gases have a wide variety of applications; oxygen production is the driver for dimensioning air separation units.

- Oxygen consumption is expected to grow due to clean coal technologies (oxy-fuel combustion) and to the growing demand for hydrogen and syngas which may be supplied by oxygen demanding processes (partial oxidation or gasification of carbonaceous feedstocks). Each of these hydrogen production sites or oxy-fuel power plants would have a very large demand for oxygen.

- Today, oxygen is produced mainly by cryogenic air separation, the sole large scale technology. New technologies are yet under investigation, especially at high temperature (temperature class 700-1 000°C), which could become a significant market for nuclear heat.

- Depending on the market penetration of high temperature processes for oxygen production, the potential heat market may represent from 3 to 25 nuclear reactors (respectively 10% to 100% penetration); an uptake of clean coal technologies would increase dramatically the equivalent number of reactor up to 61 (100% penetration).

- It must be noted that even large oxygen consuming sites would not consume entirely the heat from a 500 MW nuclear reactor, so that other heat demanding processes should be co-located.

- Large quantities of oxygen could be fed into oxygen pipelines; these pipelines are located in the same region than hydrogen ones, i.e. Benelux countries and Ruhr region. A nuclear cogeneration plant supplying a high temperature oxygen production unit would therefore be best located in this region in order to supply oxygen consumers over longer distances.

- Considering the very wide range of applications of oxygen, especially for heat-intensive industries that may consume nuclear heat, it is highly recommended to co-locate an oxygen production unit close to the nuclear reactor, whatever the production technology, in order to make the industrial gas producer benefit from competitive nuclear energy and to increase the attractiveness of the nuclear site.

- Since the new markets of gasification and clean coal technologies may drive the oxygen consumption up, it is recommended to liaise with the representative European organisations developing these technologies, especially the European Fuel Cells and Hydrogen Joint Technology Initiative and the Zero Emission Technology Platform.

- It is further recommended to partner with industrial gas producers to develop the coupling of the nuclear reactor with high temperature air separation units, in order to prepare for their possible uptake.

3.4. Pulp and paper industry

Summary:

The pulp and paper industry is energy intensive. Most of its energy is supplied by burning biological process residues or recovering process heat. Papermaking is the main activity requiring external heat. The operational conditions of papermaking could be compatible with those of a nuclear reactor. Yet, the sudden web breaks which may occur several times a week imply a volatile heat consumption and could make it difficult - but not unfeasible - to integrate nuclear energy.

This part uses information from the current reference BREF on pulp and paper industry (BREF 2001f) and its draft update (BREF 2010b) as well as from the contribution from the Confederation of European Paper Industries (CEPI) and a major Nordic pulp and paper producer.

3.4.1. Pulp and paper market and industry

Paper products

Paper is made of pulp which is extracted from trees or recycled from utilized paper. Paper covers a wide range of products whose use is correlated to societal conditions like development level (purchase power, access to information), mass consumption patterns (packaging), hygienic development (tissues) and technological development (filters, baking papers) as the table below summarises well (BREF 2001)

Functional use	Typical grade	Typical end products	Important parameters	Important trends
Information - collection - distribution - storing	- Newsprint - Coated and uncoated magazine (SC and LWC) - Coated and uncoated woodfree printing and writing	- Newspapers - Journals - Books - Computer printouts - Xerographic copies - Inserts - Illustrations	Paper is rather correlated to GDP and the development of the information society (post mail, marketing, offices printouts...)	Increased use of multicolour printing and copying; Electronic media taking over banking and trading documents; Increased recycling as raw material; Increased use of additives.
Packaging - transportation -distribution -protection	- Liner - Sack - Corrugating medium - Folding box board - Liquid packaging board - Wrapping	- Bags - Boxes - Wrappings - Containers	- Consumption patterns - Internet sales - Logistics - Trade	Increased use for distribution of food; General increase in recycling of packaging materials; Increased use of composites.
Hygienic - personal care - cleanliness - disease prevention	Tissue - dry crepe - wet crepe	- Toilet tissue - Kitchen towels - Facial tissue - Napkins - Hand towels - Hospital clothing - Wipers	- Demography - Ageing - Healthcare systems - Life quality	Use increases with general living standard; End of the chain for the recycling of fibres. Use of virgin fibre for top-end products
Speciality - a great variety	- Official papers - Filter paper - Fire resistant	- Notes - Stamps - Air filters	- Public administration - Single-use	An ever-increasing number of new applications.

	papers	- Coffee filters - Baking paper	products...	

Table 3.4-1 Type of paper products (Source: BREF 2001)

General overview of the European production of pulp and paper

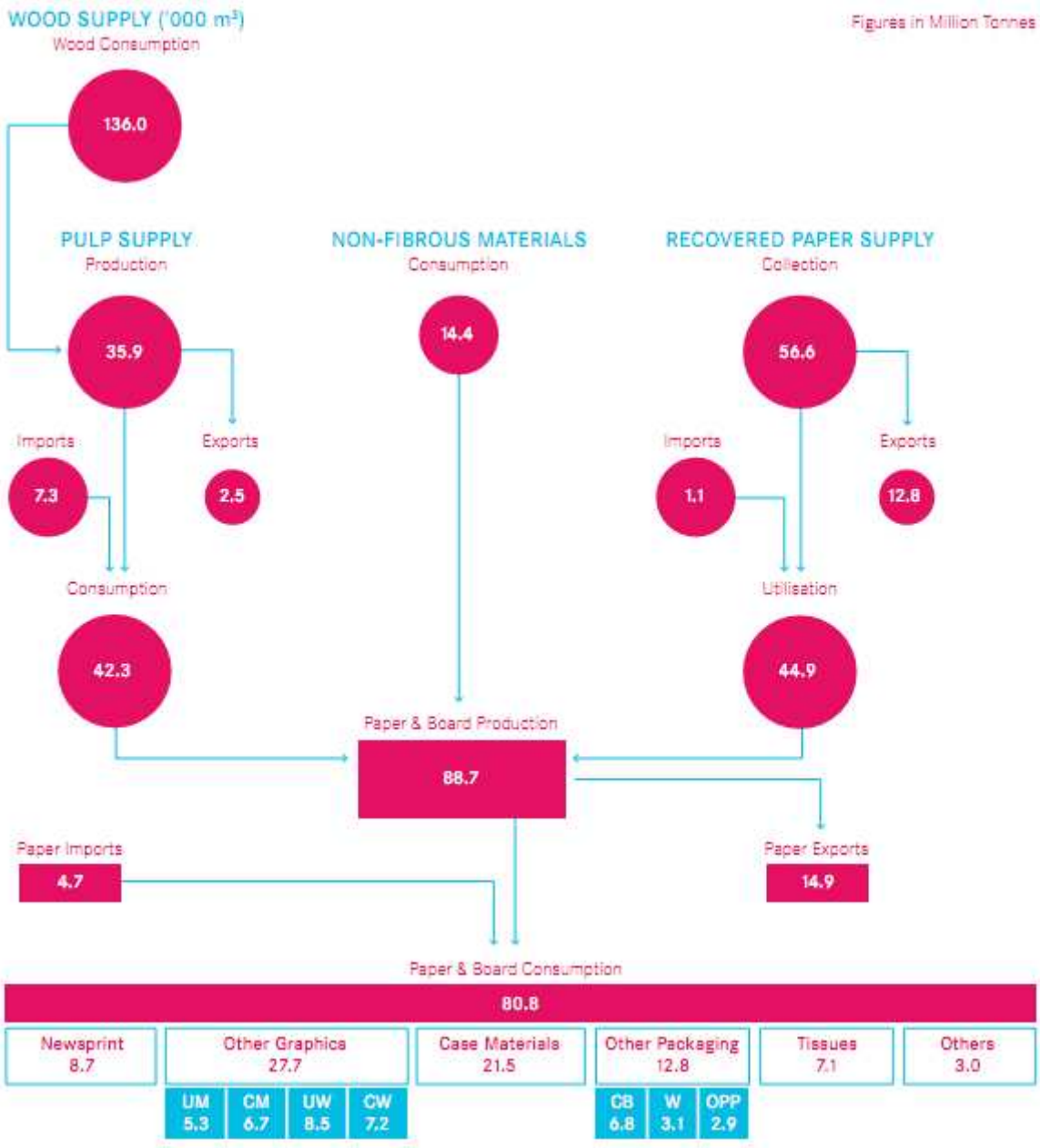


Figure 3.4-1 Pulp and paper industry in CEPI countries in 2009 (million tons, source: CEPI 2010)

Wood, pulp and paper are internationally traded commodities so the European market is exchanging its products at each stage with extra-European countries.

Pulp is produced from wood as a raw material. Europe produced a total of 42,3 Mt in 2009 and is a net importer (-4,8 Mt in 2009). The main source of pulp for paper production is however the pulp extracted from recovered paper (44,9 Mt in 2009). Europe is a net exporter (+ 11,7 Mt in 2009). The last source of pulp for paper production comes from non-fibrous materials (14,4 Mt in 2009).

European paper and board production amounted to 88,7 Mt in 2009 and Europe is a net exporter (+10,2 Mt in 2009). Paper is distributed into a wide variety of products, the principal families being newsprint and graphics (36,4 Mt in 2009) and packaging (34,3 Mt in 2009). Tissues is a smaller market (7,1 Mt) and other niche products account for 3 Mt in 2009.

European pulp industry

In Europe, Sweden and Finland are the two main producers of pulp in Europe. They account for 56% of the pulp produced altogether. Adding up Germany, Portugal, Spain and France, these countries total almost 80% of the pulp production.

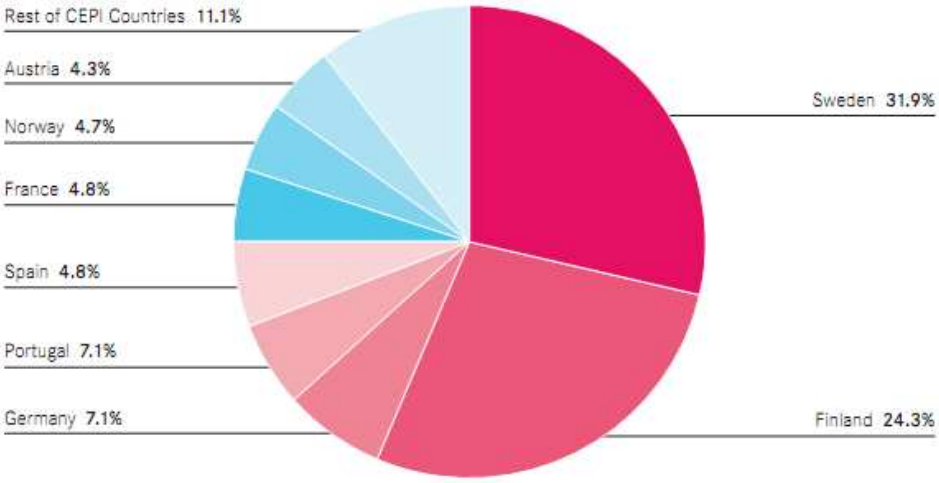


Figure 3.4-2 Pulp production in CEPI countries in 2009 (source: CEPI 2010)

Europe operates 203 pulp mills, principally in Sweden, Germany and Finland. A notable point is that Sweden and Finland are operating particularly large pulp mills, a few being larger than 1 Mt/y. In Sweden (resp. Finland), the 12 (resp. 14) largest mills account for 65% (resp. 69%) of the production.

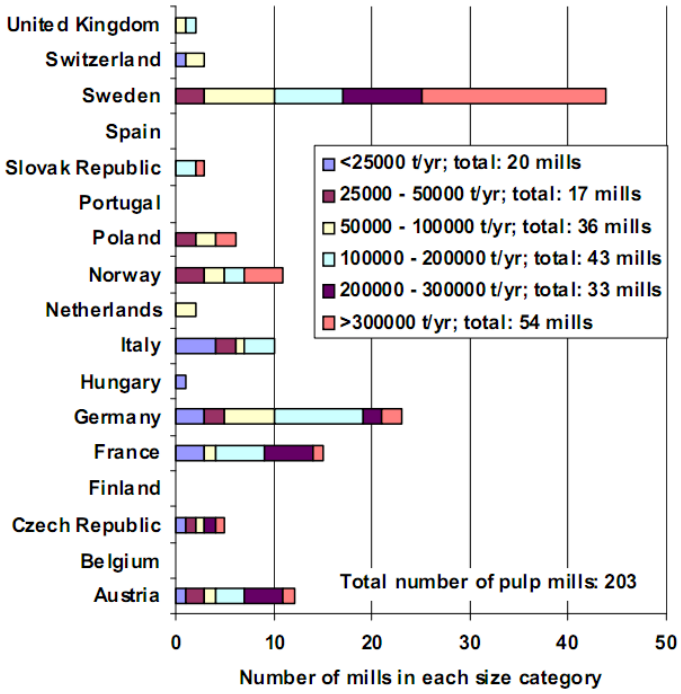


Figure 3.4-3 Geographical and size distribution across Europe for pulp mills (source: BREF 2010b)

Finland statistics are not reported in the graph above but can be found in FFI (2009): Finland operates 36 mills distributed as follows:

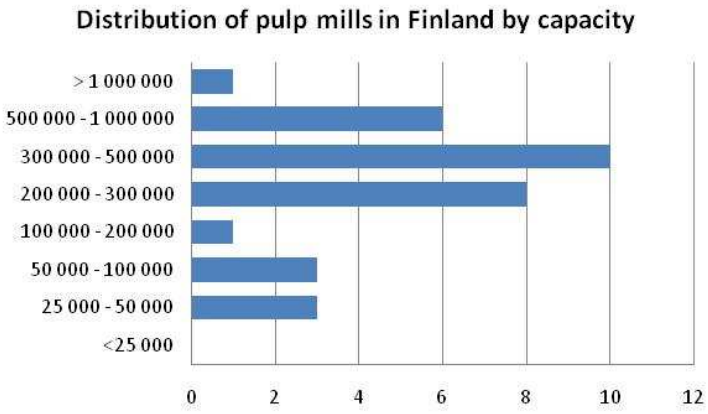


Figure 3.4-4 Distribution of pulp mills in Finland by capacity (source: FFI 2009)

The trend is to increase the mill capacity in Europe by replacing old, small units by new larger ones or by upgrading existing mills.

Pulp production in Europe

Around two third of the pulp is produced by the chemical process and one third by the mechanical process (see next paragraph).

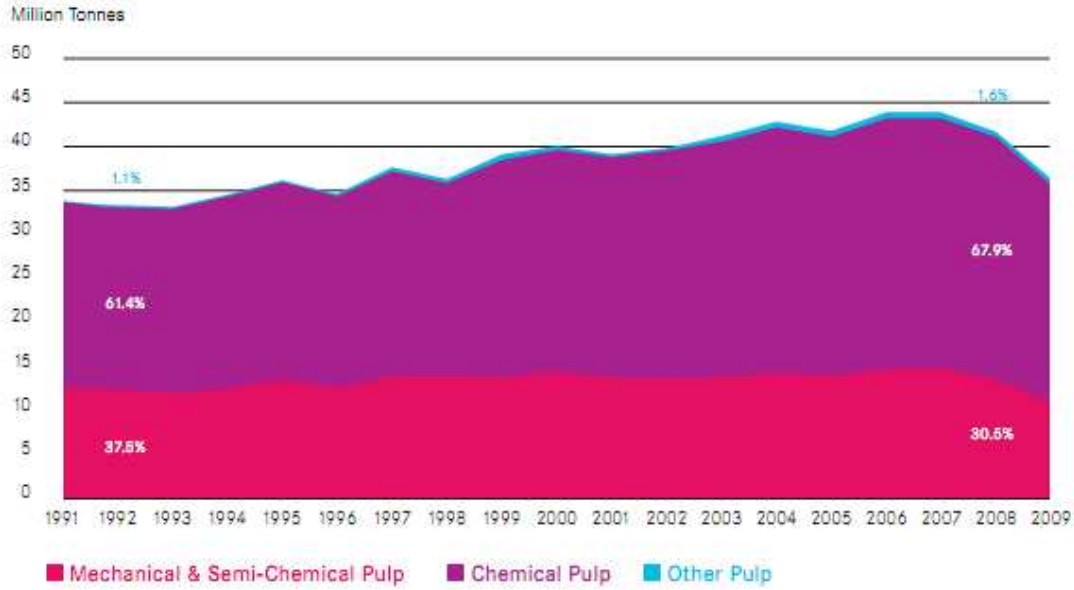


Figure 3.4-5 Pulp production by grade in CEPI countries from 1991 to 2009 (source: CEPI 2010)

The production of pulp is driven by the demand for paper, which in turn depends on the economic situation. The sharp decrease in pulp production from 2008 can therefore be explained by the global economic crisis. This reduction has been mainly accommodated by a lower operating rate in pulp mills (from a normal 90%-94% down to 82%, CEPI 2009) rather than by plant shutdowns.

European paper industry

Germany accounts for around one quarter of the European paper production, followed by Finland and Sweden representing altogether another quarter and by a third quarter of altogether Italy, France and Spain.

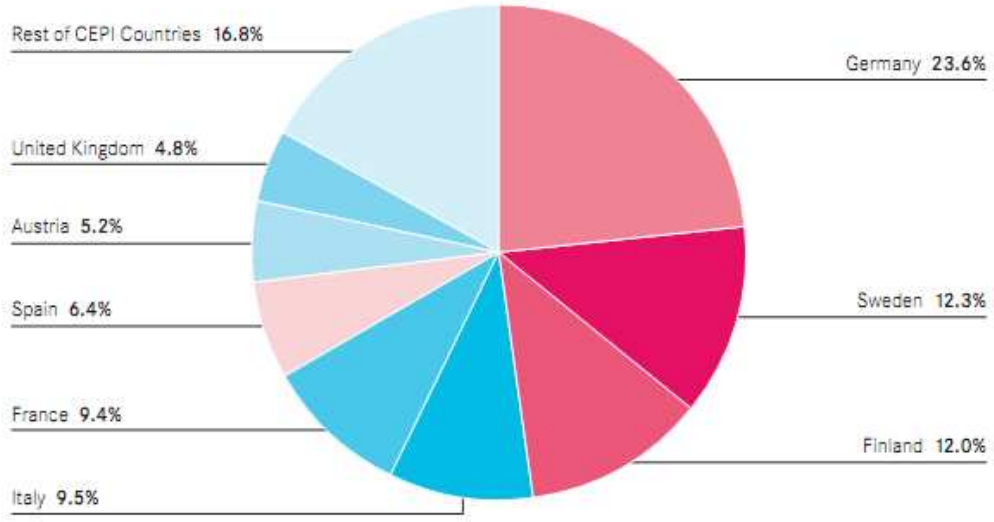


Figure 3.4-6 Paper production by country in 2009 (source: CEPI 2010)

Paper making is an atomistic industry, with 944 paper mills in operation in Europe and 845 in CEPI countries (in 2009). These 845 paper mills operated altogether 1 449 paper machines (or almost two machines by mill).

The capacity of paper mills spans a very wide range of capacities and follows some geographic patterns. Germany, Sweden and Finland operate rather very large capacity paper mills whereas Italy operates rather very small and France rather small to medium capacity paper mills. In Sweden (resp. Finland), the 12 (resp. 13) largest mills account for 70% (resp. 67%) of the paper production.

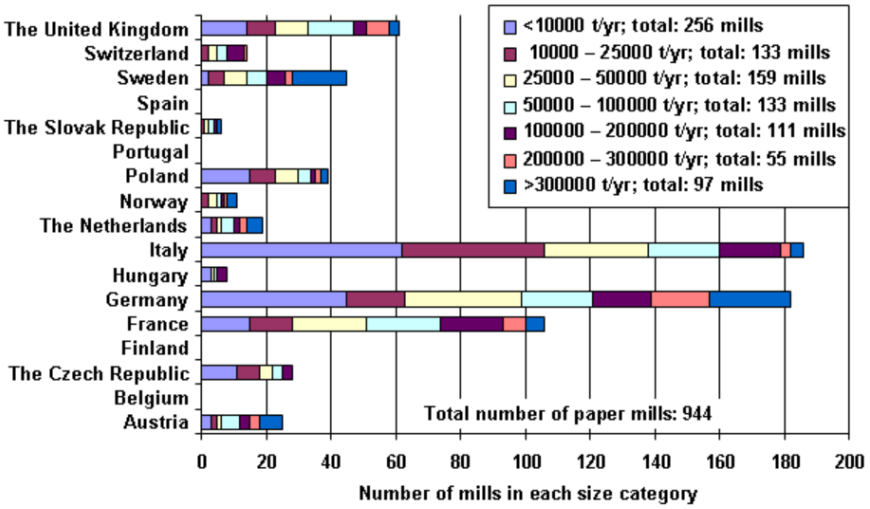


Figure 3.4-7 Distribution of paper mills in Europe in 2007 by capacity (source: BREF 2010b)

Finland's statistics, which is not represented in the figure above, can be found in FFI (2009):

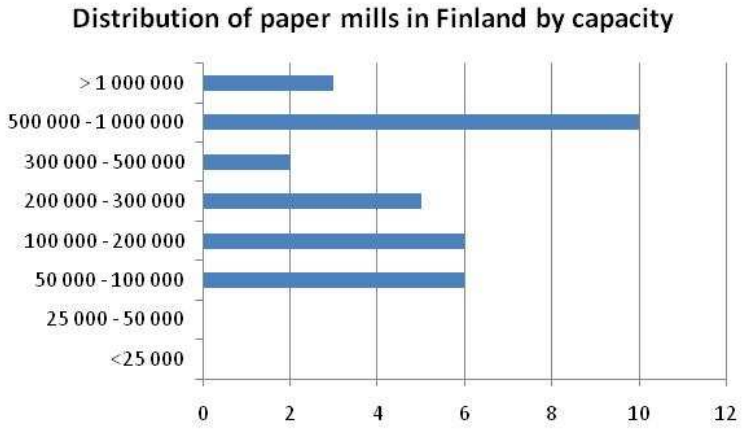


Figure 3.4-8 Distribution of paper mills in Finland by capacity (source: FFI 2009)

The main markets for paper products are newsprint and other graphic papers (altogether 46%) and packaging (43%).

Sanitary and household is a niche market but it has the specificity to be almost independent of the economic situation: whereas the demand for paper decreased dramatically from 2008 due to the economic crisis, sanitary and household were the sole paper products to keep on growing. Newsprint is a stagnating market segment which resisted rather well against the economic crisis whereas other graphic papers were strongly hit. Packaging is obviously correlated to economy and to trade.

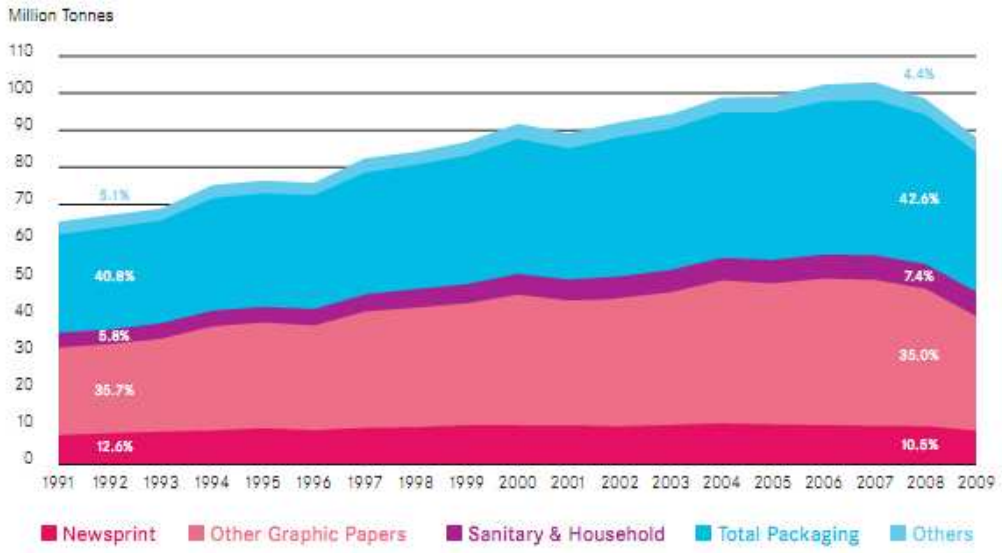


Figure 3.4-9 Paper production by grade in CEPI countries from 1991 to 2009 (source: CEPI 2010)

The paper industry is characterised by the saturation of paper mills. Although there is no overcapacity and the diversity of paper products makes specialisation possible, any new paper mill in operation is likely to trigger the closure of another one, less competitive on the same market segment.

Although there is no general rule in an atomistic industry like paper, paper mills tend to be located close to consumers or logistics infrastructures, whereas pulp mills may tend to be located close to forests. Yet, there are many integrated pulp and paper mills, especially in the two leading European countries Sweden and Finland. These integrated mills offer advantages in terms of industrial integration ensuring a certain demand and energy use.

Recovered paper

Paper is one industry with a significant recycling ratio of final products. Recovered paper accounts for 44% of the raw materials for papermaking and the trend has been growing steadily over the two last decades, as a result of encouraging regulations and of well-functioning paper collection infrastructures. The second raw material is natural pulp at 42% and the remaining share concerns non-fibrous materials (14%).

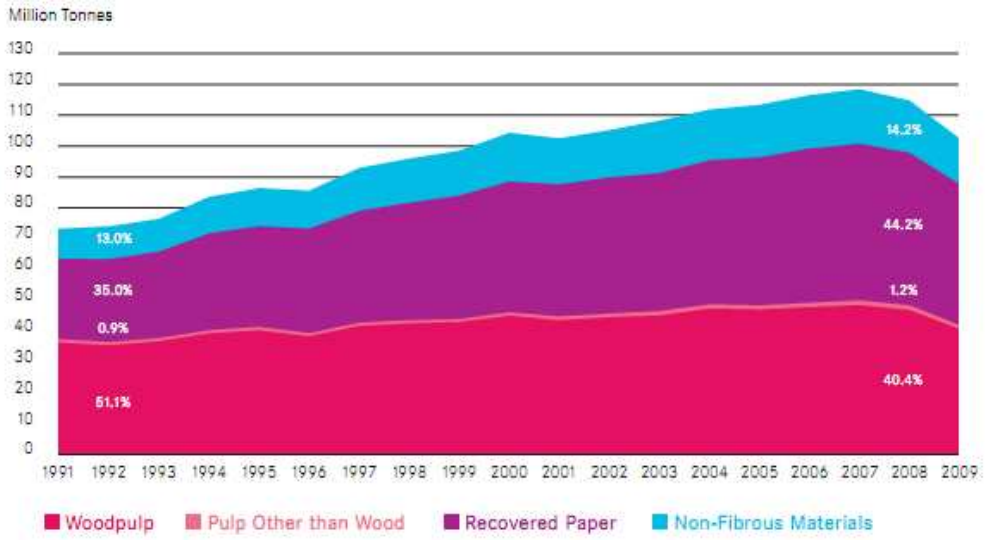


Figure 3.4-10 Raw material consumption for papermaking in CEPI countries in 2009 (Source: CEPI 2010)

Paper is recycled at 72% and this trend has been steadily increasing. The part of paper which is recycled depends on the product grade. Newsprint and case materials are recycled at more than 90% and account for altogether 35% of the paper & board production. Other graphic papers account for 40% of the production but only 10% is recycled, probably due to the difficult recycling of non-paper materials (textiles, plastics...). The remaining 25% of the production is recycled with rates between 40% and 50%.

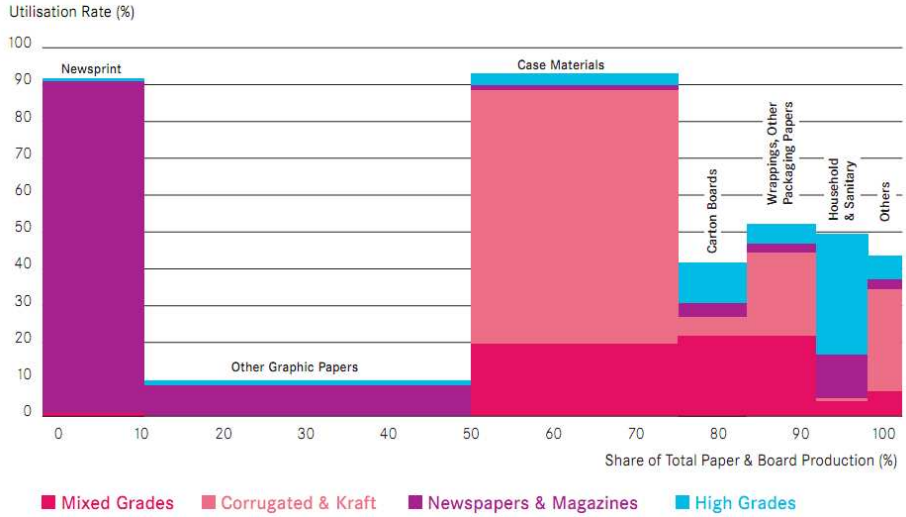


Figure 3.4-11 Recovered paper utilisation by grade in CEPI countries in 2009 (Source: CEPI 2010)

Technology providers

Pulp and paper companies are only operators. The two leading technology providers of pulp and paper machines worldwide are Finnish METSO and German VOITH. Japanese Mitsubishi Paper Mills Ltd is the third provider worldwide.

Industry economics and operational conditions

A green field new mill is a costly investment of up to 1 bn€, distributed as follows:

- Pulp mill uniquely: 300 M€
- Chemical and energy recovery system (for Kraft pulp mills, see next paragraph): 300 M€
- Paper mill uniquely: 300 M€

New plants are still built; in Europe, one new plant is built each year on average. Due to the technological development and the trend in increased mill capacities, one new large capacity plant tends to replace 4 to 5 older smaller plants.

A pulp and paper machines have a lifetime of around 30 years, but the site can operate for a longer time by replacing or upgrading the machines.

The pulp and paper industry characterises with a rather flat production profile, although short production breaks can occur several times a week (see next paragraph, papermaking).

Global pulp and paper market

Pulp and paper are internationally traded commodities. Pulp is traded in the form of dry pulp, although the major part of the production is directly used in a paper mill in the form of a liquid aqueous mixture. Paper products and recovered papers are similarly exchanged at international level. The industrial context of the paper industry is therefore very competitive.

Canada is the largest exporter of pulp, paper and sawn wood but Europe is a world leader, especially with Sweden, Finland and Germany as large paper exporters. The USA are principally exporting pulp and paper.

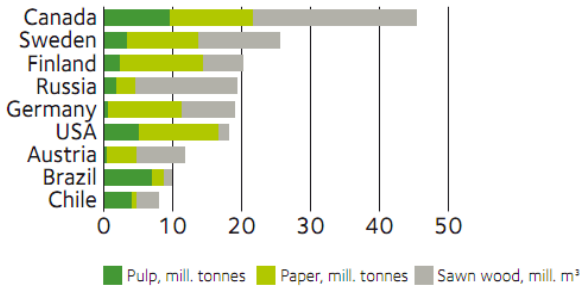


Figure 3.4-12 World leading exporters of pulp, paper and sawn timber in 2008 (Source: SKOGS 2010)

North America is the largest region producing pulp and Asia is the largest region producing paper. In all cases, Europe comes second with 26% (resp. 28%) of the global pulp (resp. paper) production.

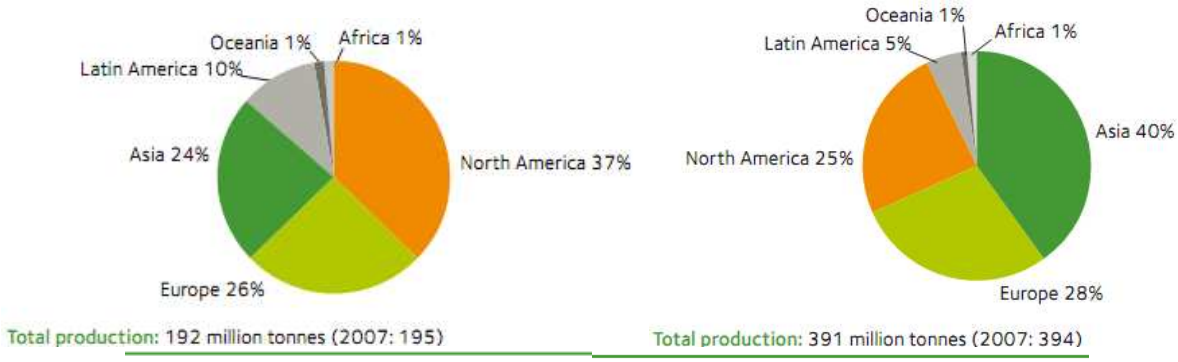


Figure 3.4-13 Global 2008 production of pulp (left) and paper (right) by region (source: SKOGS 2010)

CEPI countries are a net importer of pulp, mainly from South and North America. They export only to Asia. CEPI countries are on the contrary net exporters of paper with all trading regions (except with North America which is slightly in deficit), especially with Russia and Asia.

Figure 3.4-14 Trade flows of pulp (left) and paper (right) from and to CEPI countries in 2009 (Source: CEPI 2010)

European companies in the top 10 producers of pulp are Södra, Stora Enso, UPM, Mercer, the three world leaders being Brazilian Fibria, Chilean Arauco and Asian RGM/APRIL. The top 10 producers of paper are rather focused on specific regions as shown in the figures below and 2 European ranks among the three world leaders (Scandinavian Stora Enso and UPM). Most companies focus on a regional market.

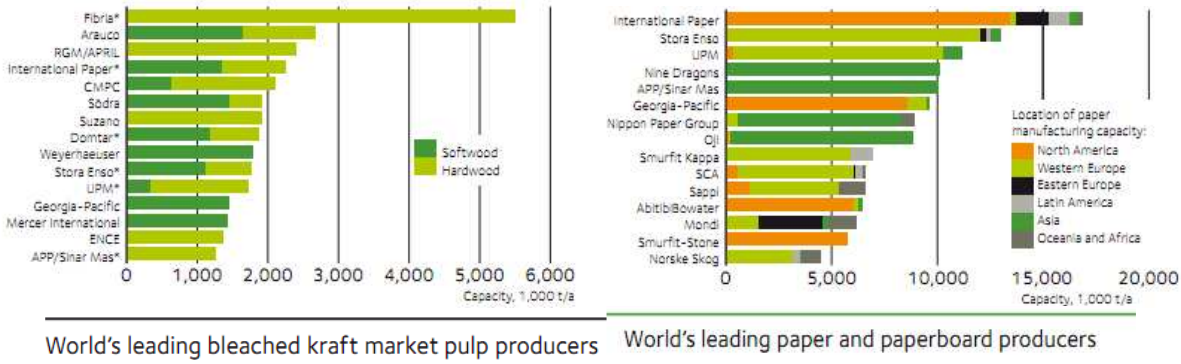


Figure 3.4-15 World leading bleached kraft pulp producers (left) and paper and board producers (right) (Source: SKOGS 2010)

As a general summary, Europe is a significant economic player in the global pulp and paper industry, especially with Sweden, Finland and Germany. The industry structure is atomistic but the major part of the pulp and paper is produced by large and very large mills. Paper consumption is directly related to the economic situation and can experience significant fluctuations.

Energy in the pulp and paper industry

Energy is an important cost for the pulp and paper industry, accounting for 22% of the total costs. Raw materials (market pulp, wood, chemicals, recovered paper) account for the majority of the costs with altogether 56% of the production costs. Maintenance and labour account for 22%.

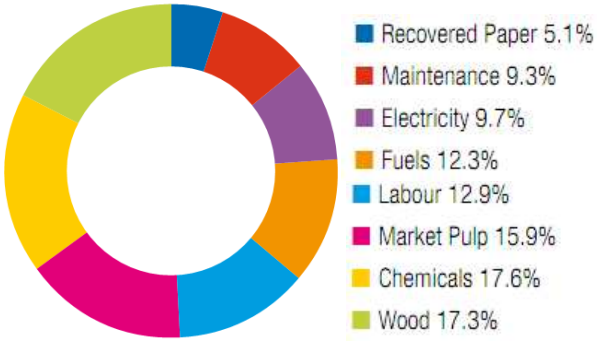


Figure 3.4-16 Cost structure of the European pulp and paper industries in 2009 (Source: CEPI 2010)

The main energy consumed in the pulp and paper industry is biomass (especially by burning the black liquor, see next paragraph). Gas comes second, especially for papermaking.

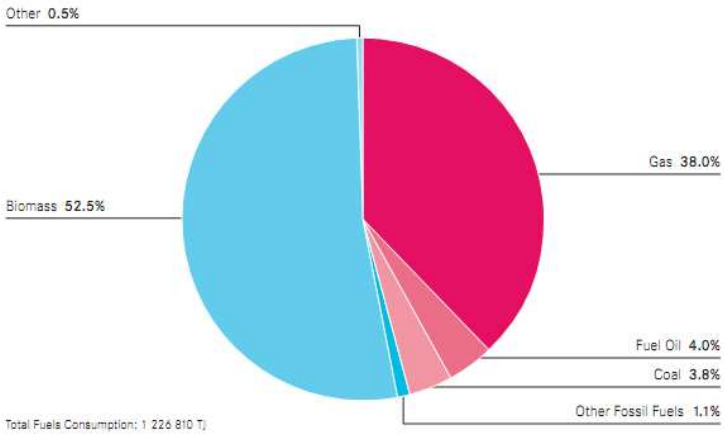


Figure 3.4-17 Fuel mix in the paper industry (source: CEFI 2010)

Pulp and papermaking are heat intensive and moderately electricity intensive processes. Cogeneration is widely used. It must be noted however that the mill energy balance depends very much on its situation, integration, the raw material, the process, etc. (see next paragraph). No general rule exists. The average CEPI figures for altogether pulp and paper and all types of mill are reported below, although they hide a multiple reality:

	1990	1995	2000	2007	2008	% Change 2008/2007	% Change 2008/1990
Energy Consumption and CHP							
Production of Market Pulp and Paper ('000 Tonnes)	71 335	84 448	100 627	115 908	111 456	-3.8	56.2
Total Specific Primary Energy Consumption (TJ/kt)	16.07	15.27	13.99	13.63	13.41	-1.6	-16.6
Specific Fuels Consumption	13.08	12.66	11.46	11.54	11.37	-1.5	-13.1
Specific Net Bought Electricity	2.99	2.61	2.53	2.09	2.04	-2.5	-31.8
Specific Electricity Consumption (MWh/kt)	1.24	1.16	1.12	1.05	1.04	-0.3	-16.1
% of Electricity Produced Through CHP Compared to Total On-site Electricity Generation	88.12	89.13	90.09	95.79	94.28	-1.6	7.0

Figure 3.4-18 Primary energy and electricity consumption in CEPI countries from 2005 to 2008 (Source: CEPI 2010)

The trend seems to reduce energy consumption and to increase cogeneration, possibly due to supporting regulations.

The total fuel consumption totalled 1 226 810 TJ in 2008 (340 781 GWh). The electricity consumption was 116 218 GWh in 2008 (CEPI 2009).

3.4.2. Pulp and paper production routes

Pulp and paper general production routes

Due to recycling, the production routes for papermaking looks like a cycle. Trees are first cut into small chips. The pulping process consists in extracting the vegetal fibres from the trees via mechanical action or by dissolving the chips into a mixture of chemical solvents.

The length of fibres or the proportion of damaged fibres and fine materials determine the optical and paper surface properties as well as the paper and board strength.

The pulp is produced in the form of a liquid solution of fibres. It can be either dried to be traded as market pulp or sent directly to a paper mill where it is refined and transformed into paper products.

Papermaking can be summarised as a drying process which evacuates the water in the liquid pulp mixture and presses it in a form of sheet.

Paper is then used in its final form (e.g. newspaper, packaging...) and collected when its use is finished (e.g. reading a daily newspaper). The collection process separates the different grades, sends them in specialised recovered paper mills which hydrate the paper, de-ink it and send the pulp a paper mill, possibly by mixing it with fresh pulp.

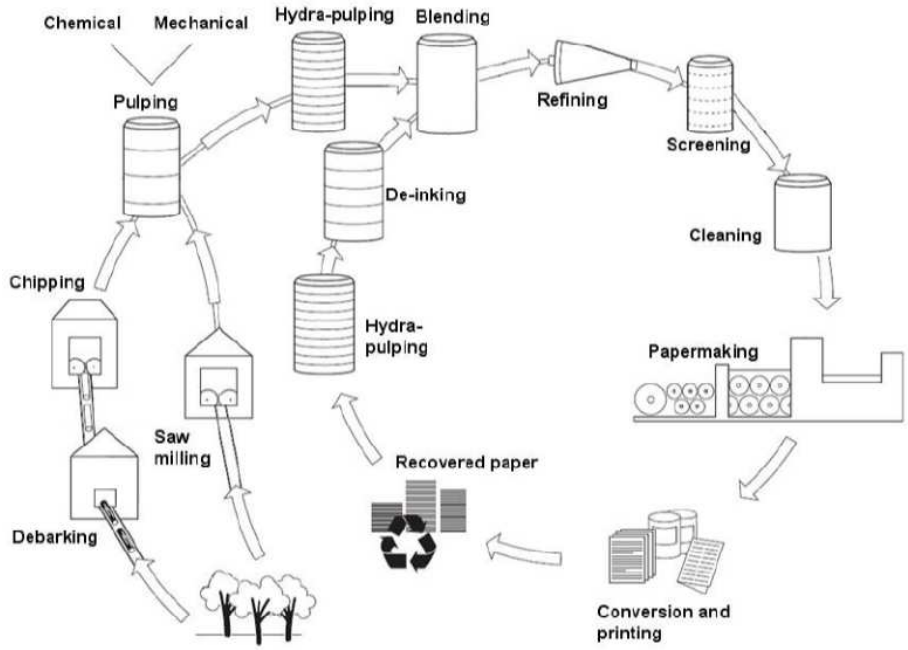


Figure 3.4-19 The general papermaking process (Source: BREF 2010b)

Pulp production: Kraft chemical process

The Kraft process represents the two third of produced pulp and consists in dissolving the lignin of the wood chips in a cooking chemical solution (white liquor). The main steps are (BREF 2010b):

- Pre-heating: Ideally, each fibre should receive the same amount of chemical treatment for the same time at the same temperature. Chemicals and energy must therefore be distributed uniformly throughout each wood chip. Air contained in wood cavities may alter the uniformity of chemicals treatment so it is usually removed by pre-heating the wood with steam so wood chips can better absorb the white liquor.
- Cooking: Chips are cooked at temperature between 155°C – 175°C for 1 to 2 hours. The heat content of the digested chips is recovered by the washing liquid which evacuates the mixture from the digesters and is used to pre-heat the chips.
- Washing: The pulp coming from the digester contains both fibres and spent cooking liquor (black liquor). This black liquor contains the inorganic chemicals of the white liquor plus organic substances with an energetic content, enough to make the Kraft pulp mill energy self-sufficient (energy content: 12,5 MJ/kg black liquor).
- Chemicals and energy recovery: The black liquor is therefore separated from the pulp and sent to the chemical recovery system which recovers chemicals for the white liquor and the energy by burning the black liquor. This system provides most, if not all, of the plant energy.
- Screening: The washed pulp is screened to take out knots and fibres bundles.
- Oxygen delignification: Delignification is continued by oxygen which takes place in alkaline conditions at 90°C – 100°C.

- Bleaching: The purpose of bleaching is to obtain a certain pulp quality (brightness, stability, strength). The process is carried in several steps, using several chemicals (ClO2, H2O2, O2, O3 or possibly CH3CO3H)
- Drying: in an integrated pulp and paper mill, the pulp is transferred to papermaking in a wet state (4% consistency). For a non-integrated pulp mill, the pulp must be transformed into dry market pulp for transport; it is first pressed and then dried with steam.

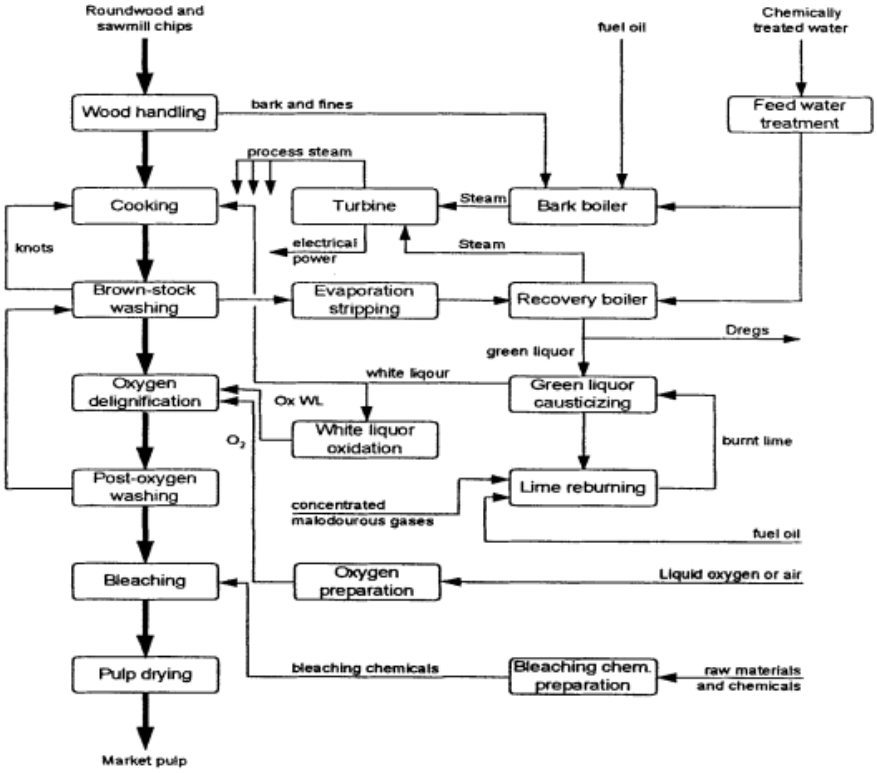


Figure 3.4-20 Schematic functioning principle of the Kraft chemical pulp process (Source: BREF 2001f)

The chemical and energy recovery system is key to the energy balance and the operation of the plant. It uses two complementary cycles of calcium and alkali chemicals (especially caustic soda).

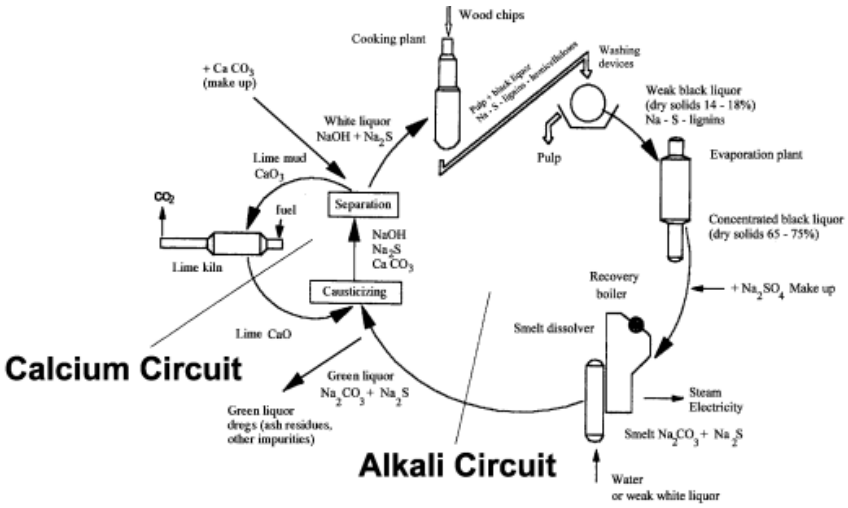


Figure 3.4-21 Recovery circuit of chemicals in a kraft mill (Source: BREF 2010b)

A kraft mill is an energy intensive process. It consumes heat up to 10-14 GJ/t of dry pulp (ADt) and electricity up to 600-800 kWh / ADt. Pulp drying alone accounts for around 25% of the heat consumption and 15-20% of the electrical energy. Over 50% of power is used for pumping.

The plant energy balance varies significantly from one mill to another and each mill is unique. The energy balance depends on:

- The wood which is processed into pulp (and consequently the energy to dissolve fibres and the energy content of the black liquor)
- The quality of pulp to obtain (in particular bleached or unbleached)
- The fact that the pulp mill is integrated with a paper mill or not, which conditions the drying of the pulp.

General averages are unavailable so the average Swedish figures are reported below. Several examples of plant energy balances are reported in annex V.

Pulp and paper grade	Process heat [GJ/t]	Electric power [kWh/t]
Non-integrated production of bleached kraft pulp - whereof external supply	14.4 1.2	760 0
Unbleached kraft pulp production with integrated production of paperboard - whereof external supply	16.4 1.5	959 388
Bleached kraft pulp with integrated production of uncoated fine paper - whereof external supply	17.5 3.5	1218 706

Table 3.4-2 Average energy consumption in Swedish pulp and paper mills in 1995 (Source: BREF 2001f)

The figures above relate to the total integrated pulp and paper mill (in case a paper mill is integrated). Pulp making account for around 10,5 GJ/t in integrated mills (because drying is not necessary) whereas the non-integrated pulp mill consume 14,4 GJ/t, in particular due to 2,9 GJ/t for drying (into market pulp).

Although current Kraft mills are mostly energy self-reliant, the situation may change with the development of second generation biofuels, which may valorise the black liquor and shift the economic rationale of burning black liquor on-site to selling the black liquor and purchasing steam and electricity.

This shift is probably a long-term option since second generation biofuels must be proven technically and the production infrastructures must be set up. Furthermore, chemical and energy recovery boilers are very expensive equipments which require several years to amortise and have a long lifetime. Supplying heat externally would require closing the boiler and replace it by a smaller system recovering chemicals only, which is necessary and implies a strategic industrial choice.

Pulp production: the mechanical pulp process

Mechanical pulping consists in separating wood fibres by mechanical grinding (groundwood pulping, GW). The process can be complexified by applying a pressure (pressure groundwood pulping, PGW), heat (thermomechanical pulping, TMP) or chemicals and heat (chemi-thermomechanical pulping, CTMP).

Mechanical pulp is used mainly for producing printing and writing papers and newsprint, and to a lesser extent tissue and packaging boards (CTMP).

Most mechanical pulping is integrated with paper manufacture.

The main processes steps of mechanical pulping are (BREF 2010b):

- Groundwood, pressure groundwood and refiner mechanical pulp: wood logs are forced against rotating grinding stones or steel bars to produce a pulp at 2% consistency. The grinding process produces heat by friction so the stones/bars must be cooled with cooling water. The process operates at 95-125°C.
- Thermo-mechanical pulping: after chipping and washing, the raw material is pre-heated with team and then refined. A large share of the higher electric demand turns into heat and self-pressurises the process by steam generated from wood moisture and dilution water (up to 5 bar). The heat value of the waste water in a TMP is too low to be recovered. TMP mills are almost always integrated with a paper mill for energy integration.
- Chemo-mechanical pulping: wood chips are first pre-heated, compressed and impregnated in a chemical solution. Cooking temperatures and time range from 70°C to 170°C and 15 min. to a couple of hours.

Mechanical pulp from any process is further screened and cleaned, possibly bleached

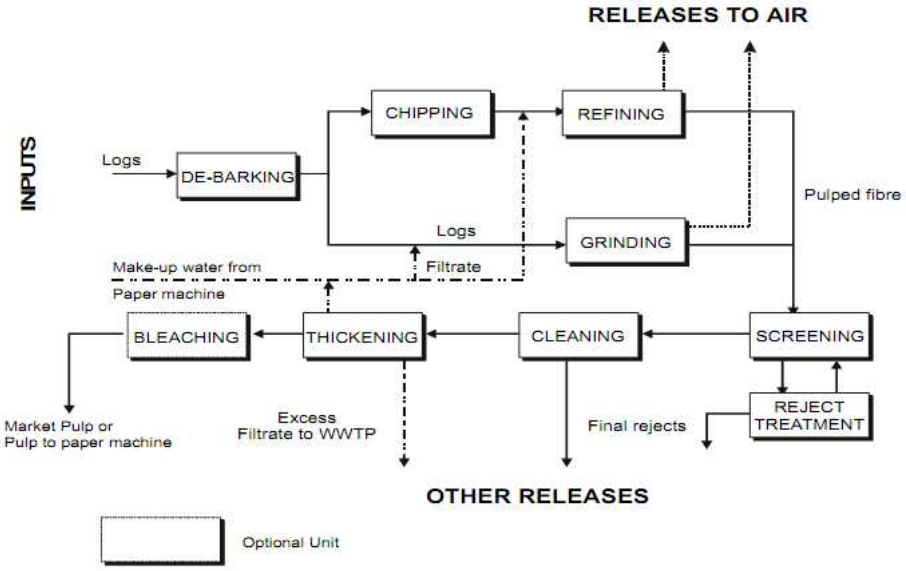


Figure 3.4-22 Main steps in the mechanical pulping (Source: BREF 2001f)

The main energy consumption for each process are summarised below (BREF 2001f). Mechanical pulping consumes mainly electricity and to a lesser extent steam, which can be also recovered from the process. The simple groundwood processes consume little energy relative to RMP, TMP and CTMP processes. Yet, the proportion of recoverable energy is 20%-30% as hot water or 20% to up to 45% as high-pressure steam, which can in turn generate electricity in a turbine or can be sent to an integrated paper mill for its energy consumption.

Mechanical pulp and freeness, ml CSF	Energy consumption (kWh/t of pulp)	Recoverable energy as hot water [%]	as steam [%]
GW 350-30	1100-2200	20	
PGW 350-30	1100- 2200	30	20
PGW-S 350-30	1100-2300	30	20
RMP 350-30	1600-3000	30	20
TMP 400-30	1800-3600	20	40-45
CTMP 700-30	1000-4300	20	40-45

Table 3.4-3 Energy consumption and recovery of energy in mechanical pulping (source: BREF 2001f)

Recovered paper production

Utilised paper is collected and sorted by grade. The recovered paper processing depends on the paper grade and the type of furnish used. Many processes are applied, but they apply similar steps:

- Repulping: the recovered paper is put into a pulper together with hot water or white liquor and pulped with mechanical and hydraulic agitation so fibres are disinteated.
- Mechanical removal of impurities: screening uses the different physical properties of fibres and impurities to remove contaminants; smaller heavy weight particles are removed by centrifugation. Depending on the furnish to produce, additional steps may be applied (fractionators, dispersers, refiners).
- Flotation or wash de-inking (optional): ink must be removed in mills producing paper products whose brightness is important (e.g. newsprint, printing, writing papers); this is done through a chemical treatment or by a multistage dewatering process.

Recovered paper mills tend to be 1/ integrated with a paper mill and 2/ located close to large paper collection centres like cities.

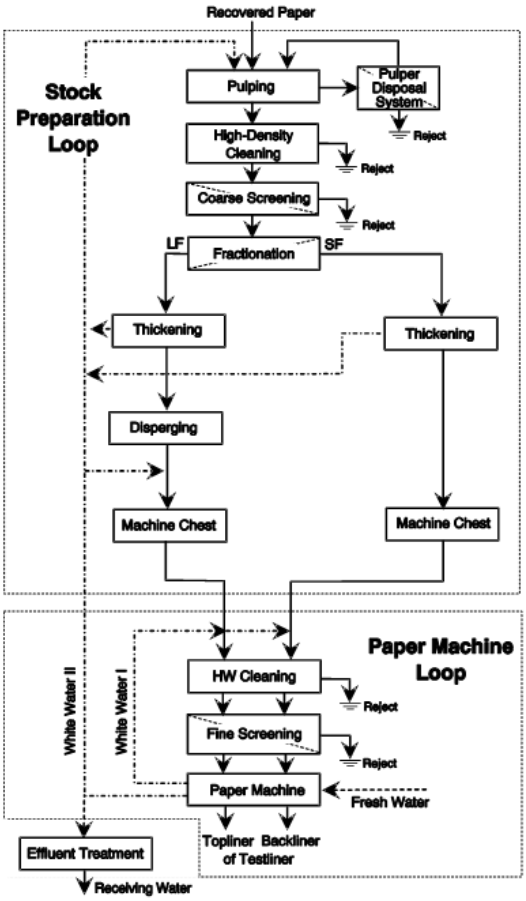


Figure 3.4-23 Flowsheet of an example stock preparation plant for processing recovered paper for case-making material (Source: BREF 2001f)

In recycled fibre mills (RCF), steam is normally produced on-site by each company and electricity can be purchased from the grid as necessary (BREF 2001f).

The energy balance of each site depends on the raw material processed, the manufactured paper products, the economic rationale of installing a CHP plant, etc. Examples of energy balances of RCF mills are reported in annex IV.

The main processes consuming energy are the pulper and the de-inking unit (dispersers and thickener), as illustrated in the two examples reported below (BREF 2001f):

	Tissue DIP-line (200 t/d)	Newsprint DIP-line (1000/d)
Raw material	Old magazines,/mixed office waste	Old newsprint/old magazines
Yield	55 - 60%	80%
Total specific power (estimated)	230 kWh/t of DIP pulp [1)]	300 kWh/t of DIP pulp [2)]
Total specific low pressure steam	0.3 t steam/t of DIP pulp	0.3 t steam/t of DIP pulp
Specific energy demand for major unit processes		
Feed conveyor	1 kWh/t of DIP pulp	0.4 kWh/t
High Consistency Pulping[1)]	39 kWh/t of DIP pulp (CHD pulping incl coarse screening)	16 kWh/t (drum pulper)
Coarse Screening	Not required	18.5 kWh/t
MC-Cleaner	Pumping energy	Pumping energy
Sand removal (cleaner)	Pumping energy	Pumping energy
Fine screening	17 kWh/t of DIP pulp	22 kWh/t
Flotation I	18 kWh/t of DIP pulp	33 kWh/t
Washing I	8 kWh/t of DIP pulp	No washing
Disc filter (thickening)	not required	1 kWh/t
Dispersion (incl. Thickener)	55 kWh/t of DIP pulp [2]	67 kWh/t [2]
Dissolved Air Flotation	no data (difficult to calculate in kWh/t DIP pulp)	no data (difficult to calculate in kWh/t DIP pulp)
Flotation II	5 kWh/t of DIP pulp	19 kWh/t
Washing II	10 kWh/t of DIP pulp	No washing
Sludge Press	no data (not main equipment)	no data (not main equipment)
All pumps	not included [3)]	91 kWh/t [4)]

Explanatory notes:
Normally the values are presented as installed KW. When specifc energy consumption is derived from these figures an approximation to the real situation has to be made.
1) CHD pulping = Continuous High Density pulping. In many mills standard batch HD is applied (higher energy demand)
2) These values are representing rather figures below average. For the best qualities a consumption of up to 70 – 80 kWh/t is not uncommon in some mills. Normally for thickening and dispersion an electricity demand between 85 – 90 kWh/t is reported (see figures further below).
3) For the tissue stock preparation equipment no pumps and agitators are included
4) Apart from the pumps for the flotation system all pumps and agitators are included

Table 3.4-4 Real world examples for the energy consumption in the production of tissue and newsprint from recovered paper (Source: BREF 2001f)

Papermaking processes

Papermaking transforms fibres, either natural chemical or mechanical pulp or recycled fibres, to produce paper products. The raw materials composition is determined by the paper products to manufacture and the desired quality. Raw materials are supplied in a wet form with low consistency (around 10%) but the stock preparation preliminary phase make the consistency drop down to 0,2%-1,5%.

Paper machines consist in drying and shaping the pulp; they follow similar steps (BREF 2010b):

- Stock preparation: Raw materials are first prepared in several lines into furnish for the production of paper by blending different pulps, diluting and adding chemicals to affect the final quality of the paper. Fibres are further refined using a rotating disk pressed against a stator.
- Head box: A head-box introduces the suspension of fibres to the wire and creates a uniform dispersion of fibres
- Wire section: A wire section drains paper web to around 12%-20% solids and the paper web forms.

- Press section: A press section removes more water out of the web by pressing down to about 50% solids
- Drying section: A dying section removes the remaining moisture by heating the web with drying cylinders and reaches 90%-95% consistency. Drying cylinders consume the largest quantity of steam.
- Rolling: A reeler reels the paper web into a roll
- Optional processes: Additional processes may be optionally installed for manufacturing certain grades (coaters, calenders, winders, rewinders).

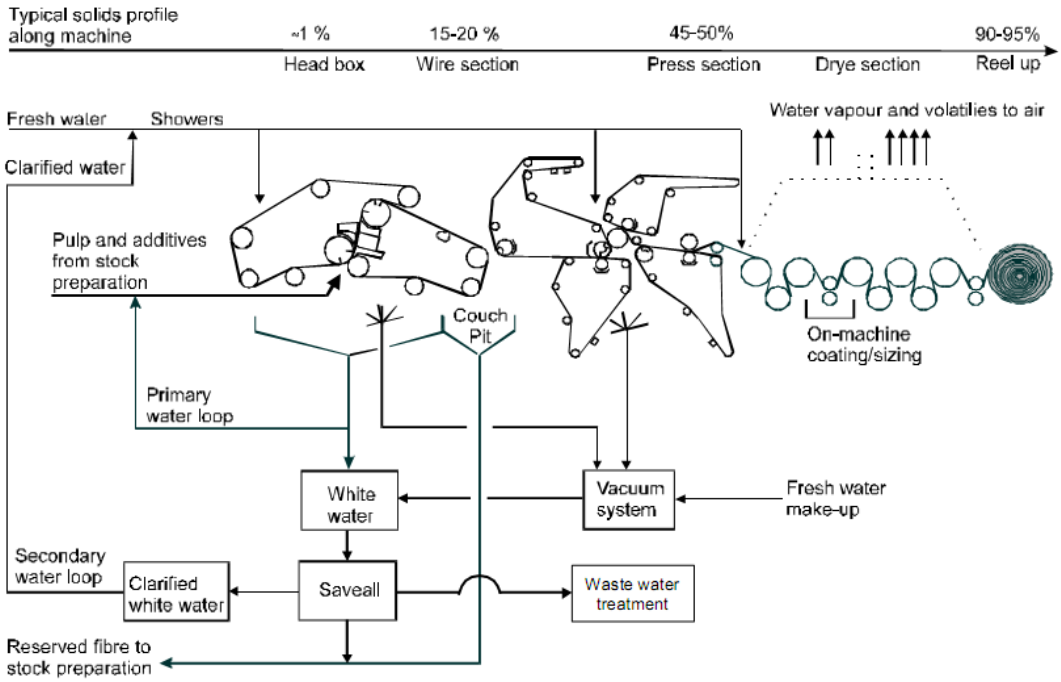


Figure 3.4-24 Key features of a twin wire paper machine (Source: BREF 2001f)

The machine speeds can reach up to 2 000 m / min. Web breaks can happen usually several times per day, a best current operational conditions being one break per week. The breaks last generally 20 minutes and the lost paper is sent back to the re-pulper.

The energy consumption depends greatly on the paper product to be manufactured, its quality, the raw materials, and the integration with a pulp mill. The energy consumption of two mill examples is reported below (BREF 2010b):

Type of mill	Fuel for steam generation (kWh/t)	Purchased electricity (kWh/t)
Biggest non-integrated wood-free paper mill in Europe	1 449	612
Typical tissue mill	1 389 – 6 944	1 000 – 3 000

Table 3.4-5 Specific heat and electricity consumptions for two real case paper mills (Source: BREF 2010b)

3.4.3. Energy systems in the pulp and paper mills

Energy applications

Pulp and paper production are energy intensive processes that require both heat and electricity for the following applications (BREF 2010b):

Heat (in the form of high-pressure steam)	Heating water, wood chips, pulp fibres, air and chemicals Evaporating water from the pulp or paper sheet in the dryer section of the pulp mill (for market pulp) or in paper machines and from spent kraft liquors before burning them To generate electrical power in turbo generators
Electricity	Grinders and refiners for production of mechanical pulp Pulpers to slush purchased pulp or in recycled fibre pulping Pulp beating and refining in paper mills Drives for paper machines and other machines Transports with pumps, fans, belt and conveyors

Table 3.4-6 Heat and electricity applications in pulp and paper mills (Source: BREF 2010b)

Energy consumption trends

The following trends may increase the electricity consumption of pulp and paper production:

- Higher quality requirements for paper will require using more energy consuming processes (mechanical pulping or coaters)
- Increased paper machine speeds
- New pressing and drying technologies that reduce heat consumption
- Tightened environmental requirements and consequently more complicated processes
- Closing of the water circuits which will require more pumping capacities

Energy consumption in pulp and paper mills

A typical paper mill produces more than one type of paper or pulp from various wood species and oten different mixes of fibre raw material. Each configuration has a specific energy consumption. Some typical consumption values are reported below (BREF 2010b):

Grade of paper produced	Range of electricity consumption (kWh/t)	Range of heat consumption (kWh/t)
Non-integrated kraft pulp mill	700 – 800	3 800 – 5 100
Integrated uncoated wood-containing paper	1 200 – 1 400	1 000- 1 600
Integrated coated wood-containing paper	1 200 – 2 100	1 300 – 1 800
Non-integrated uncoated wood-free paper	600 – 800	1 300
Non-integrated coated wood-free paper	600 – 1 000	1 200 – 2 100
RCF without deinking (graphic) paper	300 – 700	1 100 - 1 800
RCF with deinking (graphic) paper	900 – 1 400	1 000 – 1 600
RCF based carton board (with deinking)	400 – 700	1 000 – 2 700
Non-integrated tissue mill	900 – 1 200	1 900 – 2 300
RCF based tissue mill	800 – 2 000	1 900 – 2 800
Wood-free specialty paper	600 – 3 000	1 600 – 4 500

Table 3.4-7 Range of electricity and heat consumption by type of pulp and/or paper mills (Source: BREF 2010b)

The following parameters influence in particular the plant energy consumptions:

- Location of the plant (environmental conditions)
- Age of the plant (old mills have unfavourable infrastructures)
- Age of equipment
- Size of the plant (larger capacities enable economies of scale)

Energy fuels

The main fuels used for steam and power generation are:

- Black liquor which covers most of the energy needs of chemical pulp mills
- Biomass such as bark, wood residues and in some cases wood chips
- Fossil fuels
- Various types of sludge (biosludge from waste water treatment, fibrous sludge, deinking sludge, paper rejects...) from all types of pulp and paper mills and sometimes waste

The industry's fuel mix is reported below (CEPI 2010). Biomass (including black liquor) accounts for more than half of fuels and gas represents the second principal fuel (38%), especially as cogeneration plant fuel:

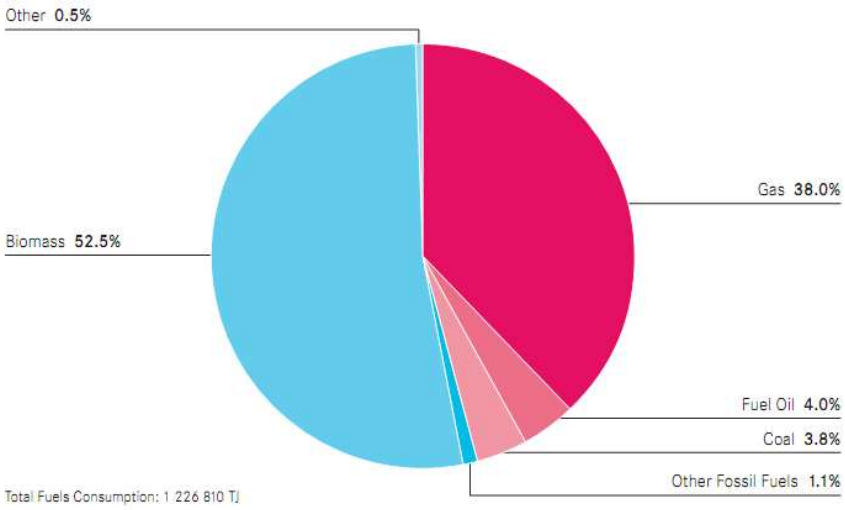


Figure 3.4-25 Fuels consumption in CEPI countries in 2008 (Source: CEPI 2010)

Steam and power generation in pulp and paper mills

Internal steam and power supply has been a core business of the pulp and paper industry but the management of some mills energy systems tend to be increasingly outsourced.

Boilers in the pulp and paper industry have variable sizes (5 to 200+ MW). The main types of boilers are (BREF 2010b):

- Recovery boilers (burning dry black liquors in chemical pulp mills, supplying the energy to the mill); some large recovery boilers can reach capacities up to 500 MWth
- Fluidised bed reactors (burning all types of fuels and waste)
- Fixed or moving grate boilers (mainly for coal)
- Combined cycle gas turbines: they are usually operated in a heat oriented mode.
- Gas or oil fired steam boilers, mostly used as peak load back-up boilers
- Small biofuels boilers were recently installed using powder and pellets

Most mills apply combined heat and power generation. These boilers operate up to 8 000 hours per year and have to adapt constantly to mill operation, accommodating wide and rapid oad changes.

In paper mills, the steam demand can even change rapidly and unexpectedly due to paper web breaks and other disturbances. Due to market reasons, maintenance and other factors the steam demand may be lower than during normal operation for considerable periods. For instance, following the economic crisis, the pulp and paper mills limited their operating rates from 90+% down to 80%.

High availability, high flexibility and high energy efficiency are therefore important criteria for the pulp and paper mills. Several plants are consequently built on-site to back-up each other.

3.4.4. Real case example

This part uses the information from a leading Nordic pulp and paper producer; it provides a generic operational envelope of its integrated pulp and paper mills.

General information on the contributor

The contributor operates half a dozen large integrated pulp and paper mills; the balance between pulp and paper production depends on each site. The production rates range from 170 kt to 840 kt for pulp production and from 190 to 1 110 kt for paper.

Cogeneration plants and back-up capacities

All integrated mills operate on-site cogeneration plants. Their capacities range from 100 to 300 MWth. This leads to a ratio of 5 to 5,6 MWth / t of pulp + paper produced at an individual site.

Steam is consumed mostly at a temperature around 150°C and pressure 3,5 bar. Normal steam pressures may range from 2,5 to 12,5 bars. The flow rate is around 120-360 t/h (assuming a steam energy content of 3 GJ/t). The steam quality must of the highest purity.

The plant availability is as high as 95% and operating hours are 8 200 h/y. Availability is a crucial parameter. The process stops instantaneously if steam is not supplied.

Cogeneration plant fuels include biofuels (wood by-product, black liquor chemical recovery system), peat and natural gas.

Back-up capacities cover normally 70% to 100% of the steam capacity. All back-up capacities are gas boilers.

Energy profile

The energy profile is greatly impacted by web breaks in the paper machine which can be of variable durations. During short time breaks, steam is directed to a steam accumulator or to the condensing tail if any. Long time breaks require powering down the cogeneration plant.

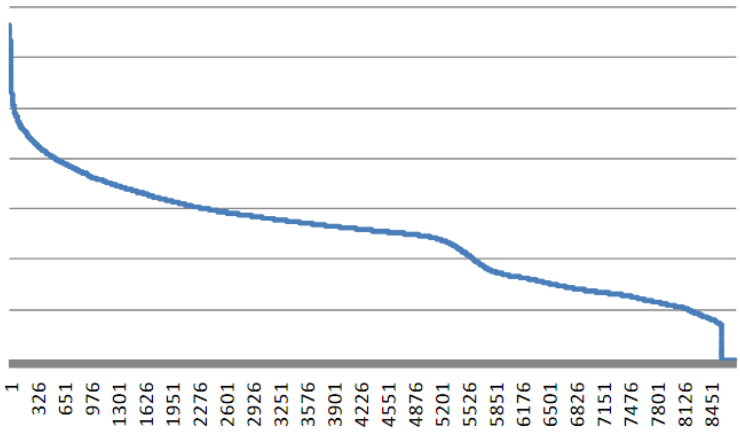


Figure 3.4-26 Real case heat load curve for one integrated mill (X-scale = hours, Y-scale = steam demand, Source: private contribution)

The heat load curve above demonstrates how papermaking is fundamentally fluctuating. It reads as follows:

Time	Steam demand
3% of time	0%
5% of time	0% < ... < 20%
30% of time	20% < ... < 40%
38% of time	40% < ... < 60%
19% of time	60% < ... < 80%
5% of time	80% < ... < 100%
1% of time	100% < ... < 140%

Table 3.4-8 Real case steam demand of an integrated pulp and paper mill as a distribution over the yeat (Source: private contribution)

A nuclear reactor may but with some difficulty accommodate this variability, all the more that large pulp and paper mills, mostly in Scandinavian countries, tend to be far from large cities or industrial facilities, at least beyond the reachable distance of heat transport, so the non-used steam could difficultly be supplied to another customer.

3.4.5. Pulp and paper heat market

The total specific energy consumption reported below from BREF (2010b):

	Total heat demand (MWh/t)		Total Electricity demand (MWth/t)	
Kraft pulp	2,78	3,89	0,60	0,80
Mechanical	0,04	0,08	1,00	2,00
Recovered fibre	0,06	0,11	0,30	0,50
Paper	1,94	2,50	0,60	0,80

Table 3.4-9 Assumed specific heat and electricity consumptions for a Kraft and mecahnical pulp mills and recovery fibre and normal paper mills (Source: adapted from BREF 2010b)

The total heat market can therefore be calculated, considering that the Kraft (respectively the mechanical) process represents 2/3 (resp. 1/3) of the pulp produced in Europe and that paper produced from recovered paper (resp. from pulp) represents 52% (resp. 48%) of papermaking

	Production	Total heat demand	Total electricity demand

	(kt)	(GWh/y)		(GWh/y)	
Kraft pulp	29 120	80 889	113 244	17 472	23 296
Mechanical	14 560	607	1 213	14 560	29 120
Recovered fibre	54 193	3 011	6 021	16 258	27 097
Paper	50 025	97 270	125 062	30 015	40 020
TOTAL	**147 898**	**181 776**	**245 541**	**78 305**	**119 532**

Table 3.4-10 Total heat and electricity demands in the pulp and paper sector

This total heat market calculated directly is significantly below CEPI's reported consumption (340 781 GWh/y). This may be due to the fact that CEPI's statistics include also the fuel burnt in the cogeneration plant. The estimated electricity consumption is yet in line with CEPI (116 218 GWh/y).

However, the preceding sections have demonstrated that this heat consumption is met mostly internally by recovering by-products. An indicative paper heat market can be estimated taking only the external heat and electricity consumption reported for some plants in BREF (2010b) as follows:

	Kraft pulp making	**Mechanical pulp making**	**Recycled fibres**	**Paper from normal pulp**
Considered example	Unbleached kraft pulp integrated	Finnish CTMP mill	Paper recycled is deinkable recoverable paper	Largest non-integrated wood free fine paper mill
Heat purchased externally (kWh/t)	350 – 450	700 – 900	200 – 300	1300 – 1550
Electricity purchased externally (kWh/t)	350 – 450	1700 – 1900	350 – 450	550 – 650
Industry heat market (GWh/y)	10 192 – 13 104	10 192 – 13 104	10 839 – 16 258	65 032 – 77 538
Industry electricity market (GWh/y)	10 192 – 13 104	24 752 – 27 664	18 968 – 24 387	27 514 – 32 516
Average pulp or paper production capacity (kt/y)	250	250	123	123
Average site heat consumption capacity (MW/site)	11 – 14	22 – 28	3 – 5	20 – 24

Table 3.4-11 Considered examples for estimating the external heat and elecitricy share of energy consumption in pulp and paper mills (Source: Adapted from BREF @10b)

Papermaking from normal pulp represents the largest heat segment ranging from 65 to 77 TWh/y as well as an electricity production which is almost in line with normal combined heat and power schemes (30%). Although the average site heat consumption capacity is only 20MW, which relates to the average production capacity, large paper mills which may reach 1,2 Mt/y would require a thermal capacity of 200 MWth. Paper is therefore the most promising market, although its energy consumption is very volatile due to unplanned web breaks.

Papermaking from recycled fibres comes second with a non-negligible heat consumption but the average site thermal capacity might be low (a few MWth to several tens of MWth).

The estimation of the heat consumption for mechanical pulp making is a maximum because the technology chosen is a chemical thermo mechanical pulp mill which consumes some heat, at the

difference from the other mechanical technologies. The average site thermal capacity would remain low (several tens of MWth).

The Kraft pulp making consumes also in total a certain amount of heat externally (most heat is taken from the chemical recovery system, see paragraph on pulp and paper technologies). The average site thermal capacity for external heat supply remains yet low.

This direct estimation for the total pulp production (20 to 26 TWh/y) is much higher than in the ETS. This may be due to the fact that 1/ the thermal capacities of the cogeneration plants are lower than the ETS threshold of 20 MWth, 2/ because it uses bio-energy sources whose emissions are not to be reported in ETS (to support biofuels) and 3/ because small pulp mills may be excluded from ETS.

The direct estimate for paper (76 to 94 TWh/y) is yet rather in line with the indirect calculation (21 TWh/y in combustion of fuels plus 63 TWh/y for the sector in the ETS tabe).

3.4.6. Potential for nuclear heat

The pulp and paper industry represents a significant heat market with steam temperatures and pressures that a nuclear reactor may accommodate.

Yet, this heat market may be challenging to supply:

- the heat market for pulp making looks unreachable because heat is mainly recovered from process residues (Kraft pulp making) and from electricity (mechanical pulping, except CTMP) and the average site thermal capacities are low
- papermaking from normal pulp or recycled fibres is a significant heat market, with large enough average site thermal capacities, but the energy profile is very volatile and it may be difficult - but not unfeasible - for a base load technology like nuclear energy to supply such mills.

3.4.7. Conclusions and recommendations

- Paper is produced from normal pulp – itself produced by Kraft process at 2/3 and mechanical process at 1/3 – and recycled fibres (with a recycling ratio of more than 52% in the pulp mix).

- Pulp and paper is a versatile industry due to the variety of paper produced and recycled; European mills have very diverse capacities, energy balances, raw materials and products mixes.

- Finland and Sweden are the largest European countries for pulp and papermaking; Germany, Italy, France and Spain are also important countries for papermaking only.

- The industry is energy and capital intensive; energy is as far as possible recovered from process residues or from mechanical actions. The outsourced energy still represents a significant market.

- The pulp and paper industry could yet be difficult to supply with external heat because of the low average thermal capacity per site (pulp making and recycled fibres) and the volatility of energy consumption due to unplanned web breaks for papermaking.

- It is recommended to:
  - make a detailed analysis of the energy balance and profile of very large integrated pulp and paper mills and of the feasibility of supplying it with nuclear energy
  - liaise with paper producers to increase the knowledge on the cogeneration coupling scheme in the industry
  - liaise with technology providers (especially METSO and VOITH) to partner and possibly develop the coupling between a nuclear reactor and a paper mill.

3.5. Metals and minerals

3.5.1. Alumina and aluminium production

Summary:

Alumina production is a small but viable heat market for nuclear heat; however the European market is subject to an ongoing de-industrialisation in this sector. Primary aluminium is not a heat market since it uses only electrolysis; heat is produced by the oxidisation of the carbon anode. Secondary aluminium production could be a viable market but the average thermal capacity is very small and only a few sites could possibly consume enough heat to accommodate a nuclear cogeneration plant.

This part uses information from the BREF report on Non-ferrous metals industries (BREF 2001) and from the contribution from the European Aluminium Association.

3.5.1.1. Aluminium applications and market

Aluminium is a light-weight metal which offers yet good mechanical and electrical properties. It has therefore a wide range of applications (market share in EU27 are added in brackets, EAA 2010):

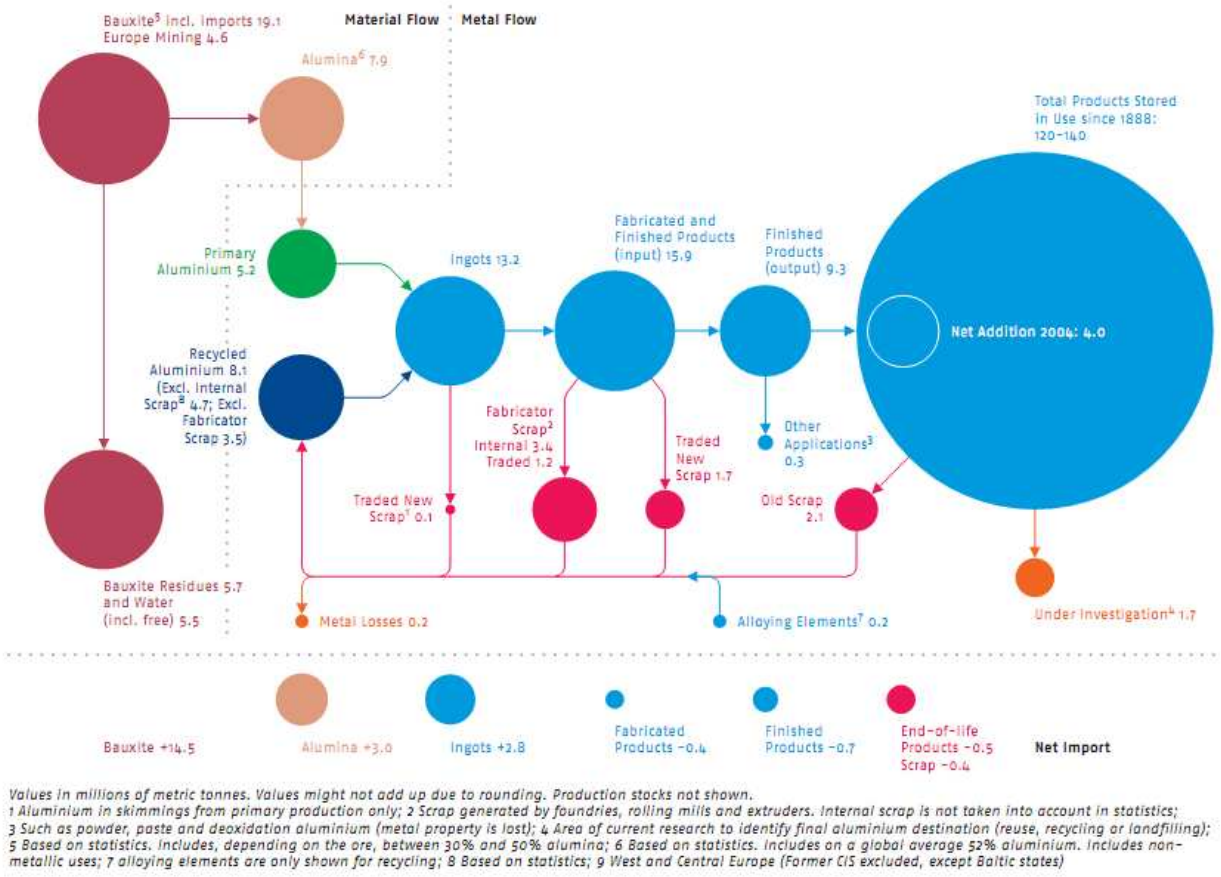
- Transport (36%): cars, trucks, buses, trains, airplanes
- Construction (26%): mainly windows and structures
- Packaging (17%): mainly cans and consumer goods in general
- Engineering (14%), including electrical engineering and computer devices
- Others (7%)

The final aluminium products

There are four main families of aluminium products:

- Rolled products (4,6Mt): foilstock, stockists, packaging, building, engineering and transport
- Extrusions (3,2Mt): in particular buildings and transport
- Castings (2,9Mt): great majority for transport
- Wire, slugs, powder (1Mt): in particular engineering

Aluminium is differing from most other metals by the extent the sector is recycling aluminium scraps (so-called secondary aluminium). This represents a feedback loop which drives the production of primary aluminium on the basis of the aluminium in circulation and the net demand of new aluminium products.



Values in millions of metric tonnes. Values might not add up due to rounding. Production stocks not shown.
1 Aluminium in skimmings from primary production only; 2 Scrap generated by foundries, rolling mills and extruders. Internal scrap is not taken into account in statistics; 3 Such as powder, paste and deoxidation aluminium (metal property is lost); 4 Area of current research to identify final aluminium destination (reuse, recycling or landfilling); 5 Based on statistics. Includes, depending on the ore, between 30% and 50% alumina; 6 Based on statistics. Includes on a global average 52% aluminium. Includes non-metallic uses; 7 alloying elements are only shown for recycling; 8 Based on statistics; 9 West and Central Europe (Former CIS excluded, except Baltic states)

Figure 3.5.1-1 Europe aluminium flow in 2004 (Source: EAA 2006)

In this case, the lifetime of the aluminium products becomes a key market driver. The average lifetime range by type of product is (EAA 2006b):

Product	Average lifetime
Packaging	1 – 3 months
Transport (cars and light trucks)	7 – 20 years
Transport (other)	30 – 40 years
Engineering	20 – 40 years
Buildings	15 – 50 years

Table 3.5.1-1 Average lifetimes per aluminium product (Source: EAA 2006b)

Packaging (especially beverage cans) is therefore the first source of scrap, although cars and light trucks have a growing share due to the return of recent cars with increasing vehicle aluminium content, a trend which will accelerate in the frame of emissions restrictions in the automotive sector and the search for even lighter vehicles.

3.5.1.2. Aluminium production

Aluminium production routes

1. Alumina is produced from bauxite.
2. Primary aluminium is produced by electrolysis from alumina
3. Secondary aluminium ("recycling") is produced from aluminium scraps
4. Semi-finished and finished products are manufactured using primary and secondary aluminium ingots
5. After the finished products are used, they are collected, sorted and sent back to secondary aluminium plants ("recycling")

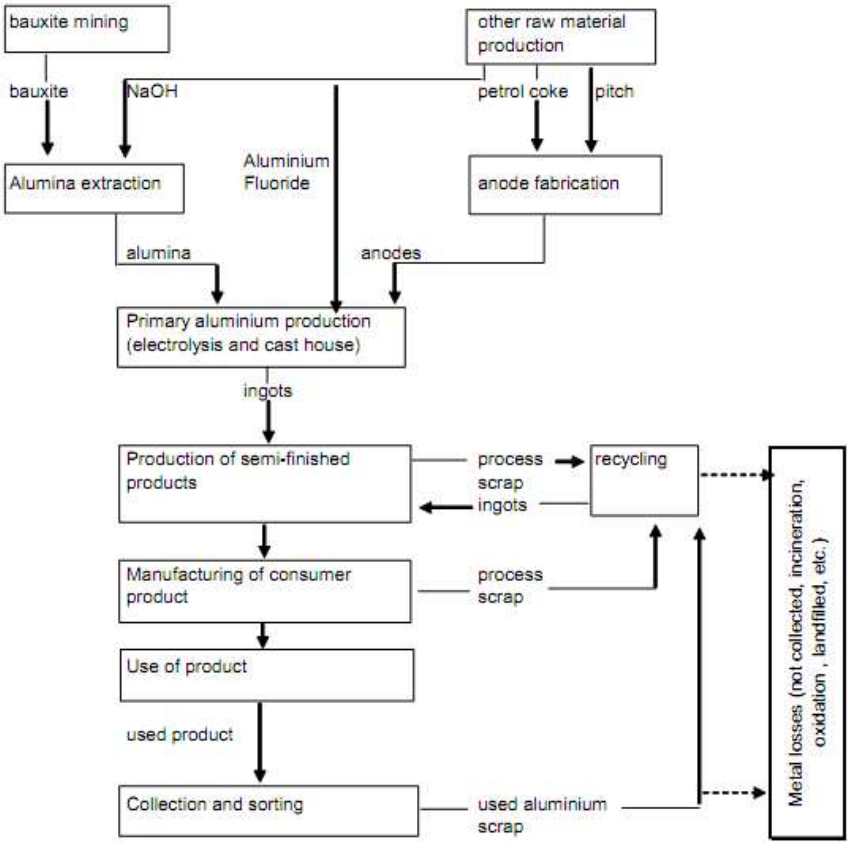


Figure 3.5.1-2 Simplified life cycle material flow chart of aluminium (source: EAA 2008)

The synthetic graph below summarises the aluminium production routes and industrial sector in Europe:

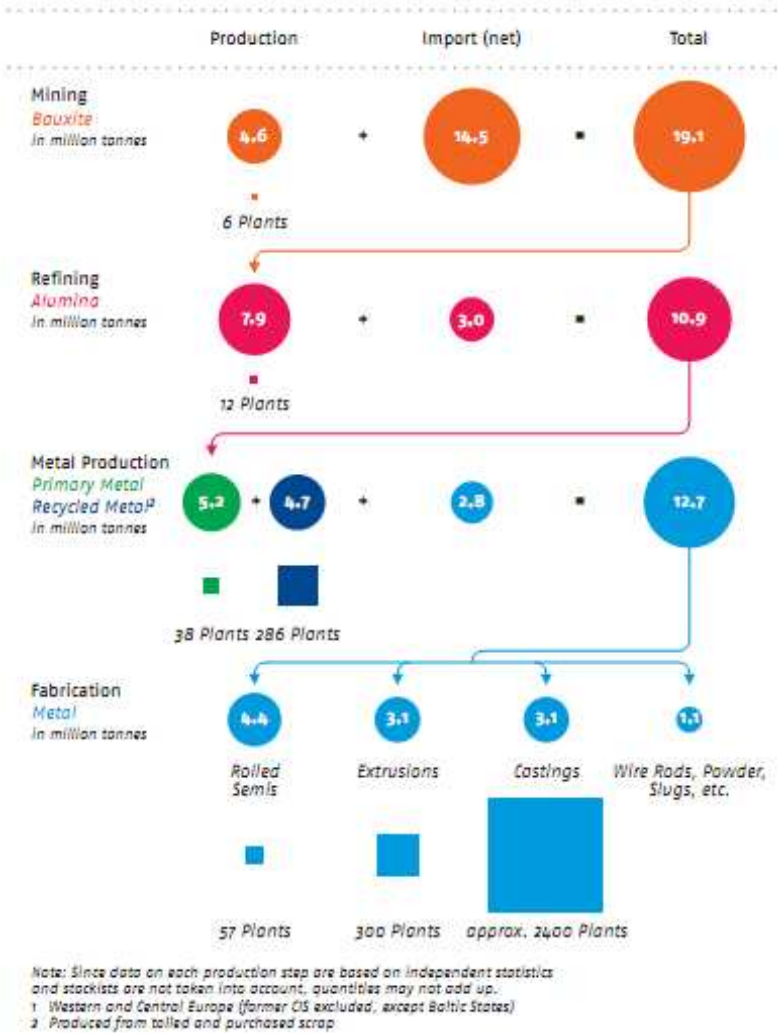


Figure 3.5.1-3 Aluminium sector in Europe in 2004 (source EAA 2006b)

- European bauxite imports are very large due to the low domestic resources (the only EU Member State producing bauxite is Greece).
- 12 plants produced alumina in 2009 (8 today) and one third is imported
- Alumina was fed into 38 primary production plants (28 now), which produce approximately the same amount of aluminium than the 286 recyclers of aluminium scraps
- Aluminium ingots are sent to dedicated plants producing semi-finished products; the industrial structure depends greatly on the type of product.

The demand of aluminium is increasing rapidly which drives the production of primary and secondary aluminium on an increasing path. The trend in the production of primary aluminium has been steadily growing since 1950 and the pace has even more accelerated since 2000 with the uptake of the Chinese production.

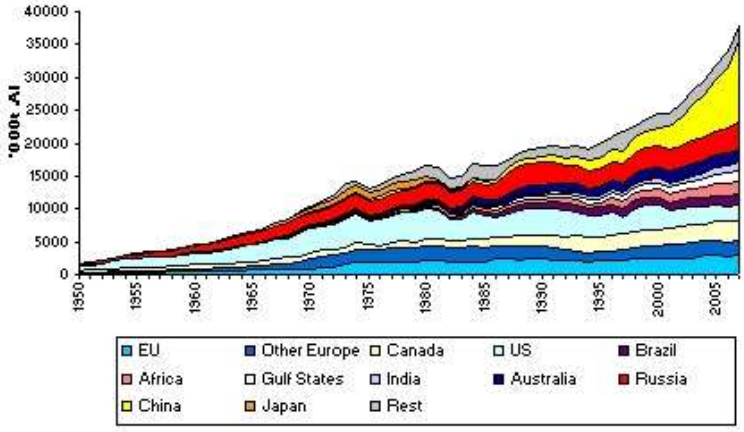


Figure 3.5.1-4 History of primary aluminium production by countries and regions (source: EAA 2006b)

The clients and suppliers of aluminium producers

Due to the two production routes, aluminium suppliers include:

- Bauxite producers from mainly West Africa and Australia (there are still a few European mines)
- Alumina producers (Australia, Jamaica and Brazil are notable producers)
- Any distribution company (packaging), manufacturing companies (manufacturing scraps), construction company (construction scraps) which sell their scrap to secondary aluminium producers.

Final general remarks on the aluminium sector

The whole aluminium sector is an energy intensive industry. Several energy policies are impacting the industry, notably EU ETS, the abolition of long-term electricity and gas contracts. Primary smelters are disappearing from Europe mainly for these reasons.

A last remark about the aluminium industry is that several companies are international companies, whose headquarters are located outside Europe. There are only few strictly European companies. This makes any decision in Europe tributary to the global context.

3.5.1.3. Aluminium production routes and energy needs

Alumina production

Alumina is produced from bauxite through the Bayer process which operates a caustic soda cycle. Bauxite is a mix of metallic oxides (aluminium mainly but also iron, silica...). There are different qualities of bauxite which require adapted alumina production plants

An alumina production plant typically produces 1 to 3 Mt Al2O3. The main process steps are (BREF 2001):

1. Bauxite is first digested to produce aluminium hydrate Al2(OH)3; this step requires steam injection at 270°C, 3-4 bars, which is consumed in the process.

2. Aluminium hydrate is calcinated by flowing hot exhaust gases from the combustion of fossil fuels (mainly gas). Exhaust gases are mainly CO2 (from the combustion of gas) and H20 (from the de-hydratation). Temperatures of up to 1000°C are reached. Air must be hot and dry but any heat, through a heat exchanger can be used.

The whole process requires energy in the range of 7,6 – 11,7 GJ / t Al2O3 with a total average of 10 GJ / t Al2O3, distributed as follows:

Application	Energy need (MWh / t Al2O3)	Temperature (°C)	Pressure (bars)	Fuel
Steam production Min - Max	1,4 – 2,1	143°C - 280°C	3 - 4 bars	Generally gas
Calcination Min - Max	0,7 – 1,2	850°C		Gas / oil
TOTAL Min - Max	**2,1 - 3,3**			

Table 3.5.1-2 Specific energy consumption by alumina process phase (Source: adapted from BREF 2001 with EAA)

Any source of heat can be used for both steam production and calcination. For the calcinations process, nuclear pre-heating could bring the first heating of the hydrated alumina, boosted in a second time by a gas-fired burner.

Alumina plant can be located anywhere. Bauxite is indeed easy to transport in bulk and does not require any special attention.

However, the small number of plants in Europe can be explained by the higher energy costs and stricter regulation which orientate international companies towards developing countries, in which most bauxite mines are in operation in the world.

Alumina production could clearly be a nuclear heat consumer but the de-industrialisation would have to be reversed.

Production of primary aluminium

Primary aluminium is produced by electrolysis of alumina, using carbon anodes. Alumina is dissolved in a molten bath of sodium aluminium fluoride at around 960°C and takes place in a large number of electrolysis cells connected in series. The process requires large amounts of electricity and some heat for producing carbon anodes (production plant is generally co-located).

Although electricity is mainly used, the process is a large emitter of CO2 because of the carbon anodes oxidisation (producing heat).

Here are some consumption figures (BREF 2009):

	Unit	Pre-Bake		Soderberg	
		Min	Max	Min	Max
Alumina	kg/t	1900	1930	1900	1930
Anode consumption	kg/t	390	440	470	530
Energy for anode production	GJ/t	2400	2400		
Power for electrolysis [DC]	kWh/kg Al	12,9	15,0	14,5	17,0
Total electrical power [AC]	kWh/kg Al	13,7	15,7	15,1	17,8

Table 3.5.1-3 Alumina, anode, energy for anode production and power for electrolysis consumptions for primary aluminium production (Source: BREF 2009)

Aluminium metal collects at the bottom of the electrolytic cell and is aspirated by a vacuum crucible. Vacuum is made by flowing high-pressure air in a vacuum making device. High pressure air is produced in a central power plant and distributed throughout the production facility. The production process uses electrical compressors or fossil fuel burners; the amount of energy required for that is negligible compared to the other values.

A lot of R&D is going on to replace carbon anodes by inert material but no viable solution (technically and economically) emerged up to now. Primary aluminium does therefore not represent any heat market.

Refining and casting

Refining and casting require usually very low amounts of heat. Liquid aluminium from the primary production plant is directly processed and its temperature must be even cooled down from 960°C to 700°C.

Production of secondary aluminium

Secondary aluminium production plant consumes aluminium scraps, that they pre-process (de-coating, purification in order to reach the aluminium grade necessary). The main feature of secondary aluminium production plants is the diversity of raw materials to process and the variety of furnaces used, which explains the significantly larger number of plants in Europe.

1. Scrap pretreatment

Some energy figures for the scrap pre-treatment are reported below (BREF 2009):

Scrap dryer	Min	Max
Energy consumption (GJ/t scrap)	3,5	5,2
Type of heating	Indirect or direct	
Type of fuel	Gas	
Drying temperature	< 500°C	
Afterburning temperature	> 700°C	
Scrap washing		
Energy consumption (GJ/t scrap)	0,4	0,6
Water solution temperature	60°C	90°C
Drying temperature	120°C	

Table 3.5.1-4 Main parameters for aluminium scrap pre-treatment (Source: BREF 2009)

2. Scrap melting and refining

Pre-treated scrap is then melted in the furnace at temperature higher than 660°C (melting temperature of aluminium). Some energy figures are reported below by type process (BREF 2009):

Processes	**Rotary drum furnace**	**Titling rotary furnace**	**Hearth furnaces**	**Blast furnaces**	**Crucible furnaces**	**Channel introduction furnace**
Purpose	Melting	Melting	Melting, holding, casting	Melting, holding	Melting (M), holding (H)	Melting (M), holding (H)
Preferred feedstocks	Thin walled new and old scraps small pieces	Old scraps	Ingots, new and old scraps	Thin walled new and old scraps	Ingots and new scrap	Ingots, new and old scraps
Preferred fuels	Natural gas, fuel oil	Natural gas, extra-light fuel oil	Natural gas, extra-light fuel oil	Natural gas, extra-light fuel oil	Natural gas, extra-light fuel oil (a)or electrically heated by resistance (b) or inductivity (c).	Electricity heated
Energy use (MWh/t metal)	0,56 - 1,31	0,56 - 0,69	0,69 - 1,22	0,67 - 1,19	(a): 1,42-2,06 (M) (a): 0,47-0,97 (H) (b): 0,58-0,75 (M) (b) 0,11-0,33 (H) (c): 0,53-0,75 (M) (c): 0,25-0,33 (H)	1
Throughput maximum (t metal/h)	20	7	30	1,5	(a): 0,1-0,43 (b): 0,075-0,26 (c): 0,25-3	7

Table 3.5.1-5 Description of the production processes for secondary aluminium (Source: BREF 2009)

The large number of processes is clearly visible, depending from the scraps quality and form. In consequence, the throughput and energy consumption are very widely ranged.

Leaving out the electricity-consuming resistance and inductivity crucible furnaces, out of the scope of this study, the average range of energy use is of 0,56 to 4,03 MWh / t metal.

Adding up the energy consumed by scraps drying and washing processes, this makes a total energy consumption of 1,64 – 5,64 MWh/t.

Extrusion and rolling

Extrusion and rolling mills consume mainly electricity but pre-heating of the material is necessary to soften aluminium.

Extrusion and rolling may consume 1-2 GJ/t (0,28-056 MWh /t metal). As the number of plant is very large, the average production capacity per site makes these processes of secondary interest. The largest rolling plants may yet have capacities ranging from 200 000 to 1,4 million tonnes/year with their own remelting facilities and may be large heat consumers.

Energy demand profiles

The demand profiles for all types of production steps are rather constant:

- Primary smelters can been put off-line in case of emergency for 1-2 hours (aluminium remains liquid); they operate several electrolytic cells in sery so that electricity consumption is constant.
- Secondary refiners operate 5-7 furnaces. The maintenance time may be only 1 day / month, and relining (replacing the whole furnace) once every 4-5 years.

3.5.1.4. Heat market represented by the aluminium sector

Alumina production

Alumina is clearly a heat market for nuclear reactors since the temperature of steam production is compatible and nuclear pre-heating could be used for calcinations. It represents however only a small market.

Total energy need (GWh)	Min	Average	Max
Steam production	11 060	13 825	16 590
Calcination	5 530	7 505	9 480
Total	**16 590**	**21 330**	**26 070**

Table 3.5.1-6 Total energy consumption for alumina production by process phase

Considering 12 alumina production plants in Europe and a total production of 7,9 Mt/y, the equivalent energy consumed by site, thermal capacity installed by site and equivalent number of 500MWth nuclear reactors are:

		Min	Average	Max
Consumption per site (GWh/site)	Steam production	922	1 152	1 383
	Calcination	461	625	790
	Total	**1 383**	**1 778**	**2 173**
Thermal capacity per site (MWth/site)		**173**	**222**	**272**
Number of 500 MWth reactors (8000h/y)		**4**	**5**	**7**

Table 3.5.1-7 Minimum, average and maximum consumption by alumina production site and related thermal capacity

The market represents few nuclear reactors but individual sites may represent a good share of the thermal output of a nuclear reactor, the remaining heat being distributed to possible other sites.

Secondary aluminium

Secondary aluminium production is probably not a viable market segment for nuclear heat. First, the temperature class is 550-700°C and second the average consumption by site is very low, therefore incompatible with the large thermal capacity planned for a nuclear high temperature reactor.

Considering a production of 4,7 Mt/y and 286 plants in operation in Europe, the minimum and maximum total energy consumption and average energy consumption by site are:

	Min	Max
Energy consumption of the sector (GWh/y)	7 724	26 513
Energy consumption by site (GWh/site)	27	93

Table 3.5.1-8 Energy consumption for the production of secondary aluminium in Europe and consumption by site

It must be noted that detailed public information on the structure of secondary aluminium producer is very sparse. This result should be checked with a detailed analysis of the recycling plants since some of them may consume significant amount of heat.

For instance, some recycling plants were reported to have production capacities of up to 200 kt/y, which would represent 1 128 GWh consumed per site, or a thermal capacity of 141 MWth.

Current R&D

R&D in aluminium is mostly carried out by universities (Aachen, NTNU, Bourgogne university, etc.) and by companies at their own research centres. Development cycles are long-term (10-15 years from design to demonstration).

The aluminium research is not organised at European scale. Launching a European Aluminium Technology Platform was an idea but has not been fully realised. The situation is worsened by the fact that decisions for an European cooperation is taken at the headquarters of multinational companies located outside Europe. Europe mostly fails to attract such companies.

Alternative routes for the production of primary aluminium were researched but none provided proving results. Alcoa / LKM is developing a new carbothermic route in a Norwegian plant but little information is available.

3.5.1.5. Conclusions and recommendations

- Aluminium is an energy intensive industry, whose main raw material is bauxite, transformed into alumina and then processed into aluminium by electrolysis (primary aluminium); secondary aluminium is produced from recycling aluminium scraps. Bauxite, alumina, aluminium scraps and aluminium are all internationally traded commodities.

- The aluminium market has been steadily growing and the trend should continue, in particular after the climate protection measures in the transport sector (which push for manufacturing lighter vehicles). The industry ownership structure makes the European aluminium industry dependent on the global context.

- Alumina production would represent a small but viable heat market for nuclear reactors; the operating conditions are compatible with nuclear heat and the average heat consumption by site is significant enough to accommodate a nuclear reactor

- Primary aluminium production does not represent any heat market, although it could be an interesting electricity consumer for a nuclear reactor (some production sites are co-located with alumina production sites)

- Secondary aluminium could be a heat market but the average heat consumption per site is very low; as information on the industry structure is sparse, this would require a more in-depth analysis.

3.5.2. Iron and steel industry

Summary:

Steelmaking is a representative example of non-"plug-in" market where nuclear energy may be used in existing furnaces by supplying syngas from nuclear assisted steam methane reforming or partial oxidation. Other possibilities include nuclear air pre-heating and oxygen production via high temperature process. On the other hand, the use of nuclear energy in direct reduced iron production units, a technology industrialised outside Europe, is a promising opportunity which should be investigated. Finally, nuclear energy could be used in breakthrough concepts that are under development by the ULCOS consortium.

This part uses information from adopted BREF on Iron and Steel Manufacturing Industries (BREF 2001e) and its revised draft (BREF 2009b) and the contributions from the European Steel Technology Platform and a major steel producer.

3.5.2.1. Iron and steel market and industry

Steel products and applications

There are two main families for steel products:

- Flat products (around 250 mm x 2 m x ... m)
    - Hot rolled wide strip (mainly for automotive, packaging, tubes)
    - Quarto plate (mainly for shipbuilding, tubes, boilers, containers)
- Long products (around 50x50 mm to 250x250 mm)
    - Wire rods (cables, wires...)
    - Beams (buildings structural steelworks)
    - Reinforced bars (construction, constraint steel)
    - Merchant bars (light construction)

Hot rolled wide strip is by far the main product.

The clients and suppliers of steel producers

Steel producers buy iron ore to mining companies (BHP Billinton, Rio Tinto, Valle hold altogether 70% of the world market). The alternative raw material is iron scraps. World distribution of consumption is 30% scraps / 70% ore; in developed countries, the distribution is closer to 40% scraps / 60% ore.

Iron ore is imported mainly from non-European countries. In Europe, only Bosnia, Sweden and Norway produce low amounts of iron ore.

The EU production is 200Mt/year in 2008 (140Mt in 2009, probably 170Mt in 2010).

Their main clients are:

- Construction (27%)

- Automotive (16%)
- Mechanical engineering (14%)
- Tubes (12%)
- Others (31%, metalwares, packaging, structural steelworks...)

The labour costs account for 15-20% of the final cost. Energy and raw materials make most of the cost. The EU directive on Emission Trading Scheme may imply an over cost which may endanger the European steel industry competitiveness. Around 2 tons of CO2 are produced for each ton of carbon; since the steel market price is around 500 Euro/ton, a CO2 price of 20 €/tCO2 would represent 8% increase in the price, putting a competitive disadvantage on the European steel industry.

Steel production routes

Like aluminium or paper, steel is an industry with a high recycling ratio. The figure below illustrates particularly well the steel production cycle:

- Steel can be newly produced from pig iron (produced from a Blast Furnace, BF) or recovered from steel containing products. Pig iron is almost the same as steel collected for recovery.
- Pig iron and recovered steel are processed via two main routes: Basic Oxygen Furnace (BOF, processing mainly pig iron) and Electric Arc Furnace (EAF, processing mainly steel scraps).
- Steel is further processed into semi-finished and finished products sold to industrial consumers, which in turn manufacture goods containing steel (e.g. cars)
- Steel products are used over a certain duration depending on the sector: 1 year for packaging. 12 years for automotive, 13 years for consumer goods, 25 years for machinery and 60 years for construction.
- Steel is then collected. The quality of steel scrap is an important parameter for EAF operations and depends on the scraps which are collected.

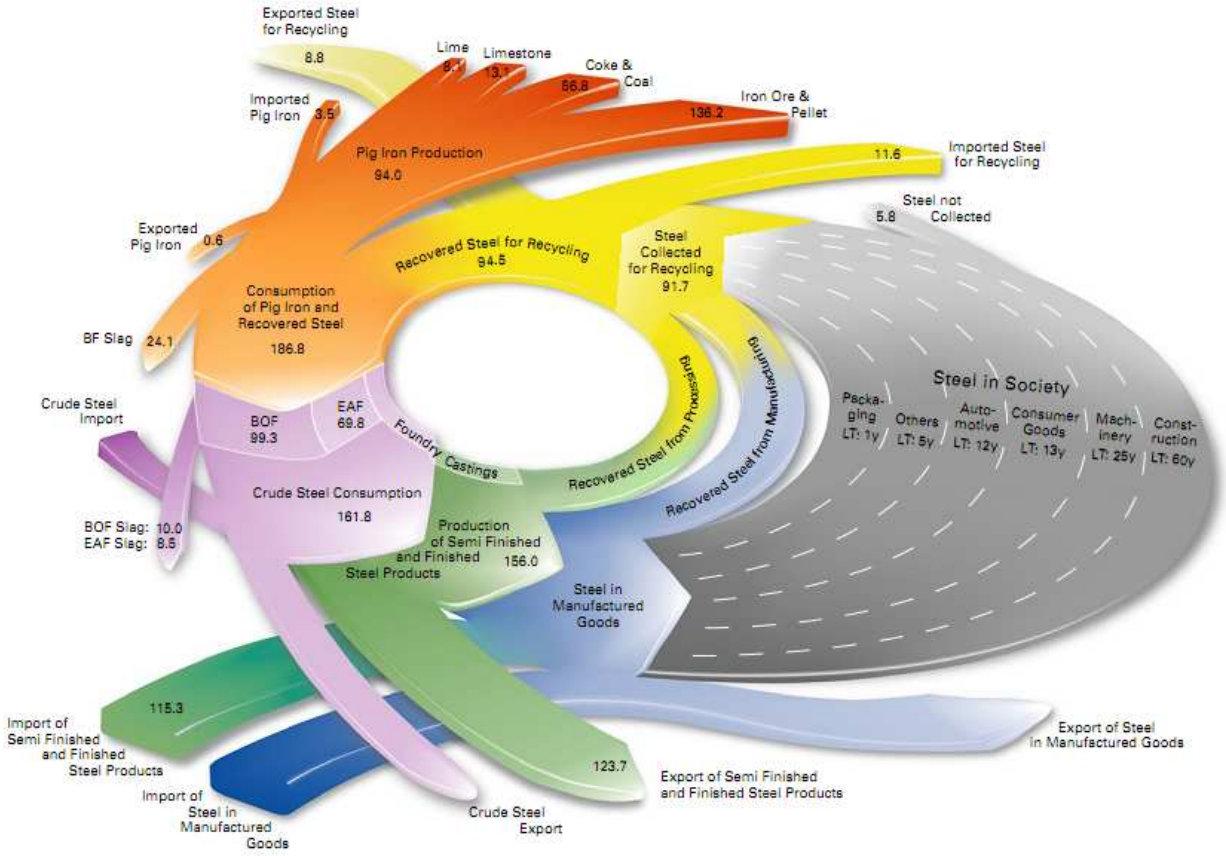


Figure 3.5.2-1 Illustration of steel flows in EU15 in 2004 (Source: EUROFER)

The crude steel production routes are depicted below (BREF 2010b):

- Blast furnace route: iron ore are sintered or pelletised and mixed with coke in a blast furnace where fossil fuels are burnt with blowing oxygen. The excess carbon content of the pig iron from the blast furnace is removed in the oxygen converter (or basic oxygen furnace), which can also use some scrap. This is the main route in Europe.
- Electric arc furnace route: steel scraps and direct reduced iron can be smelted in the electric arc furnace to produce crude steel. This is the second largest route in Europe
- Pre-reduction route is a marginal method which consists in pre-reducing and smelting the pre-reduced iron with oxygen and finish processing them in the oxygen converter.

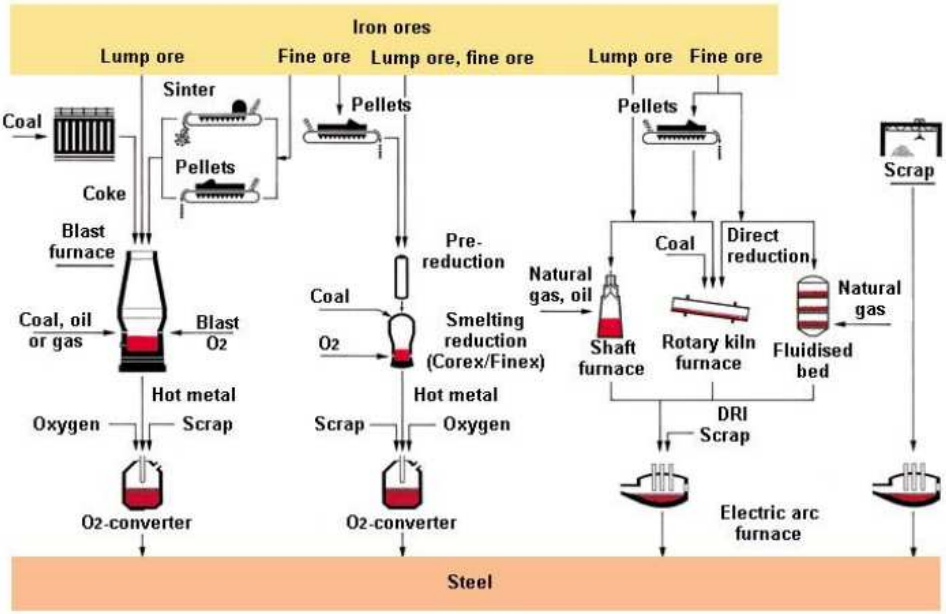


Figure 3.5.2-2 Crude steel production method (Source: BREF 2009b)

The production of steel in Europe depends on the economic situation. The economic crisis has severely diminished the production. EAF represents around 40% of the steel production in Europe, the rest being principally the Blast Furnace/Basic Oxygen Furnace route. EAF production is also more stable.

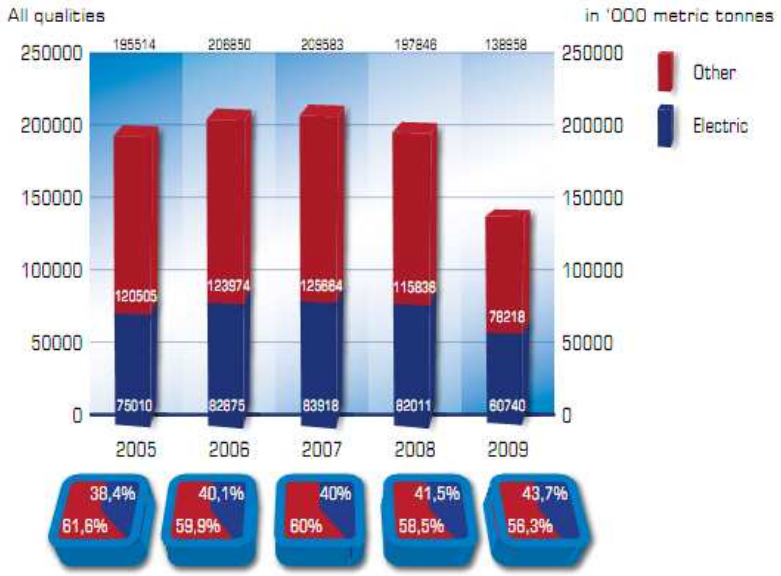


Figure 3.5.2-3 Crude steel production by process (Source: EUROFER 2010)

Electric arc furnaces are mostly dedicated to producing long products; usual individual furnaces have production of less than 1 Mt/y, usually 500 kt/y. Blast furnaces / Basic Oxygen Furnaces are used to manufacture flat products; individual furnaces capacities range from 0,5 to 5,5 Mt/y and may produce on average around 2 Mt/y.

Production mapping

The main steel producing countries are Germany (31% EAF, 69% BF), Italy (60% EAF, 40% BF), Spain (76% EAF, 24% BF) and France (37% EAF and 63% BF) which account altogether for around 60% of the European steel production.

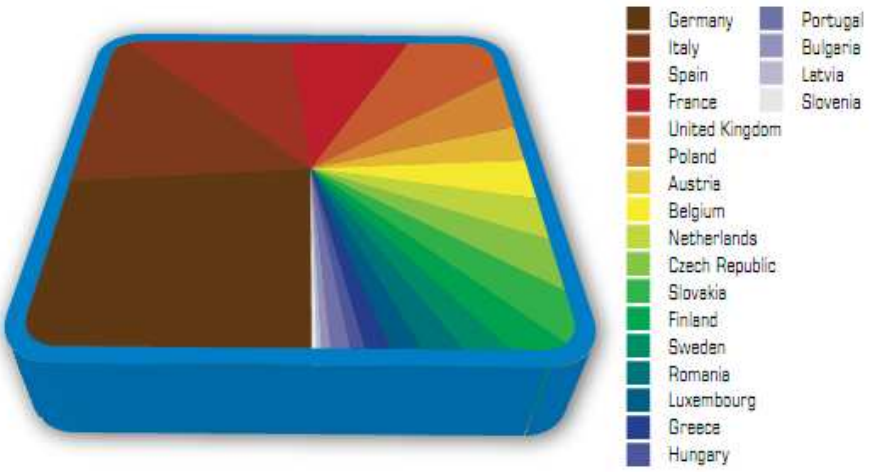


Figure 3.5.2-4 Share of crude steel output by country in 2009 (Source: EUROFER 2010)

Steelworks are spread all over Europe; integrated steelworks (blast furnace and basic oxygen furnaces) are mainly concentrated in Benelux and Western Germany.

Figure 3.5.2-5 Geographical distribution of BF/BOF steelworks in the European Union (Source: BREF 2001e)

The map above can be explained by the localisation of limestone deposits (lime was historically an important fluxing agent in steelmaking), transport infrastructures and the availability of other raw materials (especially industrial gases). Most steelmaking plants are connected to industrial gases pipelines, whenever they exist. Benelux and Western Germany are therefore attractive regions for integrated steelworks (BF+BOF).

Industry characteristics

Steelmaking is a rather non-concentrated industry. ArcelorMittal is the world leader and a global player. It holds around 15% market share. Many other steelmakers have a lower market share and are either regional companies (e.g. Corus) or small niche players. The top 10 steel producers in the world in 2007 is as follows (ECORYS 2008):

Rank	Production (Mt in 2007)	Company	Country
1	117	ArcelorMittal	EU – India
2	35	Nippon Steel	Japan
3	32	JFE	Japan
4	30	Posco	South Korea
5	26	Baosteel	China
6	21	US Steel	USA
7	20	Nucor	US
8	19	Tangshan	China
9	18	Corus	UK - Netherlands
10	18	Riva Group	Italy

Table 3.5.2-1 Distribution of production of steel in 2007 by producer and country of ownership (Source: ECORYS 2008)

Steel is an internationally traded commodity in a very competitive market. The economic pressure is therefore very important.

Steel furnaces are capital intensive facilities, which may be spread on areas as large as several square kilometers. Furnaces lifetime range from 50 to 60 years and a steel production sites have longer lifetime since a furnace can be replaced. Some sites operate several furnaces. Long maintenance breaks occur every 10 to 20 years.

Steelmakers are usually not vertically integrated (except notably ArcelotMittal) and buy iron ore from international mining companies which act in an oligopolistic market: CVRD has 32% market share, Rio Tinto 23% and BHP Billiton 15% (ECORYS 2008).

Steelmaking requires coke which is produced from a special type of coal called coking coal. The main exporting countries are Brazil, Australia and South Africa. Nine countries (especially CIS and the USA) account for 96% of the total world hard coal reserves, of which 38% is coking coal (ECORYS 2008).

Steel consumers are also mostly concentrated (automotive, aerospace, shipbuilding, cable installers…).

3.5.2.2. Steel production routes

Comparison of the two main production routes

Blast Furnace route	Electric Arc Furnace route
Pre-treating: - Coal is coked in a coking plant which emits exhaust gases (CH4+H2, 4500 kCal/Nm3, low quantity) - Iron ore is processed with some ligants to improve its mechanical resistance properties for the furnace (sponge iron)	Pre-treating: - Iron scrap is pre-heated to limit electricity consumption
Inputs: - iron ore (Fe2O3)(1,6 kg / 1 kg cast iron) - coking coal (0,45 kg / 1 kg cast iron); - very little direct reduced iron or hot briquetted iron may be used	Inputs: - iron scrap - direct reduced iron (90% Fe, 10% FeO) - A little coal or materials containing carbon (e.g. pneumatics)
Outputs: - Cast iron (FeC at 4% C) - Exhaust gases (mostly CO, CO2, N2); 800 kCal / Nm3 (high quantity)	Outputs: - Steel (FeC at 0,04% to 1% C for carbon steels)
Additional process: - Basic Oxygen Furnace: pure oxygen is blown over cast iron to decrease the carbon content - Output: steel + exhaust gases (CO+CO2, medium quantity) - Remark: the reaction is highly exothermic; steel scrap and direct reduced iron is added to use this excess heat for their liquefaction and dilution in cast iron.	
Use of carbon containing materials - Coke is used mainly as reducing agent (producing the reducing gas CO+H2) - Coal is injected within burners as heating source	

Table 3.5.2-2 Comparison of the blast furnace and electric arc furnace production routes for steelmaking

Blast furnace description

The general scheme of a blast furnace is depicted below:

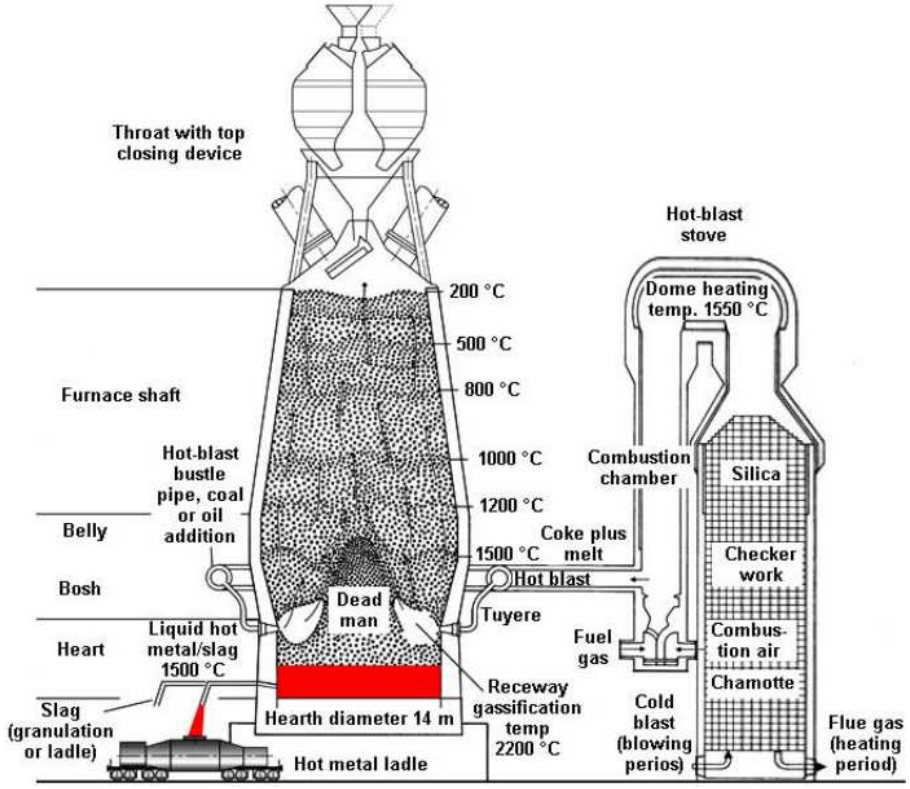


Figure 3.5.2-6 Simplified scheme of a blast furnace (Source: BREF 2009b)

A blast furnace (left-hand side of the picture) is a 70 meter high plant. Iron ore and coke are fed into the furnace from the top, which pile up in the furnace. Air is pre-heated within the hot stoves (right-hand side of the picture) up to 1 500°C and blasted through nozzles all around the furnaces with coal or oil.

The reaction in the blast furnace consists in removing oxygen from iron ores, which are made of ferrous oxides, principally Fe2O3. Oxygen is removed in a reducing atmosphere which attracts oxygen. Reducing gases include CO (which transforms into CO2), H2 (into H2O) or CH4.

Coke is used 1/ as a reducing agent since it releases so-called syngas (CO+H2) when its gasification occurs at high temperature and 2/ as a heating medium. Coke is necessary instead of coal because it offers plastic properties which enable the reducing gases to flow into the furnace so coke can be mixed directly into the furnace and can also provide a homogeneous heat to the furnace burden.

As coal and especially coking coal becomes increasingly expensive, the steel industry is keen to decrease its consumption of coke by injecting a reducing gas directly or by replacing it partially by coal.

The hot stoves are 40-50 meter high installations operating cyclically. Air is pre-heated by blowing it into a hot ceramic structure which consequently cools down. When the stoves structure reaches a defined temperature, the air blow is stopped and the ceramic structure is heated by a counter current flow of hot flue gases from the combustion of gas (usually blast furnace gas) up to a wanted temperature.

Three or four hot stoves are installed for each blast furnace so that one stove can be regenerating heat in the ceramic while the others are blowing hot air to the blast furnace.

Typical inputs and outputs are reported in annex VI. The most important are reported below (BREF 2009b):

Inputs	Units	Weighted average value
Iron ore	kg/t	1088
Coke	kg/t	359
Oxygen (purity 95%)	kg/t	54,4
Energy		
Electricity	GJ/t	0,12
Coke	GJ/t	12,4
Coal	GJ/t	1,63
Hot blast (from stoves)	GJ/t	4,52
Total energy	GJ/t	**18,67**

Table 3.5.2-3 Typical inputs and outputs of a blast furnace (Source: BREF 2009b)

Coke is the largest source of heat for a blast furnace followed by the hot blast from the stoves. Coal is a make-up energy and electricity consumption is marginal.

Blast furnaces produce calorific off-gases (BF gases). The volume and composition depends on:

- the quality of iron ores: higher oxides content requires more reducing gas so more coke, impurities requires energy to be taken out
- the mix of reducing gas put into the furnace: this is controlled by the quantity of coke, coal, oil, natural gas and other fuels that are fed into the furnace, depending on the quality and quantity of both the inputs and crude steel to produce
- the quantity of oxygen or air blown into the furnace: oxygen tend to produce CO2 and CO whereas nitrogen produce unproductive oxides NOx.

In consequence, the blast furnace gases volumes and quantity may differ in time and among sites. The heating content of BF gases ranges from 3 377 to 6 061 MJ/t hot pig iron.

BF gases are recovered and fed into the site gas network with coke oven gases, BOF gases and natural gases.

Basic oxygen furnace (or oxygen converter)

The pig iron contains high content of carbon from coke (usually around 4%) and this content is decreased in the oxygen converter by blowing pure oxygen other the hot metal. Oxygen combines with carbon into CO2. BOF serves also to remove impurities like silicate (using lime), manganese (using oxygen) and phosphor (using lime and oxygen).

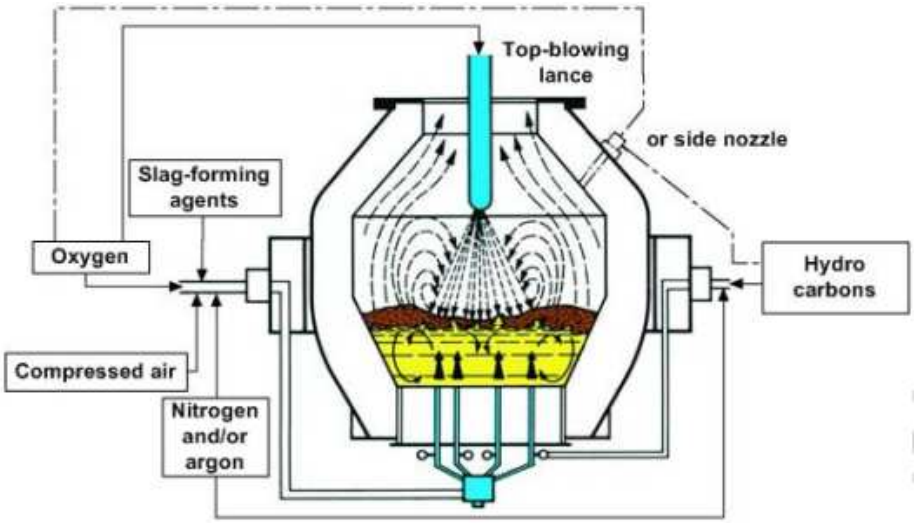


Figure 3.5.2-7 Schematic of a combined blowing converter system with top-blowing (Source BREF 2009b)

The BOF implies a set of many different reactions happening concomitantly with complex interdependencies. It is an exothermic process whose heat is controlled by injecting direct reduced iron or steel scrap (which consume heat to melt).

The sole interest for nuclear heat is that oxygen converters consume significant amounts of oxygen, nitrogen and argon (used as inert gases).

BOF emits low calorific gases (BOF gases) with an energy content ranging from 350 to 700 MJ/t liquid steel. These gases are fed into the plant gas network.

Input/output data for BOF can be found in annex VI. The oxygen consumption in BOF ranges from 49,5 to 70 m3/t liquid steel at a purity of >99,5%.

Electric arc furnaces

Electric arc furnaces (EAF) use electricity to melt steel scrap and direct reduced iron through cyclical operations. Electricity is used because electric arcs have high local temperatures (up to 12 000°C) and enable to heat scraps sufficiently to melt them. A fossil fuel burner would not be sufficiently hot to heat the refractory walls. Yet, any alternative source of heat could be used.

Steel scraps may first be pre-heated. Pre-heating reduces the electricity consumption. Pre-heating may burn EAF off-gases and heat scraps up to 800°C but this implies a costly treatment of EAF off-gases which may contain toxic pollutants (like PCB) coming from impurities inside the steel scraps (like plastics).

Steel scraps are charged from the top, electrodes are brought down and produce electric arcs to melt steel scraps.

Oxygen lances and/or oxy-fuel burners are more and more used to assist in the early stages of melting.

After steel is melted, the electrodes are removed and the furnace is tipped up and the hot metal flows through the tapping spout.

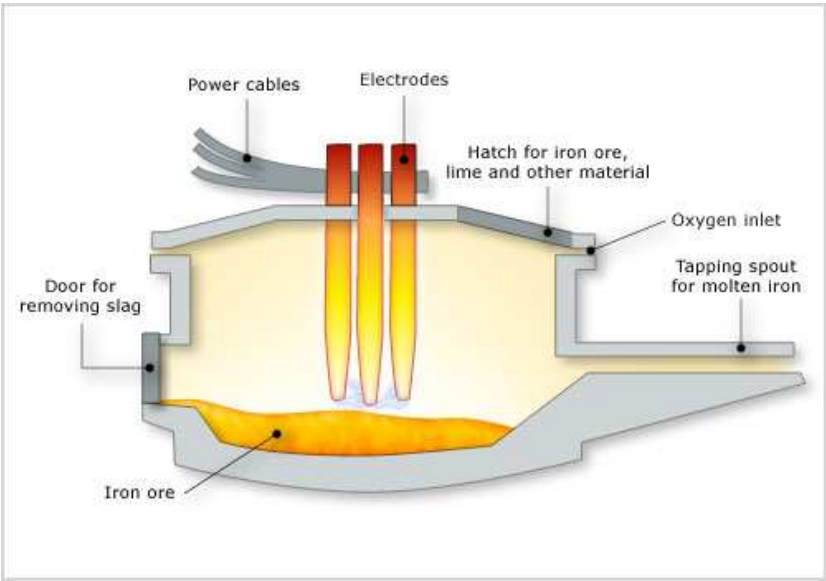


Figure 3.5.2-8 Schematic of an electric arc furnace (Source: Te Ara)

Oxygen is used to:

- improve the shielding of the furnace by combining with carbon in a foamy slag
- decarburate the melt
- react with EAF off-gases (like CO and hydrocarbons) through post-combustion in order to keep heat as much as possible in the furnace.

The input and output data for electric arc furnaces can be found in annex VI. The main data are reported below (BREF 2009b):

Inputs	Units	Range values
Iron ore	kg/t	0 - 153
Steel scrap	kg/t	1 039 - 1 232
DRI	kg/t	0 - 215
Electricity	kWh/t	404 - 768
Fuels	MJ/t	50 - 1500
Oxygen	m3/t	5 - 65
Argon	m3/t	0,3 - 1,5
Nitrogen	m3/t	0,8 - 12

Table 3.5.2-4 Typical inputs for an electric arc furnace (Source: BREF 2009b)

The energy consumption and usage in an electric arc furnace is as follows (BREF 2009b):

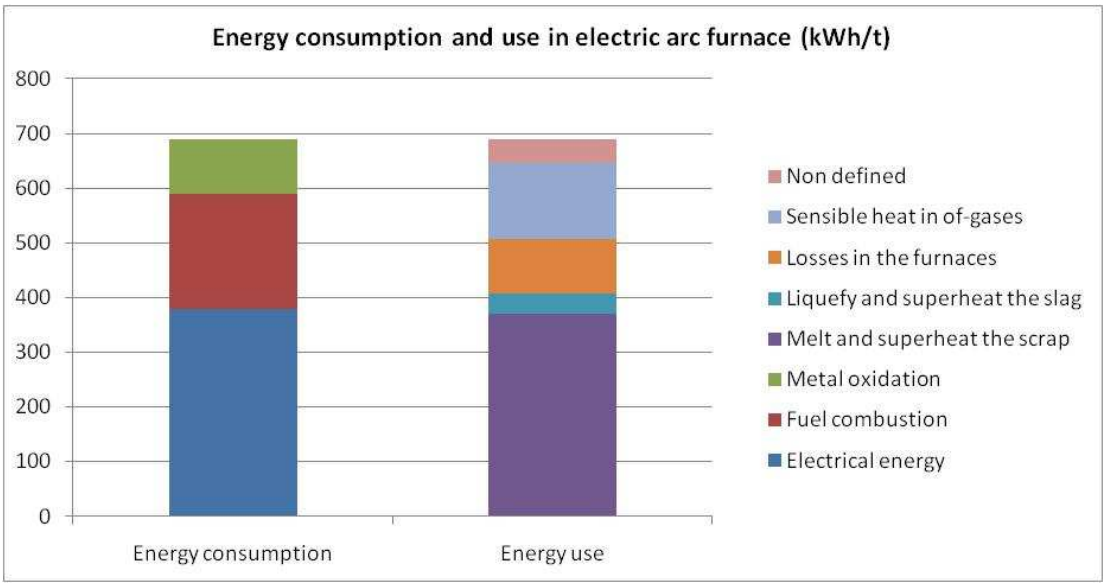


Figure 3.5.2-9 Typical energy consumption and use in electric arc furnace (Source: adapted from BREF 2009b)

In a typical electric arc furnace, electrical energy is the main energy but fuels combustion provides a non negligible heating to the process. This energy is used principally to melt and superheat the scraps; losses are important either through the refractory walls of the furnace or by exiting hot off-gases.

Further processing to manufacture steel products

Post-treatments are required to transform crude liquefied steel leaving any type of furnace into steel flat or long products. This consists of two phases:

- Hot transformation: stretching, rolling, crushing at 800°C-1200¨C; the same treatments are successively applied until the product has reached a certain mechanical resistance. Indeed, any effort applied to steel increase its fragility (hardening). Beyond a certain width, the steel breaks.
- Some cold transformation may be further necessary. Steel is cooled to ambient temperatures to apply similar processes.
- Hot processing can again occur; heating is necessary up to 700°C.

This processing requires large amounts of electricity. Heat may be required for re-heating phases.

3.5.2.3. Example of an integrated steelworks (blast and basic oxygen furnaces)

The real case of a classical integrated steelworks of 4 Mt/y from a major steel producer is reported in this section.

An integrated steelworks consists of one or more blast furnaces (here 2), one or more basic oxygen furnaces (here 2), one or more hot rolling sections, one or more coke making plant, one or more sintering plant and possibly one or more lime production facility.

The energy flows of the plant are depicted below. The steelworks border is represented by the yellow dotted line.

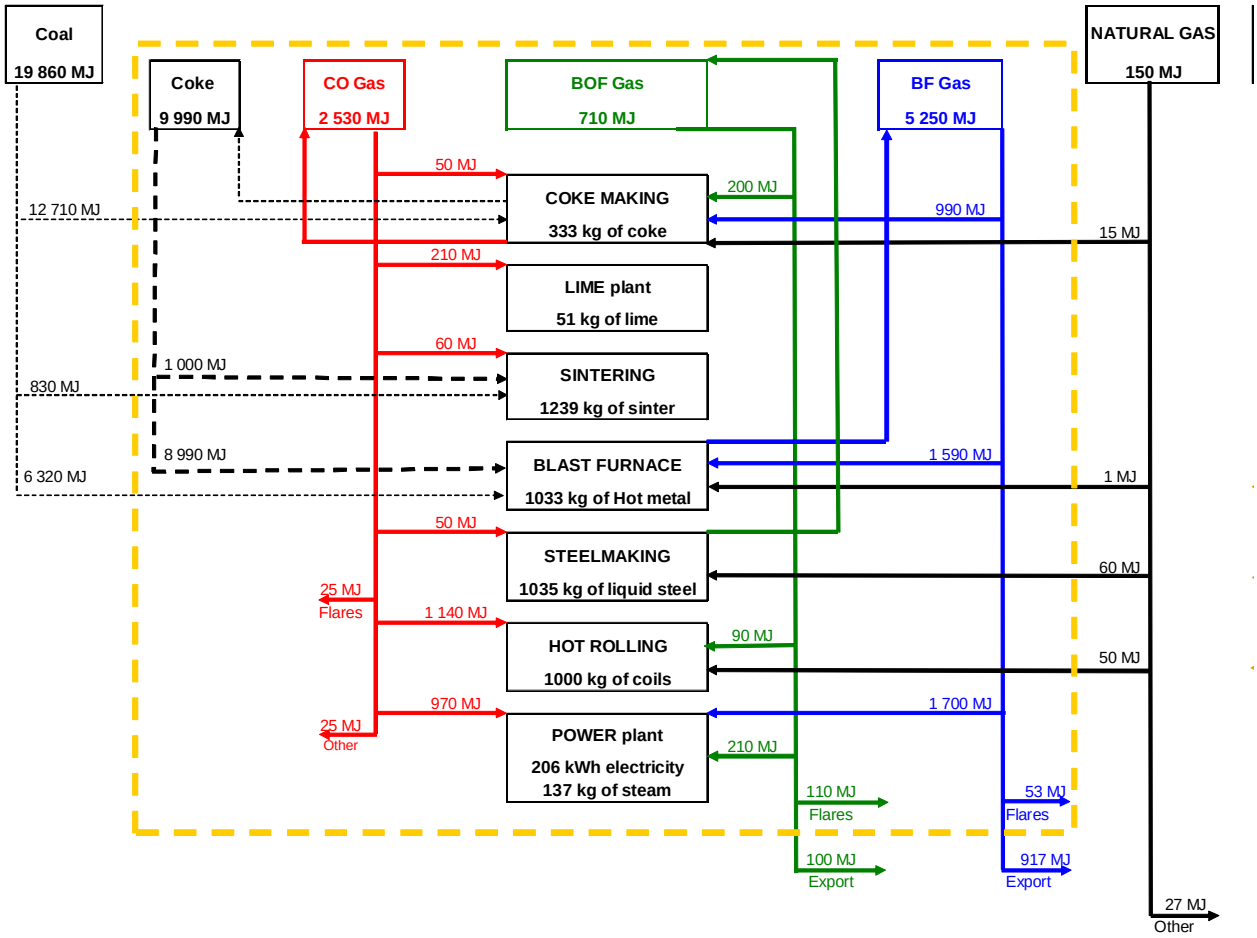


Figure 3.5.2-10 Energy flowsheet for a classical 4 Mt/y integrated steelworks (Source: private contribution, figures may be rounded)

The complex interdependencies especially from the gas network system which has to manage different quality off-gases with make-up natural gas appear well.

Blast furnace

In this plant, coke (8 990 MJ/t coil) is used first as reductant and second as heating source. The heating function of coke is replaced as far as possible by coal, a less costly raw material.

The process temperature reaches up to 2 000°C; steel gets out of the furnace at a temperature of around 1 500°C.

BF gases are used with a marginal amount of natural gas to heat the hot stoves (1 590 GJ/t coil).

The rest BF gases are burnt in the coke oven plant (990 MJ/t coil) and the power plant (1 700 MJ/t coil).

Basic oxygen furnace (“steelmaking“)

The heat input is very small and restricted to coke oven gas (COG, 50 MJ/t coil) and natural gas (60 MJ/t coil). The reaction is exothermic and produces 710 MJ/t coil of BOF gases. The process temperature is 1 600°C.

The BOF gases are used in the coke oven plant (200 MJ/t coil) and the power plant (210 MJ/t coil) mainly.

Hot rolling

Hot rolling consume non negligible amounts of heat (1 140 MJ/t coil of COG and 140 MJ/t coil of both BOF and natural gases) to process steel into coils at 1 200°C.

Power plant and electricity and steam utilities

A cogeneration plant is usually installed on-site to recover energy from process off-gases and produce steam (140 kg of steam / t coil) and electricity (210 kWh / t coil).

The steam is produced at 10 bar and 200°C, solely from the cogeneration plant.

Electricity is mainly produced at the cogeneration plant (210 kWh/t coil) and to a lesser extent in recovering boilers (20 kWh / t coil) and 190 kWh are purchased externally.

Steam is mainly consumed in the basic oxygen furnace ("steelmaking") and to a lesser extent in the coke oven plant and the blast furnace.

Electricity is consumed mainly in the blast furnace (blowing fans) and the hot rolling.

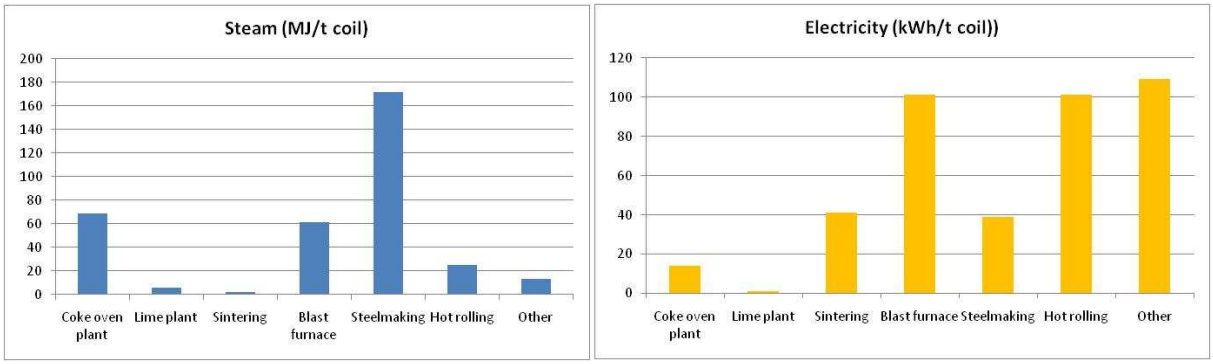


Figure 3.5.2-11 Steam and electricity consumption by unit in a typical 4 Mt/y integrated steelworks (Source: private contribution)

Finally, non-negligible amounts of oxygen are consumed in the process (a total of 140 m3/t coil) purchased either from the grid or from a neighbouring air separation unit.

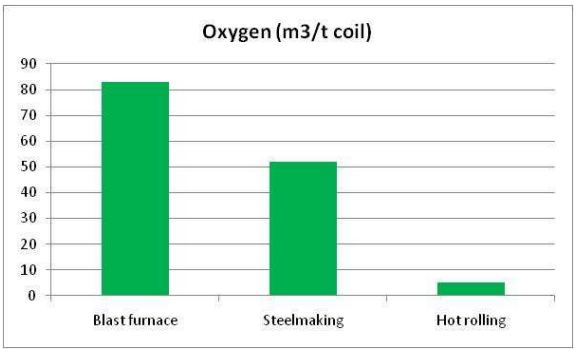


Figure 3.5.2-12 Oxygen consumption by unit in a typical 4 Mt/y integrated steelworks (Source: private contribution)

Blast furnace is the main oxygen consuming unit, followed by the oxygen converter (“steelmaking”).

Consolidated site energy consumption

The total site consumption is as follows:

Energy consumption	Produced on-site	Purchased	Total consumption
Electricity (GWh/y)	912	760	**1 672**
Steam (GWh/y)	422		**422**
Oxygen (Mm3/y)		564	**564**
Oxygen equivalent heat market if produced by HT process (GWh/y)		161	**161**
Coal (GWh/y)		22 070	**22 070**
Natural gas (GWh/y)		170	**170**
Coke (kt)	1 132		**1 132**
Off-gases produced (GWh/y)	9 430		**9 430**
Of which BF gas for hot stove heating (GWh/y)	*1 770*		***1 770***
Of which BF, BOF and COG gas to power plant (GWh/y)	*3 203*		***3 203***

Table 3.5.2-5 Energy consumption internally and externally of a real case integrated steelworks (Source: private contribution)

The total site consumption (except the hypothetical heat consumption for the production of oxygen via a high temperature process) is 23 000 GWh/y which is very significant.

Coking coal is the largely predominant source of energy with 22 070 GWh/y. Coal is used to produce coke in the on-site coke oven and coke serves as heating carrier (and reducing agent) in the blast furnace.

Coke acts as a reducing agent indirectly by producing syngas so that a part of the energy from coke can be compared with the energy that would be required to produce syngas via another route (steam methane reforming or partial oxidation).

Most processes (blast furnace, coke oven, basic oxygen furnace) produce calorific off-gases which are used on-site. There energy derives from the energy in coal and is used in the cogeneration plant producing electricity and steam and directly for heating the processes, in particular the hot stoves (heating the combustion air injected in the furnace).

Estimation of the potential energy that can be externalised

As a preliminary remark, the impact of any measure on the calorific off-gases must be evaluated carefully. These gases are used to cogenerate steam and power. Replacing partially or totally their heating value in the steelworks would:

- require re-designing the gas network but could represent an economic interest
- increase the electricity and steam cogenerated from burning them
- impact their volume and composition because the use of raw materials like coke could change.

The main potential input for an external heat supply to an integrated steelworks would include:

- Steam: As steam is produced from off-gases via the cogeneration plant, it can be considered that steam, as produced by the cogeneration plant, is unnecessary. However, high temperature nuclear steam could be used to pre-heat air for the blast furnace in or before the hot stoves. Considering the 1 770 GWh/y of air heating up to 1 200°C by burning BF gases in the site, nuclear pre-heating to 500°C would represent up to 720 GWh/y (41% of heat), the remaining heat to 1 200°C representing 1 050 GWh/y (59% of heat).
- Electricity: The electricity that could be brought to the site is only the part which is purchased; if more off-gases were to be burnt in the cogeneration plant, this share of purchased electricity could become lower.
- Oxygen: Oxygen is produced today from cryogenic air separation units (see dedicated paragraph) which consume mainly electricity. If oxygen was produced by high temperature processes, this would represent around 161 GWh/y of heat consumption (or an equivalent 20 MWth thermal capacity considering a 8 000 h/y available reactor)
- Coke: coke is used as reducing agent by producing syngas at high temperature but its functions go further by providing a homogeneous heating in the furnace and structuring the burden. Assuming a composition by weight of 92% carbon and 3% hydrogen and a total gasification into syngas, blowing hot oxygen would produce a syngas of weight composition 99% CO and 1% H2 (1 kg coke produce 4,58 kg syngas). Syngas can alternatively be produced (with a higher H2 content) either by steam methane reforming or by partial oxidation, which enables to use other carbonaceous feedstock like heavy oil distillates or wood. The composition of the syngas used in a blast furnace is an important input since it impacts its reducing capacity. The primary reforming of methane by steam (ΔH = 206 kJ/mol) of the equivalent weight of syngas, assuming the replacement of 10% of coke as reducing agent, would require 3 034 GWh/y.

These results are summarised in the table below:

Parameter	Equivalent heat that may be externalised
Steam	720 GWh/y
Oxygen (if produced from HT process)	161 GWh/y
Syngas production	3 034 GWh/y
TOTAL	**3 915 GWh/y**
Equivalent thermal power	**447 MWth**

Table 3.5.2-6 Estimation of the potential of nuclear pre-heating and polygeneration market for a real case integrated steelworks (steam, oxygen and syngas)

The 3 915 GWh/y are to be compared to the 23 000 GWh/y of total external energy consumption. Syngas is the major input that a nuclear reactor could provide.

It must be noted that:

- the pre-heating of air by nuclear steam would probably require more heat to compensate heat losses other heat transport and would decrease the consumption of BF gases
- the heat value of oxygen production applies only if oxygen is produced via a high temperature process which is under development today
- the production of syngas externally would mean that the syngas
  - would require more heat to produce a similar coke syngas from lower carbon containing hydrocarbons
  - would be supplied cold if it is produced distantly so it may require heating,
- the lower consumption of coke as reducing agent would
  - decrease the use of the coke oven and therefore reduce the COG production
  - decrease the volume and alter the composition of blast furnace gases
  - decrease the carbon content in the pig iron so the oxygen converter (basic oxygen furnace) may require less oxygen to remove a lower carbon content

3.5.2.4. Future steel production routes

The direct reduced iron production route

In its operating principle, direct reduced iron (DRI) replaces coke consumption for ore reduction by syngas and for heating by natural gas. Iron ores are generally reduced at 60%, contrary to blast furnaces which achieve almost 100% of iron ore reduction using an almost pure CO syngas.

DRI is a process requiring large amounts of energy, mainly natural gas, for producing syngas but emits fewer CO2 (due to the lower carbon content of methane). Its production costs are higher than processing iron ore directly into a blast furnace. More stringent environmental regulation could make it an attractive in Europe though.

The reformer operates at around 900°C and consume 1,1 MWh/t DRI. A typical DRI unit produces 1 Mt/y and would consume for reforming 1 100 GWh/y (or equivalent 125 MWth).

Hot Briquetted Iron is a direct reduced iron in the form of briquettes which demonstrate higher mechanical properties but is more expensive.

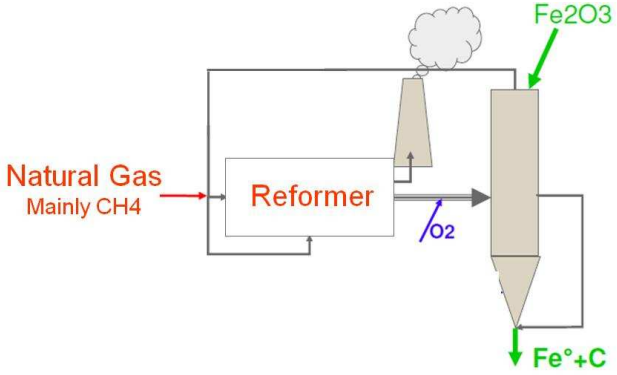


Figure 3.5.2-13 Schematic of the MIDREX process (Source: Private communication)

DRI is a proven technology and DRI production unit are in operation mostly in countries rich in natural gas (e.g. Venezuela, Mexico, Iran). There is no DRI unit in Europe because of its lower attractiveness as regards the low availability of natural gas in Europe and the higher operating costs. The global leading vendor of DRI technology is US-based MIDREX.

The carbon content of DRI is usually 2,65% and requires therefore using an oxygen converter to remove carbon.

Long-term research programmes for breakthrough steelmaking technologies

Long-term breakthrough technologies investigate all the options for reducing iron ores (i.e. removing oxygen from iron oxides). The principal reducing agents are carbon (which combines with oxygen into carbon oxides), hydrogen (into water) and electricity (ionising oxides).

The options are depicted in the graph below other a large triangle representing the three reducing routes:

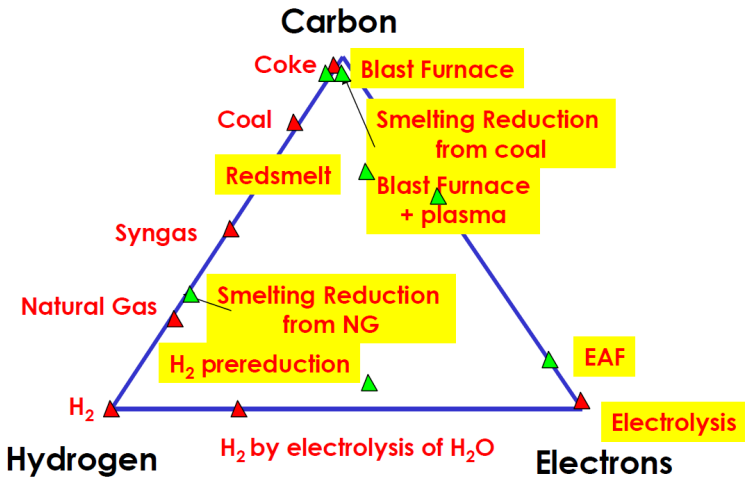


Figure 3.5.2-14 Conceptual representation of the various breakthrough steel production routes (Source: Private contribution)

Small green triangles represent technologies where iron and reducing agent are melted and red triangles the possible reducing agent. For instance, syngas is a mixture of CO and H2 and therefore stands in the edge from carbon to hydrogen whereas hydrogen produced from water electrolysis stands in the edge hydrogen-electrons.

A European consortium called ULCOS gathers 48 European companies (steel producers, equipment manufacturer, energy, industrial gases producers, research institutes and universities) from 15 countries to organise a cooperative research and development programmes on new radically innovative steel technologies. ULCOS aims at reducing the CO2 emissions of 50% by 2050.

ULCOS has a 6 year budget of 75 M€, 40% of which is financed by the European Commission. The programme is run by a core group made of most of the Western European integrated steel producers.

ULCOS was originally launched as a FP6 research project in 2004. It first sorted out the different potential concepts (in total 80) and short listed 4 major concepts for demonstration which are detailed in the table below. The level of detail is low by the little information available. All technologies seem to have been proven at laboratory scale.

Concept	Brief description	Demonstration
Top Gas Recycling Blast Furnace	Leader: ArcelorMittal This concept is rather close to existing blast furnaces. It recycles and separates blast furnace top gases (CO2+CO). CO is re-injected in a second-level burner as reducing gas whereas CO2 is captured and stored using CCS technologies. CO2 emissions are divided by two. The concept does not offer more opportunities than current blast furnaces.	Pilot plant: 2012-2013 Demo plant: 2014-2016 Budget: 500-550M€
ULCORED	ULCORED is merely an amelioration of the current direct reduced iron and electric arc furnace production route. It tries to improve the economics of this route as compared to current blast furnaces	Demo: around 2015
HISARNA	Leader: Corus group HISARNA combines coal pre-heating and partial pyrolysis in a cyclone, pre-reducing iron ores and a smelter vessel for final ore reduction. Combustion gases (CO+CO2) are separated. The concept could be ready by 2025.	Pilot plant: 2010 Demo: around 2020
ULCOWIN / ULCOLYSIS	ULCOWIN/ULOLYSIS investigate the industrial development of the electrolysis of iron ore (mainly iron oxides), a breakthrough technology. The concept is similar to water electrolysis and consists in separating iron ores into iron and oxygen in a dissolving molten oxide mixture at 1 600°C. ULCOWIN is in a more advanced stage of development.	Pilot plant: 2010-2015 Demo: around 2030

Table 3.5.2-7 Main concepts for future steelmaking researched within the ULCOS consortium

3.5.2.5. Potential for nuclear heat

Blast furnaces

Nuclear heat could be used at several places for steelmaking:

- Blast furnaces
  - Pre-heating air or oxygen to be injected in the furnace either as a separate pre-heated before the stoves or as direct input through heat exchangers in the stove
  - Producing competitive oxygen from high temperature process
  - Producing a reducing gas, whether syngas through nuclear assisted steam methane reforming or electrolysis hydrogen (although hydrogen cannot be used as the single reducing gas in the furnace).
  - Possibly pre-heating the iron ore and coke fed in the furnace
- Basic oxygen furnaces

- Produce air gases (argon, nitrogen and oxygen) or only oxygen through high temperature process

- Electric arc furnaces
  - Pre-heat steel scraps: the direct input of energy in EAF can improve the efficiency of utilisation of carbon resources far above 40% (ESTEP 2005). Considering a thermal capacity of steel scraps of around 500 J/kg/K, pre-heating steel scraps from 20°C to 500°C would require 240 GJ/t.
  - Provide competitive nuclear electricity
  - Produce oxygen for blowing into the furnace

The most promising breakthrough technologies for nuclear cogeneration could be HISARNA, ULCOWIN/ULCOLYSIS and ULCORED.

HISARNA would consume pure oxygen, possibly pre-heated. Coal would be gasified by partial oxidation producing a mixture of CO/CO2/H2 which would pre-reduce the iron ore injected in the upper cyclone part of the reactor. It may be possible to increase the pre-reduction and thus reduce the use of coal by feeding in the cyclone other reducing gas like syngas or hydrogen.

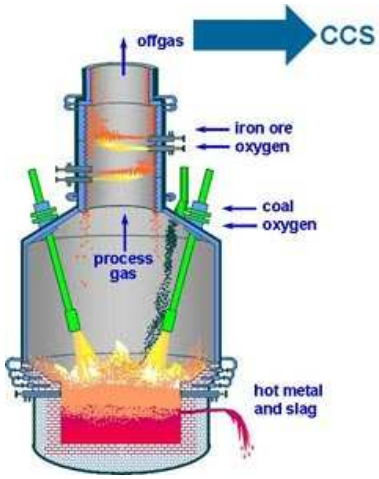


Figure 3.5.2-15 HISARNA concept (Source: ULCOS project presentation on European Commission website)

ULCOWIN could also represent a significant interest for nuclear high temperature reactors. 1 nuclear power plant could produce 2Mt/y (Meijer 2010) and nuclear heat could assist in the melting of iron ores and their electrolysis.

The European Steel Technology Platform (ESTEP) recalls in its Strategic Research Agenda that the reduction through thermodynamic path using high temperature nuclear reactors was investigated as early as in the 1950s and 1960s (ESTEP 2005). It lists also nuclear high temperature reactors as promising technologies to produce hydrogen competitively as a reducing gas.

3.5.2.6. Evaluation of the indirect heat market of the steel industry

Although steel industry is not a direct market for nuclear heat (so-called “plug-in” market), it is a very large heat market, of which a non-negligible part could be taken over by nuclear energy.

The total heat market in Europe can be estimated as follows:

- Taking from BREF and the case study a range of heat consumption of 18,55-20 GJ/t for the blast furnace
- Taking from BREF a range of 404-768 of electricity consumption (considered as a heating source) and 50-1500 MJ/t of fuel as make-up heating sources and scrap pre-heating.

	Number of steelworks in Europe	Capacity (kt/y)	Heat market (GWh/y)	
			Min	Max
Blast furnaces	86	116 284	599 186	646 539
Electric arc furnaces	231	82 736	34 574	98 015
TOTAL	**317**	**199 020**	**633 760**	**744 554**

Table 3.5.2-8 Estimation of the total heat market related to steelmaking

The iron and steel sector is a very large heat market, the largest share of which being related to the conventional steel production route (blast furnace).

This estimation can be double checked with the data from the case study above. The 4 Mt/y steelworks corresponds to 3,51% of the total capacity of EU blast furnaces and the total external energy consumption of the steelworks (23 000 GWh/y) corresponds also to 3,56% to 3,84% of the total estimated heat market for blast furnaces.

The direct calculation is higher but of the same order of magnitude with the indirect calculation (555 TWh for combustion of fuels in pig iron and steel production, direct emissions from the iron and steel and production of coke sectors). The difference may lay in the fact that the role of coke is not only related to energy but also to reducing iron ores.

Yet, most of this heat cannot be replaced by an external supply of heat: in electric arc furnaces, electricity is used to reach very high temperatures for melting steel scrap and in blast furnaces, coke which is the largest source of heat is a reducing agent and structuring material which cannot be replaced easily (except by supplying a reducing gas like syngas).

The heat market represented by blast furnaces and electric arc furnaces is therefore evaluated with the following assumptions:

- Blast furnaces: the amount of heat that could be supplied directly through steam or indirectly through the production of high temperature oxygen and of syngas using a nuclear assisted steam methane reforming is calculated by dividing the total estimated (hypothetical) heat demand for the 4Mt/y plant reported which gives a total of 1 MWh/t steel (considered range 0,9 – 1,1 MWh/t). It must be noted that this heat includes the production of syngas that can be done distantly from the site.
- Electric arc furnaces: considering the pre-heating from 20°C to 500°C of steel scraps only, the heat demand would be 67 kWh/t steel (to be compared with the total typical energy consumption of an electric arc furnace, amounting to 690 kWh/t, of which 210 kWh/t fuels). The considered range is 60 to 75 kWh/t.

Type of furnace	Number of steelworks in Europe	Total EU capacity (kt/y)	Total potential heat market (GWh/y)	
			Min	Max
Blast furnaces	86	116 284	104 656	127 912
Electric Arc Furnaces	231	82 736	4 964	6 205
Direct Reduced Iron (assuming a 10% market share)	-	19 902	19 902	23 882
TOTAL	**317**	**199 020**	**109 620**	**134 118**

Table 3.5.2-9 Estimation of the hypothetical pre-heating market related to steelmaking

The potential heat market that may be supplied externally by nuclear heat is a non-negligible part of the total market.

The blast furnaces represent an important potential for nuclear heat. The amount is not to be compared to the 474 TWh/y calculated from the emissions because it includes energy for high temperature oxygen production, a process which does not exist industrially, and syngas production which is not accounted for in the emissions declared by the steel sector.

DRI could represent a non-negligible heat market, depending on its market share; this would require production units to be installed in Europe.

Electric arc furnaces represent only a marginal heat market, but could be of interest for nuclear electricity generation.

3.5.2.7. Conclusions and recommendations

- Steelmaking is a major European industry. It operates under severe competition on a global basis. Europe is an important player worldwide but stringent emissions regulations may put an economic pressure hardly acceptable to European steelmakers.

- Steel is produced through different production routes, depending on the inputs (iron ores or scraps) and the products (long or flat). The main routes in operation today in Europe are the blast furnace + oxygen converter and electric arc furnace.

- New production routes are actively investigated and may use nuclear energy in their process; the R&D programme is carried out by the large European consortium ULCOS. Demonstration plants are forecasted before 2020. The European Steel Technology Platform (ESTEP) mentions in its Strategic Research Agenda nuclear high temperature reactors as a relevant energy source for these concepts.

- Steelmaking is not a real “plug-in” market; the principal process where nuclear energy could have a use is the blast furnace route. Nuclear energy could be used to pre-heat air, to produce oxygen (via the high temperature process still to be developed) and to produce syngas as a

reducing gas. Any such input would significantly impact the normal operation of the steelworks (off-gases production, coke production in particular).

- Direct reduced iron is another promising technology (already industrialised but not in Europe), which may have an interest for nuclear energy to produce syngas by nuclear assisted steam methane reforming or hydrogen by water electrolysis. The main global technology vendor is US based MIDREX.

- It is recommended to
  - study in detail the opportunity to supply syngas to existing steelworks and possibly the feasibility of nuclear pre-heating
  - liaise with MIDREX to look at the integration of nuclear energy in the direct reduced iron route, a technology that may be implemented in Europe or globally.
  - liaise with ULCOS and the European Steel Technology Platform to examine the potentialities of integrating and coupling nuclear energy from high temperature reactors in the breakthrough concepts under development.

3.5.3. Lime industry

Summary:

The lime industry is a small heat market. Despite the variety of production routes, the same production principles are applied. This market is interesting as regards the potential of nuclear pre-heating. A simple pre-evaluation would indicate the coupling of a nuclear reactor as 1/ feasible and 2/ saving significant amounts of natural gas. A more in-depth analysis is recommended, which could also apply to other industries like cement, ceramics and glass-making.

This part uses information from BREF on Cement and Lime Manufacturing Industries (BREF 2010) and the contribution from the European Lime Association (EuLA), member of the Industrial Minerals Association (IMA Europe).

3.5.3.1. Lime market

Lime characteristics

Lime comprises different products: quicklime (CaO), dolomitic lime (CaO.MgO), caustic lime or slaked lime or hydrated lime (Ca(OH)2) and dolomitic hydrated lime (CaMg(OH)4).

Lime has a wide range of applications, some of them existing for a few thousands of years. Lime products have indeed two main properties:

- Being a natural base, lime serves to neutralize acids liquid and gases
- Being a binder, it is an additive in construction mortars.

Quick lime is an instable material which transforms in a few days into hydrated lime and then in a few weeks in calcium carbonate. It has therefore to be supplied to consumers quickly. For instance, steelmakers require 3 days between the lime production and its use in the steel furnace. Industry has therefore very low stocks.

Lime markets and applications

Lime is mostly an intermediary bulk product, i.e. it is used widely by industry and not directly by individual consumers.

The EU27 production in 2006 was estimated at 28 Mt, representing 12% of the world production (227 Mt). The EU27 lime industry generates a turnover of around 2,5 bn€, which makes an average price of 80€/t lime product.

The main markets are summarized below (BREF 2010, EuLA contribution):

Sector	Application
Steelmaking	Reduce sulphur and phosphorus, modify slag viscosity, protect refractories
Non-ferrous metals	Fluxing agent and acid neutralizer

Environment – gas	Neutralise pollutants and heavy metals in flue-gas
Environment – water	Effluent treatment (pH adjustment, removal of nitrogen and phosphorus, water clarification), potable water softening and removal of impurities in drinking water
Environment – contaminated lands	Adjustment of pH and immobilization of sulphur, phosphates and heavy metals
Agriculture	Soil treatment to adjust pH for optimum growing conditions
Construction and civil work	Raw material for bricks and structured blocks, additive in masonry and plaster mixes, soil stabilization and road binder
Chemical and paper	Raw material for precipitated calcium carbonate, input in pulp manufacturing, oil additive for lubricants, desicant for petrochemicals, used in leather tanning, glassmaking, soda ash and for acid neutralization
Pharmaceutical, personal care and food	Drug additive for matrix composition, as toothpaste additive, food and drink additives, precipitator in the sugar industry and odours neutralizers

Table 3.5.3-1 Main markets for lime products (Sources: BREF 2010 and EuLA contribution)

Steelmaking uses mostly quick lime and dolomitic lime. Agriculture uses mostly dolomitic lime because magnesium is a natural fertilizer. Construction uses mostly hydrated lime because its liquid form is more easily processed and because the hydrating process involves some safety issues which are best handled by lime producers.

Market segment share, trends and possible substitutes

The indicative shares of the different uses by sector in 2003 are (EuLA contribution):

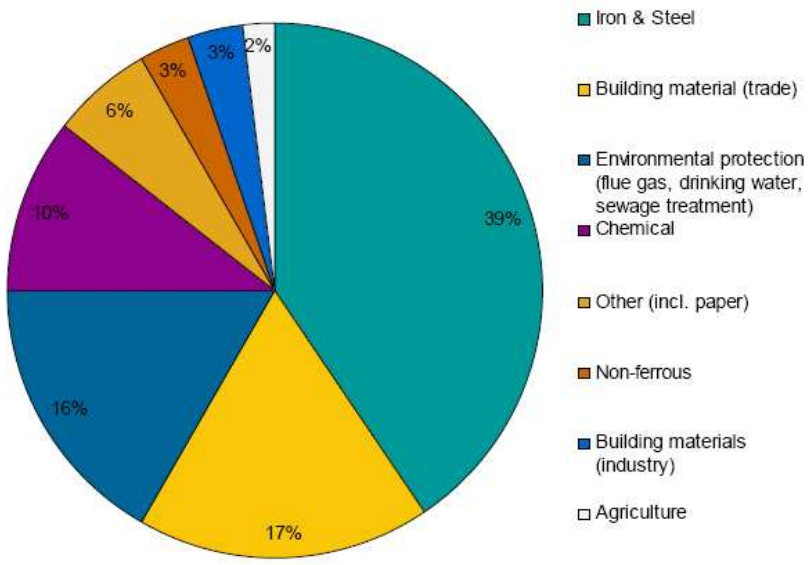


Figure 3.5.3-1 Indicative European lime demand by sector in 2003 (Source: EuLA contribution, adapted from BREF 2007 and a NERA analysis)

Steelmaking has been and still is the historical largest lime consumer since the 19th century. Its consumption has driven the emergence of the lime industry. The steel industry has yet significantly decreased its lime consumption in the 1980s from around 100 kg/t to 10 kg/t; this value looks as a minimum and the market should remain stable from now on.

In steelmaking, lime is the sole acid neutralizer that can resist at high temperature and no substitutes should appear in the foreseeable future.

Lime applications in environment are rather new and the trend is growing since 1990s. The market is increasing and new environmental regulations should support this trend further.

Caustic soda and sodium carbonate may be competitors for water treatment; for soil treatment, lime has the advantage to be solid and to fix the soils over the long term (it does not dilute in rain water and infiltrate into lower soil layers). Sodium bicarbonate may be a competitor for gas treatment.

Lime has been historically used in construction materials and some substitutes took some part of the market in the last decades, especially polymers.

The EU27 lime market is mature and is not expected to grow significantly in the short term. Outside Europe, emerging countries with a booming economy are the main growing markets, in particular in Asia.

Industry production and structure

The EU27 lime production was estimated at 28 Mt in 2006, being the second world producing region with a 16% share of the world production (172 Mt), the main other producer being China (75 Mt), the US (20 Mt), Japan (10 Mt) and Russia (8 Mt) (BREF 2010, EC 2009).

The European lime industry is quite concentrated although there is a wide range of company sizes. There are some 100 companies in Europe operating approximately 600 kilns at 210 sites (Ecofys 2009h). The 8 largest producers control 65% of the production. Out of these 8 companies, 5 are operating on a global level.

European lime production sites range from very small (a few tens of thousands of tons) to very large (2 Mt/y/site). Very large sites usually operate several kilns and supply mainly steelmakers.

Some final consumer sectors of lime operate “captive” lime kilns, especially the sugar industry, soda ash manufacture and the pulp manufacturing industry. Steelmaking has externalized its kilns which are now mostly operated by lime producers.

For the last 15 years, there have been many new kilns constructed in the world but only a few in Europe.

Industry characteristics

The lime industry is capital-and energy-intensive. Investing in a lime kilns is thought to cost the equivalent of 3 years’ turnover and energy costs account for half of the production costs (EC 2009)

Lime kilns have a lifetime of 40 years and lime production sites, especially the larger ones, operate several kilns, which can be upgraded or replaced so the lifetime of lime production sites can be longer than 100 years.

The economics of the plant, the existence of market consumers close to the plants, the availability of raw material on-site, the market concentration are yet some parameters that can trigger a plant shutdown.

The number of companies is relatively stable. There is thought to be no over-capacity in Europe (EC 2009).

The lime industry is significantly impacted by greenhouse gases emissions regulations. Lime is doubly impacted by emissions as the production process emits itself CO2, in addition to energy CO2 from fuel combustion. Regulation is even tougher for the sector as the (draft) benchmarks do not take account of the different production processes which however each have their advantage (see lime production routes below).

Since the market is open to international trade. EU27 neighboring countries may especially benefit from uncompetitive production costs to supply EU markets.

As such, lime producers are very keen to find alternative low-carbon competitive sources of energy.

A final remark, lime producers are kiln operators only and not technology providers. The main technology suppliers worldwide are by order of importance the Swiss März Ofenbau AG, a subsidiary from German conglomerate Thyssenkrupp, Italy’s Cimprogetti and Japan’s Mitsubishi.

Industry mapping

Germany counts the largest number of kilns in Europe, followed by Italy, Spain, France and Greece.

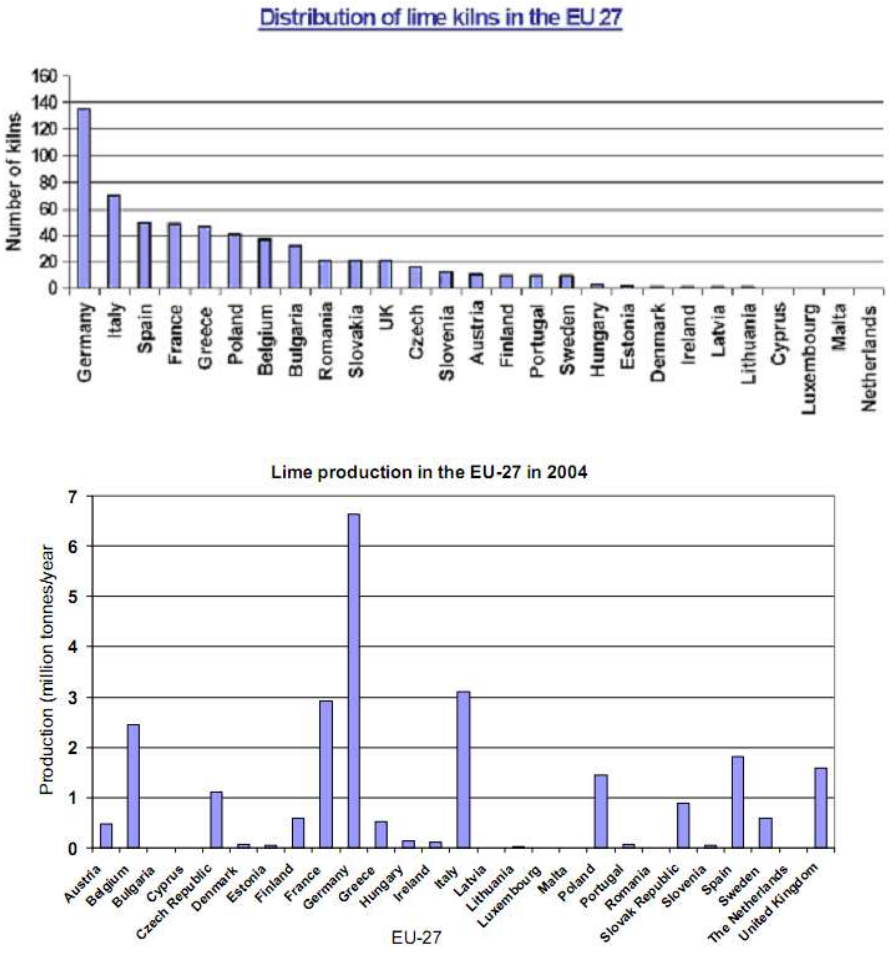


Figure 3.5.3-2 Distribution of lime kilns and production in the EU27 by country (source: Ecofys 2009h, BREF 2010)

Comparing both figures, it appears that large average kiln capacities can be found in particular in Germany, Belgium, France, United-Kingdom and Czech Republic.

The average production capacity per site is 133 kt/y/site but some site may reach 2 Mt/y/site.

The industry is usually close to its market because lime is mostly transported over short distances (0 – 300 km). Since steelmaking is the largest historical consumer, most large production sites are located close to steel production sites.

Furthermore, limestone is usually extracted on-site so that lime kilns are located on the same site than a limestone quarry.

Finally, large kilns are also in place where logistical infrastructures enable to transport bulk lime in the right conditions (especially duration of transport) to the final consumers.

3.5.3.2. Lime production routes

Lime production process

Quicklime (CaO) is the product of heating limestone (CaCO3) which releases CO2 as a by-product. The reaction begins from 800¨C, and the kinetics accelerate with temperature so the process temperatures is usually comprised between 900°C and 1 200°¢, and up to 1 800°C.

$$CaCO3 + energy \rightarrow CaO + CO2$$

Dolomitic lime (CaO . MgO) is produced from the decomposition of dolomite (CaCO3 . MgCO3) following several reactions, usually carried out between 500°C and 700°¢:

$$CaCO3 . MgCO3 + heat \rightarrow CaCO3 . MgO + CO2$$

$$CaCO3 . MgO \rightarrow CaO . MgO + CO2$$

$$CaCO3 . MgCO3 + heat \rightarrow CaO . MgO + 2CO2$$

Hydrated lime (Ca(OH)2) is produced from quicklime (CaO) following a strongly exothermic reaction

$$CaO + H2O \rightarrow Ca(OH)2$$

Lime production routes

The lime manufacturing process is as follows: limestone is extracted from the quarry, generally located on the production site, then crushed, washed, prepared in small pebbles and fed into a lime kiln. Hydration process comes after calcination in the kiln.

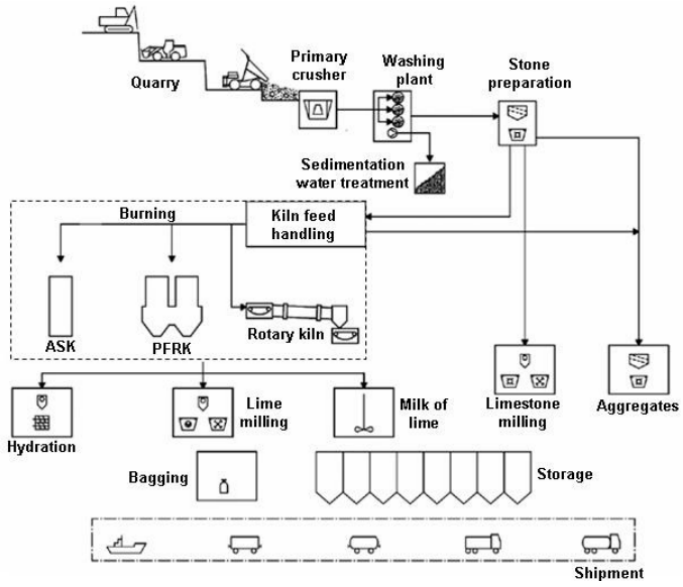


Figure 3.5.3-3 Overview of the lime manufacturing process (BREF 2010)

Both products follow roughly the same production routes which can be split in two categories. The most important factors for choosing the kiln type are (BREF 2010):

- Nature of the mineral deposit
- Input granulometry
- Customer application
- Kiln capacities
- Availability of fuels
- Costs (fuel, investment and operating)

One main parameter is the size of the limestone pebbles produced from grinding the raw limestone of the quarry (Ecofys 2009h).

Limestone pebbles > 40 mm	**Limestone pebbles 2< … < 50 mm**
Vertical or Shaft Kilns	**Horizontal or Rotary Kilns**
Parallel Flow Regenerative Kiln (PFRK) Annular Shaft Kiln (ASK) Mixed Feed Shaft Kiln (MFSK) Other Kilns	Rotary Kiln with Pre-Heater (PRK) Lon Rotary Kiln (LRK)
551 vertical kilns in operation in 2007	46 horizontal kilns in operation in 2007

Table 3.5.3-2 Types and number of lime kilns in Europe (Source: Ecofys 2009h)

Rotary and Shaft kilns are complementary to process all the raw limestone which is extracted from the quarry and grinded into pebbles. Indeed, the grinding process is not uniform and provides a continuous distribution of size of pebbles as depicted in the graph below.

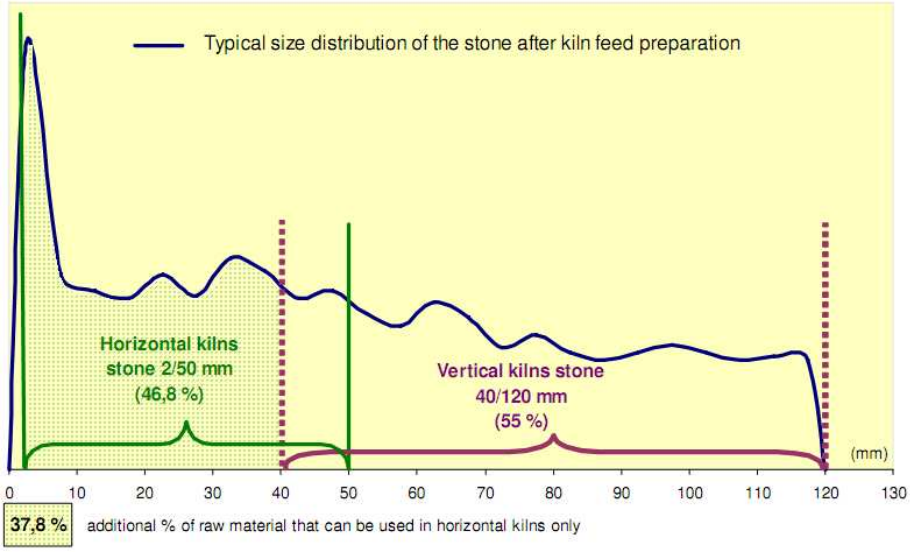


Figure 3.5.3-4 Typical size distribution of the stone after kiln feed preparation (source Ecofys 2009h)

The production share by type of kiln and type of lime product shows that rotary kilns represent around one fifth of the production of quicklime against 4 fifth for vertical shaft kilns. The share is roughly equivalent for dolomitic lime but sintered dolomitic lime is produced almost exclusively by rotary kilns.

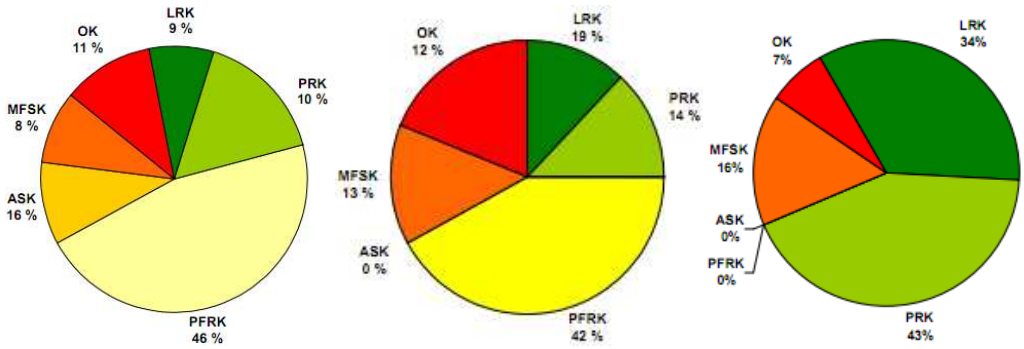


Figure 3.5.3-5 Production of commercial lime (left), dolime (centre) and sintered dolime (right) by type of kiln in the EU27 in 2004 (BREF 2010)

MFSK are historically the first and most simple type of kilns. They are the sole able to burn solid fuels. ASK were introduced in the 1950s as an innovative kiln with more homogeneous operational conditions. PFRK are the latest and reference technology, which allows a relatively low energy consumption and the required flexibility for manufacturing different types of lime qualities.

Lime generic production principle

The production principle is roughly the same in all type of kilns. Prepared limestone is fed into the kiln as pebble at the top of the kiln. Processed lime is taken away at the bottom of the kiln.

The philosophy is to make the most use of energy by recovering heat in exhaust gases for pre-heating incoming lime and during cooling of the processed lime to pre-heat the combustion air.

As the kiln is full of pebble, this creates a bed of pebbles from the bottom to the top of the kiln for vertical shaft kilns or a horizontal bed of pebbles surrounded by a gaseous atmosphere in rotary kilns.

For vertical kilns, the bed of pebble makes a porous set; the size of pebble is therefore crucial because the fuel, the combustion air and the exhaust gases must pass through the porosities. Too small pebbles would asphyxiate the kiln. On the contrary, horizontal rotary kilns can process small pebbles because the surrounding gaseous atmosphere enables the gases to circulate.

Fuel is injected in the burning zone where the lime is calcinated at temperatures higher than 900°¢. Exhaust gases are rich in CO2, a reaction by-product and a combustion output, which flow up, pre-heating the lime which is fed at the top of the kiln.

Calcinated lime falls down to the cooling zone where cooling air is fed from the bottom, taking benefit from the remaining heat in lime to be pre-heated and burn in better conditions in the burning zone.

Pebbles remain around one day in the kiln, each step (pre-heating, burning and cooling) taking approximately one third of the time.

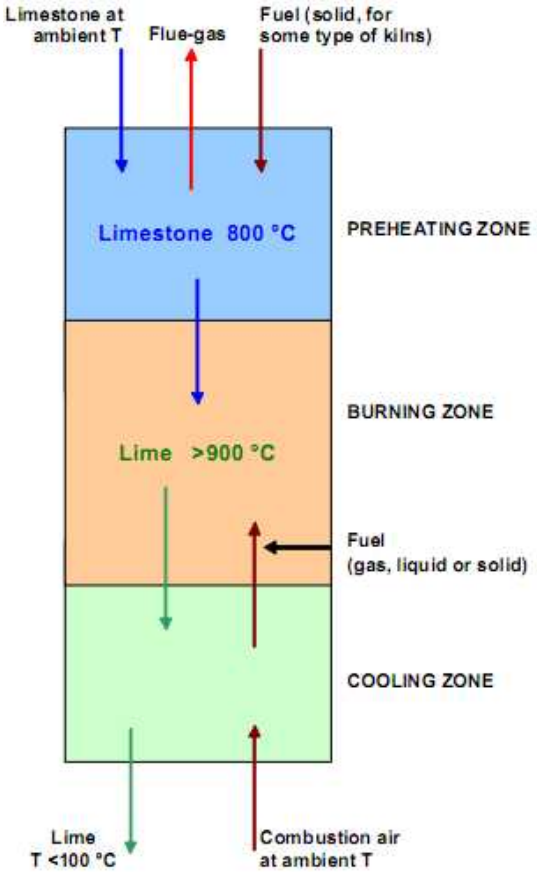


Figure 3.5.3-6 General principle of lime calcination (source: BREF 2010)

Due to the general principle and the kinetic of the reaction, the production profile, and consequently the energy consumption profile, of the lime industry is rather stable with no fluctuation on the short term.

Energy intensity of the different lime kilns

Horizontal kilns consume significantly more energy than vertical ones, due to the lower surface of contact between hot air and pebbles (in rotary kilns, smaller pebbles are used but the set of pebbles offers a smaller specific surface altogether than for vertical shaft which is literally infiltrated by hot air):

Kiln Type	Specific heat consumption (GJ / t lime)
Horizontal kilns	
PRK	5.1 - 7.8
LRK	6.4 - 9.2
Vertical kilns	
PFRK	3.6 - 4.2
ASK	3.8 - 4.6
MFSK	3.8 - 4.7
OK	3.5 - 7.0

Figure 3.5.3-7 Range of specific energy consumption for lime kilns (source: Ecofys 2009h, from BREF 2010)

The main fuels used are:

Fuel	Percentage
Gas (fossil)	38 %
Solid (fossil)	47 %
Liquid (fossil)	8 %
Waste (fossil and biomass)	6 %
Biomass	2 %

Fuel	LRK	PRK	ASK	PFRK	MSFK	OK
Gas (fossil)	3	26	69	64	0	51
Solid (fossil)	81	60	6	20	100	32
Liquid (fossil)	1	3	14	10	0	10
Waste (fossil and biomass)	14	11	11	3	0	7
Biomass	0	0	0	3	0	0

Figure 3.5.3-8 Fuels mix in the lime industry for 2007 and 2008 (left) used in lime kilns in 2003 (right) (Source: Exofys 2009h, from BREF 2010)

Solid fuels, which have the largest carbon content by mass of fuel, represent almost half of the fuel mix. They are especially used in MSFK and rotary kilns, which operate a high temperature flame to calcinate limestone.

It must be noted that MSFK requires steelmaking grade coke, a very costly type of coal which has physical structuring properties. This coke makes possible to structure the lime and fuel set and let exhaust gases and combustion air infiltrate in the Mixed feed Shaft Kiln, which a vertical kiln.

Gas is the second the second largest fuel and is used especially in all other vertical shaft kilns than MSFK.

3.5.3.3. Lime heat market

The graph below details the total heat consumption by type of kiln and type of fuel in 2005 in EU27:

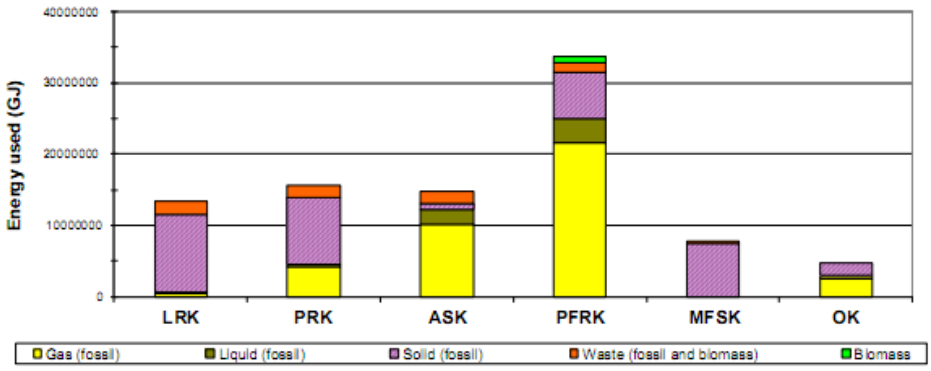


Figure 3.5.3-9 Energy consumption by EU27 lime kils by type of kilns and type of fuel in 2005 (source: BREF 2010)

PFRK is the main energy consumer being the main type of kiln today and its fuel mix is based mostly on gas. Although rotary kilns produce less lime, they consume significant amounts of fuels due to their higher energy intensity.

		Heat market (GWh/y)		Share
		Min	Max	
Vertical kilns	PFRK	18 247	27 907	51%
	ASK	7 964	11 449	21%
	MFSK	2 240	2 613	5%
	OK	3 251	3 936	7%
Horizontal kilns	LRK	2 660	3 290	6%
	PRK	2 722	5 444	10%
TOTAL		**37 084**	**54 639**	**100%**

Table 3.5.3-3 Heat consumption of the lime industry by type of kiln (based on BREF 2010)

The direct calculation of the heat market is in accordance with the indirect estimate from the emissions declared in the ETS (50 821 GWh/y).

The average heat consumption by site (210 sites in EU27) is 20 to 30 MWth. Yet, this hinders large disparities in sites capacities. The average site production is 133 kt/y/site (28 Mt/y divided by 210 production sites). A large production site may produce up to 2 Mt/y and would have an equivalent thermal capacity of 303 to 447 MWth, perfectly compatible with a nuclear reactor, although the number of such sites is certainly low.

It must be noted that this heat market cannot be supplied externally. Yet, a nuclear reactor with a steam output at 550°C may theoretically supply a part of this market by pre-heating the load.

3.5.3.4. Potential for nuclear pre-heating for the lime industry

Energy supplied to the system

The process temperature of lime calcinations is around 900°C – 1 200°¢, which is largely higher than the highest reachable outlet temperatures of the high temperature reactors. Yet, nuclear pre-heating could be a viable solution.

Consider the quicklime reaction:

$$CaCO3 \leftrightarrow CaO + CO2$$

The main approximate parameters of the quicklime reaction are reported below:

	Unit	CaCO3	CaO	CO2	Reaction total
S^0_{solid}	J/mol·K	93	40	214	161
ΔH liquid	kJ/mol	-1154			
ΔH solid	kJ/mol	-1207	-635	-393,5	178,4
Specific heat	J/g/K	0,82			
	J/mol/K	82,1			
Molar mass	g/mol	100	56	44	

Table 3.5.3-4 Main parameters for the chemical reaction related to lime production

The thermodynamics of chemistry enables to calculate the temperature at which the reaction is at the equilibrium, i.e. the free energy of Gibbs is zero:

Free energy of Gibbs:

$$\Delta G = \Delta H - T\,\Delta S$$

At ambient temperature, ΔG = 130 kJ/mol > 0 so the reaction tends to be reversed, i.e. that quicklime combines with carbon dioxide to produce calcium carbonate. Indeed, this reaction occurs naturally with a low kinetics of a few weeks.

At 1 000°C, Δ = -27 kJ/mol < 0, so the calcium carbonate tends to decompose into calcium oxide and carbon dioxide, with a faster kinetic of around one day.

The temperature at which the free energy of Gibbs is zero is T = 835°¢, which is indeed in the order of temperature at which the reaction is triggered in lime kilns.

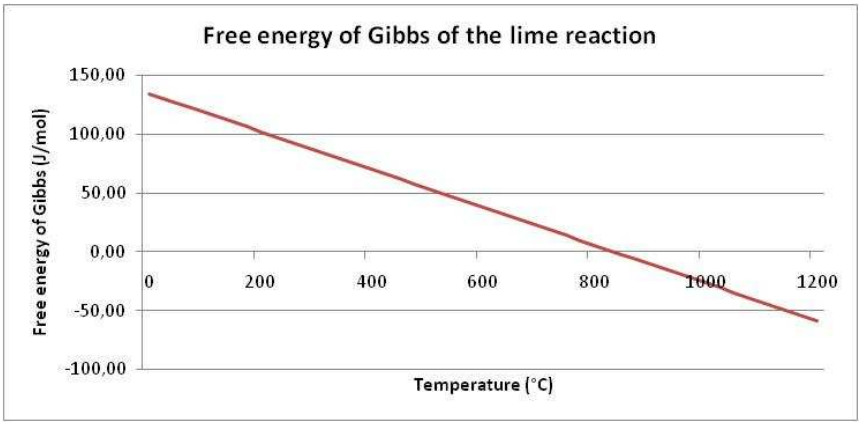


Figure 3.5.3-10 Free energy of Gibbs of the quicklime reaction

The energy supplied to the system is simply the energy to heat the calcium carbonate from ambient temperature to the process temperature, say 900°C, at which the reaction occurs naturally.

Considering the specific heat of calcium carbonate, the energy to heat it from 25°C to 900°C is 717 J/g CaCO3, equivalent to 1 282 J/g CaO (using the molar masses and the reaction stoechiometry).

Final process temperature	800°C	900°C	1 000°C	1 100°C	1 200°C	1 300°C	1 400°C	1 500°C
Nuclear pre-heating (J/g CaCO3)	389	389	389	389	389	389	389	389
Gas make-up heating (J/g CaCO3)	246	328	410	492	574	656	738	820
Total energy by mass (J/g CaCO3)	635	717	799	881	963	1 045	1 127	1 209
Total energy by mass (J/g CaO)	1 136	1 282	1 429	1 575	1 722	1 868	2 015	2 162
Total estimated energy of sector (GWh/y)	8 833	9 973	11 113	12 253	13 393	14 532	15 672	16 812

Table 3.5.3-5 Estimation of the total energy market for lime production and portion that could be taken by nuclear pre-heating depending on the final process temperature

The total energy market estimated from these theoretical parameters is 9 973 GWh at 900°C and 16 812 GWh at 1 500°C. The difference with the 25 417 GWh reported in the previous paragraph may originate

from 1/ the fact that only quicklime is considered, 2/ the process temperature may reach up to 2 000°C in rotary kilns and 3/ the efficiency of heat exchanges is not taken into account, whereas the heating efficiency depends on the thermal isolation in lime kilns and the specific surfaces of pebbles and limestone bed in the kiln.

Keeping in mind its incomprehensiveness, this theoretical estimation is yet used below for the purpose of simplicity to evaluate the potential of nuclear pre-heating.

Nuclear pre-heating

Now considering that nuclear heat could be used to pre-heat the calcium carbonate up to 500°C, the energy to heat can be decompose as follows:

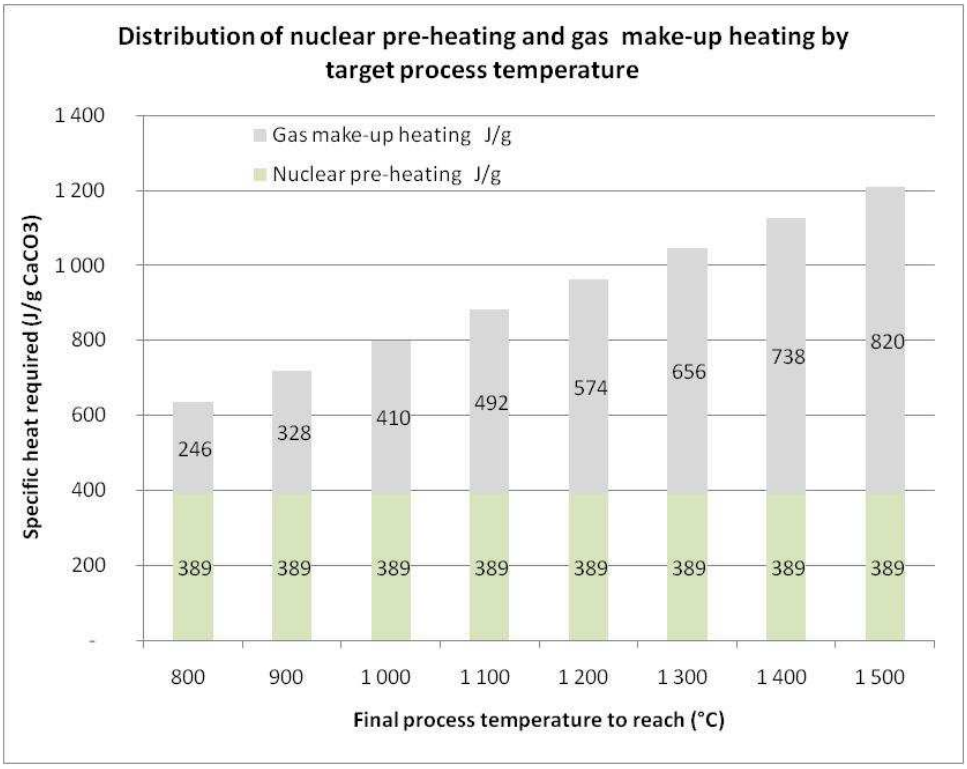


Figure 3.5.3-11 Decomposition of nuclear pre-heating and gas make-up heating by final process temperature

At a usual target process temperature of 900°C (respectively 1 000°C), nuclear pre-heating could therefore provide 54% (resp. 49%) of the energy to heat calcium carbonate to 500°C, the remaining temperature increase being taken over by a gas burner.

This corresponds to a total market of 16 386 GWh/y to 29 661 GWh/y (considering the 49%-54% range and the heat market estimate range (37 084 - 54 639 GWh/y).

Considering a nuclear pre-heating at 500°C would save 49% to 54% of gas heating and considering the total EU lime heat consumption to 25 417 GWh and a gas industrial market price of around 36 €/MWh, the equivalent saved fuel cost would range between 446 M€/y to 497 M€/y out of around 915 M€/y (this total fuel cost corresponds to 37% of the 2,5 bn€ total sector turnover).

The kinetic of the lime production kiln would make it possible to use a surrounding nuclear steam heat exchanger to pre-heat at the top pre-heating zone for a few hours.

The technical and economic feasibility as well as the economic interest of coupling a nuclear reactor with a lime kilns should therefore be analysed in more detail.

3.5.3.5. Conclusions and recommendations

- Lime is an important bulk intermediary product used in many industrial applications. The EU market is mature and the industry is quite concentrated with larger sites in operation in particular in Germany, Belgium, France, United-Kingdom and Czech Republic.

- There are many production routes for lime products, horizontal and vertical kilns being complementary in processing limestone pebbles of different sizes. All routes demonstrate a production inertia due to the long calcinations process, despite the fact that quicklime must be used within several days after its production so the industry operates just-in-time with little stocks.

- The industry is capital and energy intensive and is significantly impacted by EU energy and emissions regulations.

- Lime represents a small heat market with a few large sites whose consumption would reach a few 100 MWth, compatible with a nuclear reactor.

- Although lime is produced at very high temperatures (> 900°C), it is an example of pre-heating market; nuclear steam could be used to pre-heat limestone up to 500 or 600°C, saving the related gas heating. The kinetic of the calcinations process would enable to heat constantly with nuclear steam.

- Should nuclear pre-heating reveal feasible for the lime industry, a wide range of other sectors could be interested in nuclear heat, including cement, ceramics and glassmaking, due to similarities in process schemes.

- An in-depth study is therefore recommended to evaluate the applicability of nuclear pre-heating in a lime kiln, its technical feasibility and economic interest. This study could possibly extend its conclusions to other equivalent sectors.

3.5.4. Glass, cement, ceramics and non-ferrous metals

Summary:

Glass, cement, ceramics and non-ferrous metals are interesting sectors as regards the potential of nuclear pre-heating. Nuclear pre-heating could be of interest in the glassmaking via a combination with fossil fuels, oxygen production and electric heating. In ceramics, the drying process is compatible with nuclear heating, as well as for certain non-ferrous metals. Nuclear pre-heating may also be applied in the cement production process, which is close to the lime process.

This part uses information from adopted BREF documents on Glass manufacturing industry, Cement, lime and magnesium oxide manufacturing industries, Ceramic manufacturing industry and Non-ferrous metals industries (BREF 2001c, 2010, 2007 and 2001) and their revised draft documents when available (BREF 2009c and 2009).

Stakeholders from these sectors did not respond to the market survey so the level of detail is lower; these are yet interesting sectors, especially as regards the "nuclear pre-heating" market.

3.5.4.1. Glassmaking industry

Glass products and applications

Glass products and applications are:

Product	Share of EU production	Applications	Main companies	Industry structure
Container glass	53%	Packaging for food, drinks, cosmetics, perfumes, pharmaceuticals and technical products	Saint-Gobain, Betropack, Vidrala, Ardagh Glass, BA Vidro, O-I Europe	70 companies, 170 installations with capacities mostly 300-600 t/d
Flat glass	25%	Building (75-85%) and automotive (15-25%)industries	Saint-Gobain, AGC, Pilkington, Guardian, Euroglas	9 manufacturers 58 float tanks with capacities mostly 400-700 t/d
Continuous filament glass fibre	3%	Building, automotive and transport and electrical and electronics industries mainly	Saint-Gobain, Ahlstrom, Lanxess, P-D Oschatz, Owens	24 furnaces in 17 sites
Domestic glass	4%	Glass tableware, cookware and decorative items, glasses, cups, bowls, plates...	Arc International, Bormioli Rocco e Figlio, RCR	More than 300 installations, out of which 61 are >20t/d
Special glass (without water glass)	2%	Cathode ray tubes, lighting glass borosilicate glass tubes, laboratory and technical glassware, optical glasses		23 main special glass production plants

Mineral wool	10%	Building thermal insulation, (70%), heating and ventilations applications, pipes, chemical plants, fire protection	Saint-Gobain, Rockwool International, Parock, URSA, Knauf	62 installations, mostly with capacities 27-274 t/d
High temperature insulation wools	0,1%	High temperature thermal insulation in industry		6 installations
Frits	3%	Manufacture of ceramic glazes and pigments, storage tanks, silos, ovens		48 installations with capacities 50-150 t/d

Table 3.5.4-1 Glass products and applications (Source: 2009c)

The sector has been steadily growing over the last decade but international competition becomes hard and environmental regulations may reveal an uncompetitive advantage for the industry.

Industry

The industry is versatile. Production capacities range from a several tons to thousands of tons per day. Only 5% of the industry is below the 20 t/d threshold of ETS (BREF 2009c). Glass is a globally traded commodity.

Glassmaking is a high temperature energy intensive activity resulting in large emissions of greenhouse gases. The total energy consumption of the industry was approximately 86 500 GWh in 2005. Most energy is used to melt the raw materials at high temperatures. The fuel mix is as follows:

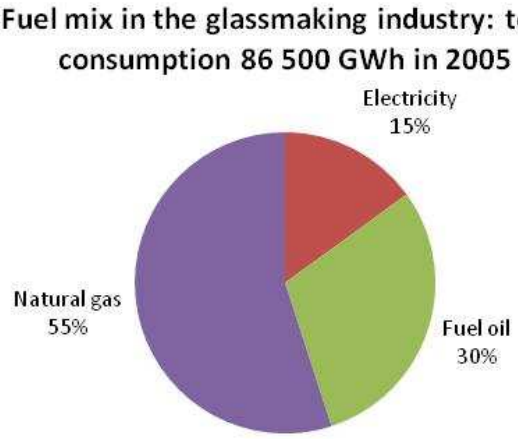


Figure 3.5.4-1 Fuel mix in the European glassmaking industry in 2005 (Source: BREF 2009c)

Many sub-sectors use large continuous furnaces with lifetimes up to 15 years. These furnaces represent large capital investment. When a furnace is to be replaced, the most energy economical melting technology is chosen.

Process

Glass is produced from various chemical materials which can form a vitreous structure such as oxides of silicon (the main raw material), boron, germanium, phosphorus and arsenic. These materials are melted and then cooled very quickly to keep their non-crystalline structure at liquid phase.

The general processes in glassmaking are:

- Raw materials handling and storage
- Mixing and transfer
- Melting and refining
- Forming
- Conditioning
- Coating
- Surface treatments
- Curing and drying
- Milling
- Machining, cutting and packaging
- Waste storage, handling and processing

Melting accounts for75% of the total energy consumption of the sector and will be the sole phase described in this study. It is composed of several phases (BREF 2009C):

- Heating: raw materials are heated as a bath of batch material by the flame from burning fossil fuels; the temperature necessary for melting and refining ranges between 1300°C and 1550°C
- Primary melting: due to the low thermal conductivity of raw materials, the melting process is slow. As the materials heat up, the moisture evaporates and trapped gases escape and many chemical and physical reactions occur. Decarbonisation occurs at around 500°C and materials begin to melt between 750°C and 1200°C.
- Fining and homogenisation: the glass must demonstrate homogeneous properties and be free of bubbles.

The most important melting techniques are selected depending on the required capacity, the glass formulation, fuel prices, existing infrastructure and environmental performance (BREF 2009c):

Type of furnace	Number of units	Melting EU capacity (Mt/y)	Average melting capacity (t/d)
End-fired	225	16,1	196
Cross-fired	145	20,3	384
Electric	43	0,8	51
Oxygen	35	1,6	125
Recuperative	120	3,3	75
Others	60	0,9	41

Table 3.5.4-2 Type, number, EU total capacity and average capacity per site for glass melting (Source: BREF 2009c)

Glassmaking being an energy intensive industry, the choice of energy source, the heating technique and the heat recovery method are central to the design of the furnace. Together with oil and natural gas,

electricity is used either as exclusive energy source or in combination with fossil fuels. Electrical heating can be done by resistive heating (the sole industrial scale technique) and induction heating.

Melting techniques

The basic objective of melting is to bring to the raw materials energy in the form of heat by any mean (burning fossil fuel, heating air or electricity) in order to melt them.

Regenerative furnaces

They include cross-fired furnaces and operate a cyclical firing system with heat recovery in the non-firing sections. Pre-heat temperatures are in the range of 1300-1400°C

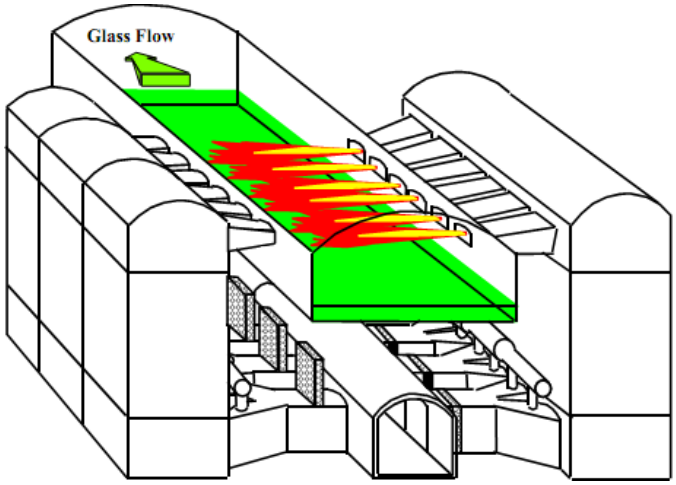


Figure 3.5.4-2 Schematic picture of a cross-fired regenerative furnace (Source: BREF 2001c)

Conventional recuperative furnaces add an air-preheating phase using waste gases. Air is preheated up to 800°C.

Oxy-fuel meting

This technique replaces the combustion of air by the combustion of oxygen (>90% purity). The elimination of nitrogen reduces the waste gases volumes which are composed mainly of CO2 and water. Except this specificity, they are close to normal fired melting units.

Electric melting

An electric furnace consists of a refractory lined box supported by a steel frame with electrodes inserted in the bath. The energy is provided by resistive heating. This technique is commonly applied for low volume special glass production. since heat losses are lower than in fired furnaces, this lowers the difference between fossil fuel fired and electric furnaces at small scale. Electricity offers also a better flexibility and environmental performance.

Combined fossil fuel and electric meting

This is certainly an interesting melting technique for nuclear high temperature reactors.

There are two approaches: either predominantly fossil fuel firing with electrical boost or predominantly electrical heating with fossil fuel support.

Electrical boost is commonly used, also in fossil fuel fired furnaces to bring an extra heat to the process, although it incurs high operating cost.

Energy consumption and industry heat market

Energy specific consumption

The theoretical energy consumption for melting soda-lime glass (the main type for glass for flat and container glass) is:

Type of glass	Heat of reaction to form glass from the raw materials (GJ/t)	Enthalpy of glass to raise the glass temperature from 20 to 1500°C (GJ/t)	Enthalpy of the emitted gases (principally CO2) released during melting (GJ/t)	Theoretical energy requirement (GJ/t)	Real energy requirements (GJ/t)
Soda-lime glass	0,49	1,89	0,30	2,68	3,3 – 40 Average: 8 GJ/t

Table 3.5.4-3 Main parameters of the chemical reaction for the glass melting (Source: BREF 2009C)

The distribution of energy is as follows (BREF 2009c):

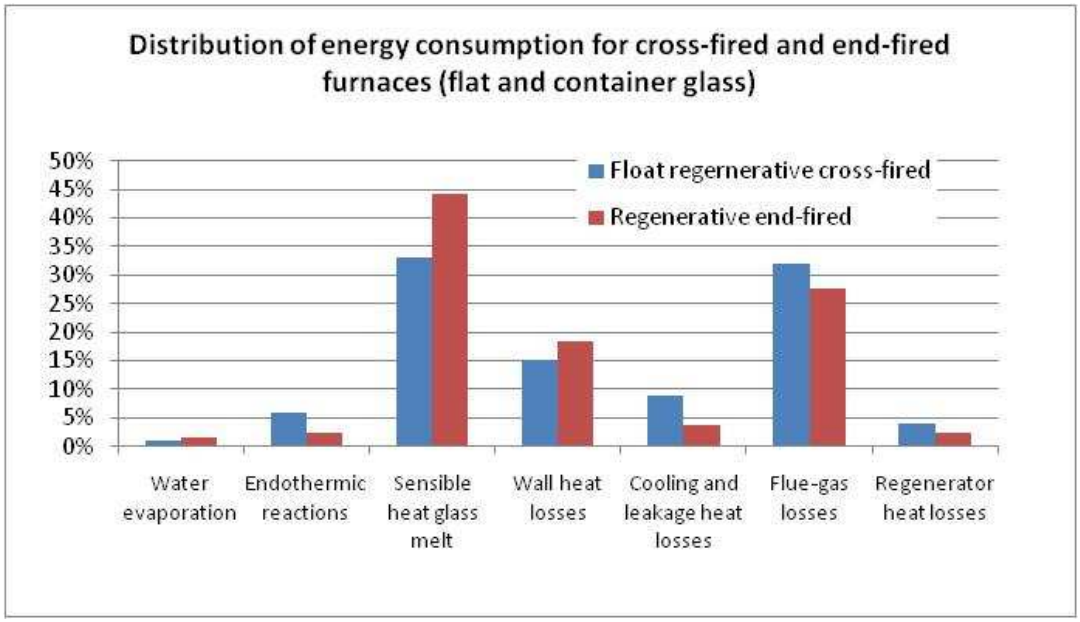


Figure 3.5.4-3 Typical energy output distribution for the production of the most common industrial glasses (flat and container glass) (Source: BREF 2009c)

The sensible heat to melt glass is the principal source for energy consumption.

Heat losses through walls, cooling, leakage, flue gas and regenerator account for 52% to 60% of the energy consumption, which explains the high energy intensity of the sector. The use of an electric boost improves the energy efficiency but high electricity prices may make it uncompetitive.

Industry heat market and potential for nuclear energy

As said before, the energy may come from any source whether fossil fuel burning or electricity. Nuclear high temperature reactors may therefore be used to pre-heat the raw materials up to 550°C and providing the remaining energy by electricity. A detailed techno-economic analysis is necessary to evaluate whether this may have an interest.

Pre-heating from 20°C to 550°C would represent 36% of the heating need from 20°C to 1500°C. A simplifying assumption is to consider that this ratio applies to the overall specific energy consumption.

Considering the total European glass production capacity of 37,75 Mt in 2005 and the average specific energy consumption of 8 GJ/t, a simple calculation leads to:

	Energy consumption (GWh/)
Total energy consumption	83 875
Energy for pre-heating (36%)	30 036
Remaining consumption for final heating (64%)	53 839

Table 3.5.4-4 Estimation of the total energy market for glass making and the related hypothetical nuclear pre-heating market

First, it can be noted that the total energy consumption for melting is considerable, whatever the energy source. Second, the heat market represented by nuclear pre-heating could be significant. Third, the remaining energy could be brought via either a pure electric heating or more probably a combined fossil fuel and electric heating. It would yet represent a significant amount of electricity, which may be supplied in addition to heat by the nuclear reactor.

This figure is lower than the indirect calculation for the sector from the declared CO2 emissions because 1/ it concerns melting only whereas other processes may consume heat (e.g. shaping processes) and 2/ it considers the average specific energy consumption of 8 GJ/t of flat and container glasses, two low energy consuming processes, as representative of the whole sector.

For a relatively large furnace producing 500 t/d glass, the related energy consumption would be 406 GWh/y, out of which 145 GWh/y would be pre-heating. The remaining 260 GWh/y could be electricity, which would then be equivalent to 781 GWh/y of heat, assuming a thermal efficiency of 33%.

Conclusion

Despite the fact that glass is a high temperature process, it may reveal a promising market for nuclear energy from high temperature reactors. Glass represents indeed an excellent example of an industrial sector operating high temperature processes that may be supplied with heat and electricity by a high temperature nuclear reactor efficiently. This heat market is rather significant. It would yet necessitate a furnace re-design.

3.5.4.2. Cement industry

Cement industry

Cement is a basic material for building ad civil engineering. Whereas the world consumption has been growing rapidly, the European market has been stagnating since the 1970s. China is the world leader in cement production with 47% of the world production, followed by EU27 with 11%.

The EU25 cement production in 2006 totalled 267,5 Mt. The leading producing countries are Spain (52 Mt/y), Italy (45 Mt/y), Germany (32 Mt/y) and France (22 Mt/y) (BREF 2010). The total number of kilns operated in EU27 is 268.

The world's five largest cement producers are French Lafarge, Swiss Holcim, Mexican Cemex, German Heidelberg Cemend and Italian Italcementi. These companies produce also aggregates, concrete, plaster, etc.

Cement is mainly delivered by road. There is a limit to the distance, usually 200-300 km, over which cement can be transported due to the low price of cement. Global trade does exist and in some cases it may be economically viable to shop cement around the world.

Typical kiln size is 3 000 tons of clinker per day and very few kilns have capacities lower than 500 t/d. 90% of the production follows the so-called dry process (7,5% semi-dry and 2,5% wet processes).

The cement industry is an energy intensive industry with energy accounting typically for 40% of the production costs (excluding capital costs and including electricity costs).

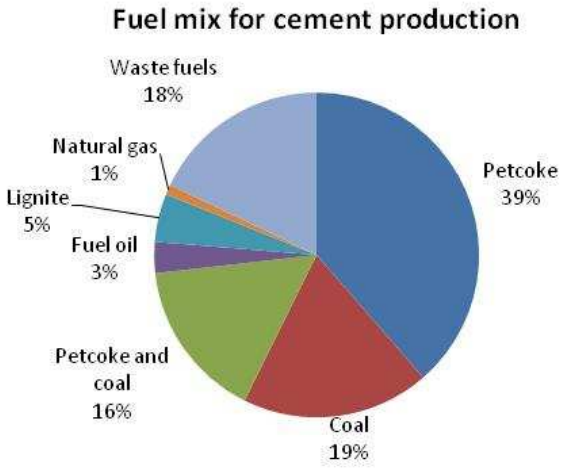


Figure 3.5.4-4 Fuel mix for cement production (Source: BREF 2010)

The main fuels are petcoke and coal but wastes are increasingly used. Natural gas and fuel oil are only marginal.

Cement manufacturing process

Cement is very close to lime processes. The basic chemistry is to decompose limestone (CaCO3) to lime (CaO), emitting CO2 at about 900°C, followed by the clinkering process which makes lime react at high temperature (1400-1500°C) with silica, alumina and ferrous oxides. The clinker is then grounded or milled together with gypsum and other additives to produce cement.

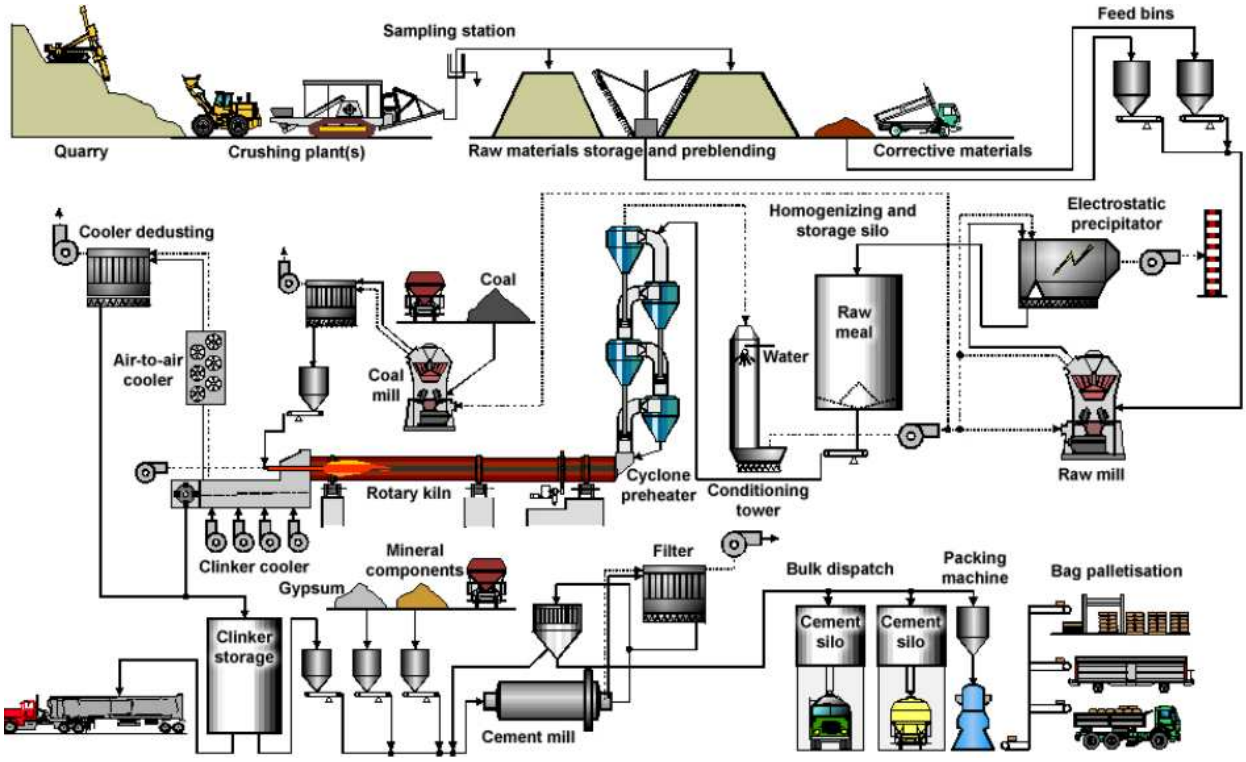


Figure 3.5.4-5 General overview of a cement manufacturing process (Source: BREF 2010)

The clinker kiln (on the picture, the rotary kiln) is the central process as regards energy and environment. It is where raw materials are heated and reacted and where CO2 is released.

To reach the process temperature of 1400-1500°C, a flame temperature of 2000°C is necessary. Heat from hot counter-current off-gases is recovered to pre-heat the feed (in the vertical pre-heater part of the kiln) and excess heat is increasingly used for district heating and electricity generation.

The gas and solids temperatures throughout the kilns are schematically reported below:

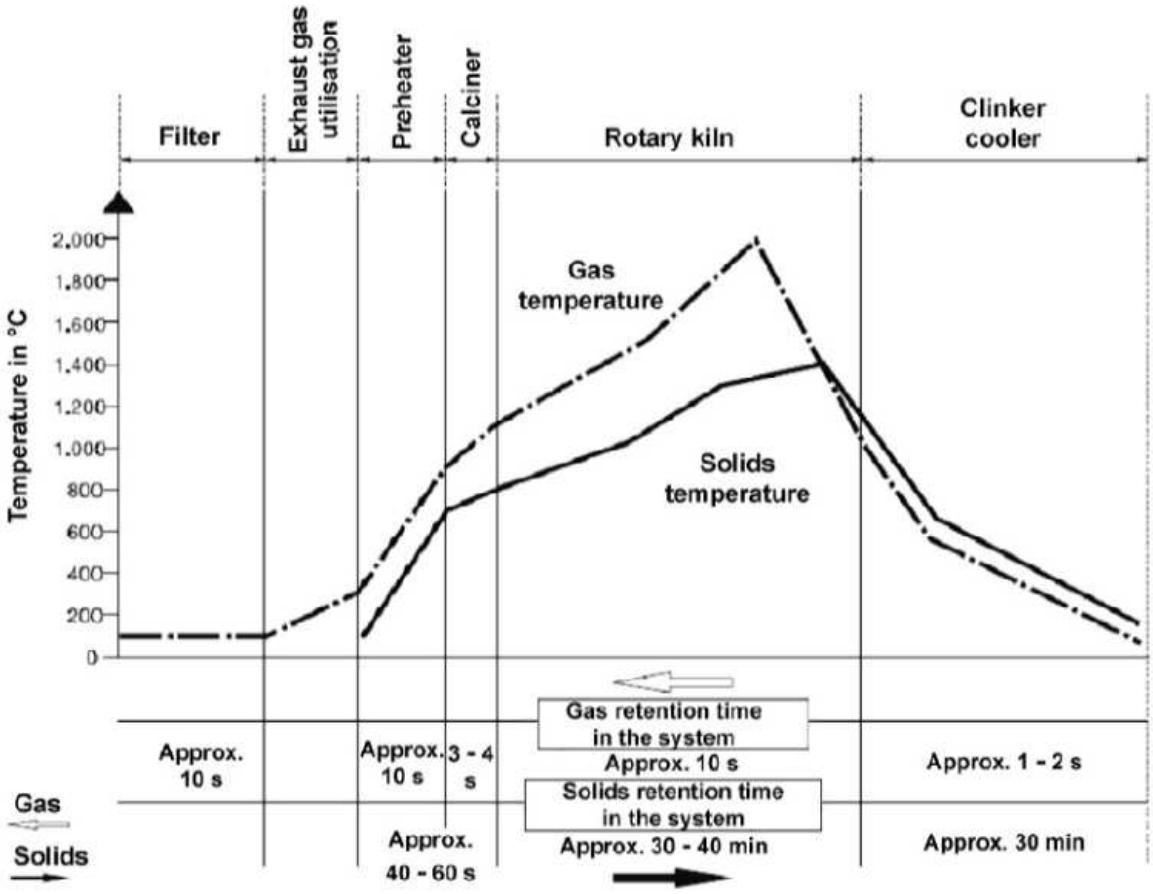


Figure 3.5.4-6 Gas and solids temperature profiles in a cyclone preheater kiln system (Source: BREF 2010)

Like for lime production, the process aims at heating the reactants together at high temperature and is based on a complex recovery of heat from hot off-gases released from fossil fuel combustion. If nuclear heat was brought to the system, it would disturb the whole balance by possibly lowering the fossil fuel burning but also the pre-heating by off gases.

Energy consumption and potential of nuclear energy

Energy consumption is predominantly related to the kiln operation of drying the raw material (depending on the moisture content), pre-heating it and burning it.

Energy market	Min	Max
Total sector energy market (GWh/y)	222 917	282 361
Pre-heating market (GWh/y)	79 828	101 116
Typical site heat consumption (capacity of 3000 t/d) (GWh/y)	913	1 156
Pre-heating of a typical site (3000 t/d, 36% preheat) (GWh/y)	327	414

Table 3.5.4-5 Estimation of the total energy market for cement production and the related hypothetical nuclear pre-heating market

The direct calculation of the total heat consumption is in accordance with the indirect one (275 TWh).

The nuclear pre-heating market represents a significant market although a single kiln would not consume all heat from a 500 MWth reactor. It must also be noted that electricity could not be used like in the glassmaking industry and that fossil fuels would still be necessary. The thermal and mass balance of hot off-gases which are used for pre-heating should therefore be impacted and may limit the potential for nuclear pre-heating.

3.5.4.3. Ceramic industry

Ceramic industry

Ceramics refer to inorganic materials made of non-metallic compounds and produced by a firing process. Clay is an important raw material.

Clay resources are widely distributed throughout Europe so ceramic products are relatively inexpensive. Transport costs are yet significant due to the weight of the products.

The EU15 output in 2000 by main ceramic product is reported below (BREF 2007):

	EU15 output in 2000 (Mt)
Wall and floor tiles	25
Bricks and roof tiles	55
Table- and ornamentalware	0,5
Refractory products	4,5
Sanitaryware	0,5
Technical ceramics	0,15
Vitrified clay pipes	0,7
Expanded clay aggregates	3
Inorganic bonded abrasives	0,04
TOTAL	**89,39**

Table 3.5.4-6 Main ceramics products and their related EU output in 2000 (Source: BREF 2007)

Energy consumption

Ceramic production is an energy intensive process. The specific energy consumption depends on the product and range from 2,3 GJ/t to 50 GJ/t. Taking into account the different production costs by product, the share of energy costs in the total costs can range from 10% to 30% (from the lowest porcelain estimate to the highest brick estimate).

Despite the fact that brick and roof tile and the wall and floor tile sectors are the thermally efficient processes, they are nevertheless the largest energy consumers due to the larger tonnage outputs.

Sector	Unit	1980	1985	1990	1995	2000	2003
Brick and roof tiles	GJ/t	2,65	2,45	2,19	2,06	2,38	2,31
Wall and floor tiles	GJ/t	11,78	9,16	6,76	5,45	5,74	5,6
Refractory products	GJ/t	4,88	4,96	6,51	4,91	5,41	5,57
Sanitaryware	GJ/t	26,56	24,214	22,27	22,76	20,88	21,87
Vitrified clay pipes	GJ/t			5,75	5,77	6,1	5,23
Table- and ornamentalware	GJ/t			47,56	38,91	43,46	45,18
Technical ceramics	GJ/t					34,72	50,39

Table 3.5.4-7 Specific energy consumption by type of ceramic product (Source: BREF 2007)

Natural gas is the main fuel used in the industry with a share of more than 96% in household ceramics, sanitary ware, technical ceramics, wall and floor tiles and vitrified clay pipes. For bricks and roof tiles, gas accounts for 89% of the fuel mix.

General process description

The production process is rather independent from the materials used and the main steps are as follows (BREF 2007):

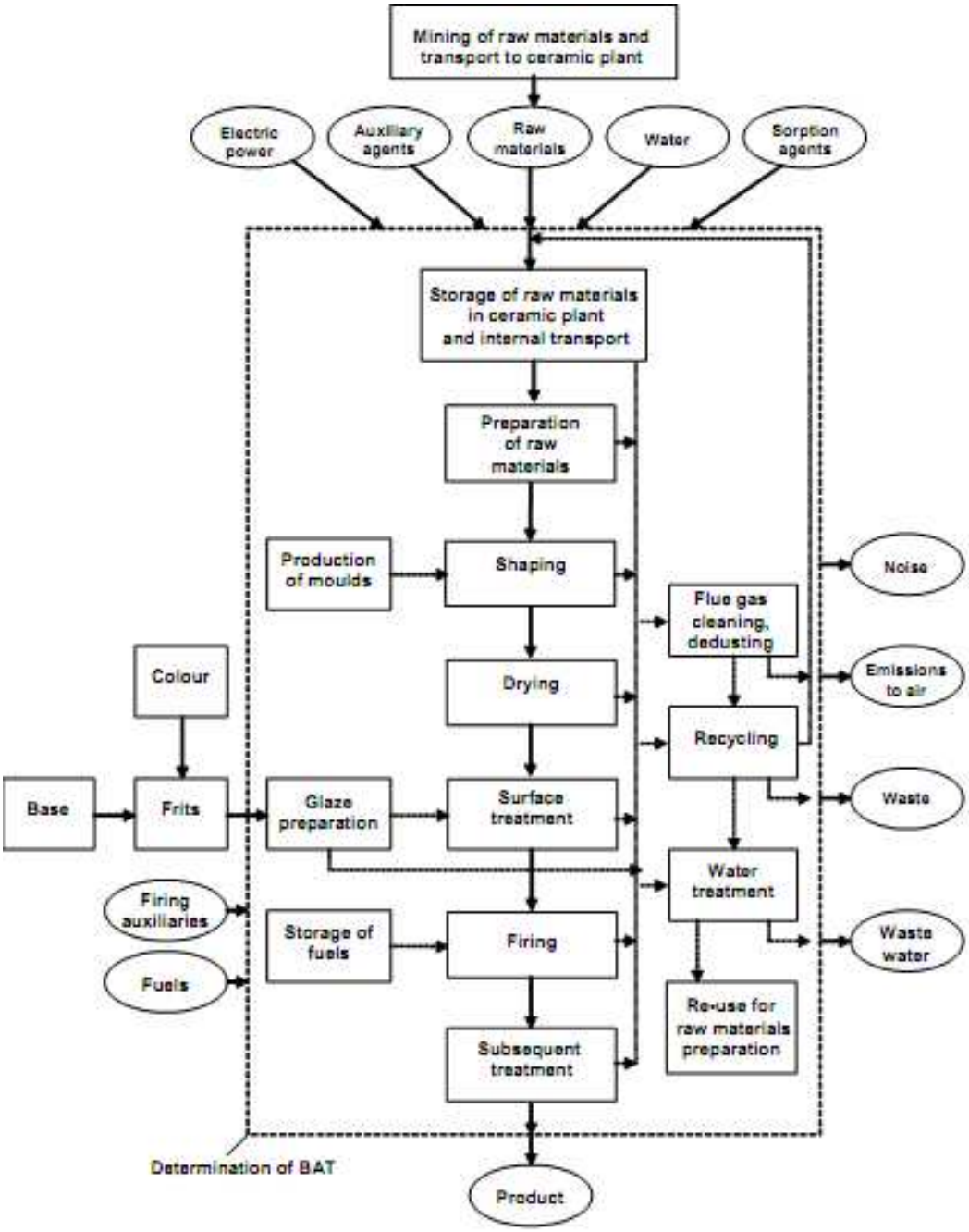


Figure 3.5.4-7 Stages in the manufacture of ceramic products (Source: BREF 2007)

The two principal heat consuming phase are drying and firing. Non-negligible amounts of electricity are consumed in the machinery parts of the plant (transporting, mixing, grinding, forming, etc.). electrical heating is also used in the manufacture of certain tableware and technical ceramics.

The process temperatures for drying and firing are widely spread depending on each type of ceramic.

Drying process

Drying aims principally at removing moisture from the shaped materials. Traditionally, the clay articles were dried by standing in the air at ambient temperature but this slow process is now replaced by a hot air drying process. The heating rates, air circulation, temperature and humidity are closely controlled.

Heat for the drying air is now mainly supplied by gas burners or recovered from the cooling zone of kilns but can also be supplied by a cogeneration unit.

There are many types of dryers:

Type of dryer	Comment
Hot floor dryers	No longer used because of their low efficiency
Chamber dryers	They consist of a battery of chambers served by automated rail tracks. or articles of different shapes with high water content or intermittent production
Tunnel dryers	These are long tunnel structure and drying is a continuous and automated process
Vertical basket dryers	Mostly for tiles, the dryer temperature is normally less than 200°C and a drying cycle last 35-50 minutes.
Dehumidifying dryers	These dryers maintain a level of humidity in air well below saturation so water keeps on evaporating by condensing water vapour or by introducing saturated steam.
Infrared and microwave dryers	This is a rather emerging technique.

Table 3.5.4-8 Main types of dryers used in the ceramic drying (Source: BREF 2007)

Firing

Firing is a key process in the manufacture of ceramic products because it controls many important properties of the finished ware.

Temperature level	Physic-chemical reactions
100°C – 200°C	The residual moisture is driven off
300°C – 500°C	The organic matter and iron pyrites are oxidized
500°C – 650°C	The water combined within the structure of clay minerals is released
750°C – 950°C	Carbonates such as calcite and dolomite dissociate and release carbon dioxide
900°C – 1100°C	The clay materials are vitrified (the crystal lattice breaks) and non-clay minerals are incorporated such as quartz, oxides, iron, lime.
> 1100°C	The final process temperature depends on the ceramic article to be produced.

Table 3.5.4-9 Description of the main physic-chemical reactions by temperature during the firing of ceramic products (Source: BREF 2007)

The maturing temperatures for different product groups are reported below (BREF 2007):

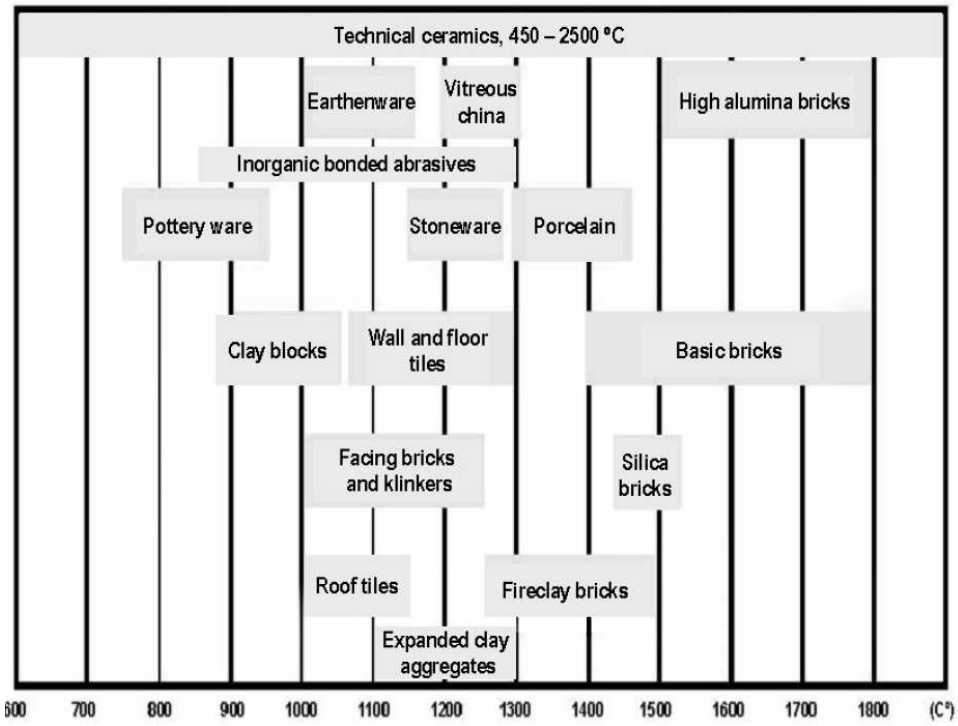


Figure 3.5.4-8 Ranges of industrial maturing temperatures for different product groups (Source: BREF 2007)

Natural gas is the main fuel burnt in the firing process.

Example of the bricks and roof tile and the wall and floor tile sectors

Bricks and roof tiles accounted for 62% of the EU15 output in 2000 (but only 25% of the sales due to their lower value) and wall and floor tiles for 22% (but 38% of sales). These are the major sectors in the ceramic industry.

Bricks and rood tiles are first dried at low temperature (60-90°C) and then fired in tunnel kilns in an oxidising atmosphere at maturing temperatures between 800°C and 1 300°C and then cooled down to 50°C.

The specific energy consumption in the bricks and roof tile sector is reported in the table below (BREF2007):

Tunnel kilns	Unit	Facing bricks and clay pavers	Clay blocks	Horizontally perforated clay blocks	Roof tiles
Throughput	t/h	1 – 15	3 – 15	3 – 15	3 – 6
Kiln length	m	35 – 160	60 – 120	60 – 120	80 – 140
Cross-section	m^2	1.3 – 6.0	4 – 12	4 – 12	4 – 10
Setting density	kg/m^3	650 – 1500	350 – 500	250 – 750	200 – 400
Firing temperature	°C	1000 – 1300	900 – 1050	950 – 1050	1000 – 1150
Specific energy requirement (drying + firing)	kJ/kg	1600 – 3000	1000 – 2500*)	1000 – 2500	1600 – 3500
Flue-gas volume flow	m^3/h	5000 – 20000	10000 – 50000	10000 – 50000	10000 – 40000
Flue-gas temperature	°C	100 – 230	100 – 300	100 – 150	170 - 200
*) Including heat content of the pore-forming agent					

Table 3.5.4-10 Main parameters for the production of several ceramic products (Source: BREF 2007)

Brick and roof tile kiln are very long kilns up to 140 m. The firing temperature ranges from 900 to 1300°C. The specific energy requirement is sadly not distributed among drying and firing but ranges from 1 to 3 GJ/t.

A kiln may have an annual output of 10 kt/y to 130 kt/y.

More precise data are available for an Italian plant producing wall and floor tiles (BREF 2007):

Process	Specific heat consumption (GJ/t)	Specific electricity consumption (GJ/t)
Body preparation		0,09 – 0,42
Spray drying at 350-450°C	0,98 – 2,2	0,01 – 0,07
Shaping		0,05 – 0,15
Drying (200-350°C for 1-4 hours)	0,25 – 0,75	0,01 – 0,04
Firing at 1 150°C	1,9 – 4,8	0,02 – 0,15
TOTAL	**3,15 – 7,75**	**0,18 – 0,56**

Table 3.5.4-11 Specific heat and electricity consumption by process phase for an Italian plant producing wall and floor tiles (Source: BREF 2007)

Heat is the main energy required in ceramic manufacturing and represents 93% to 95% of the total energy needs, the rest being electricity.

Heat is mostly used for firing (60% of heat) and spray drying (30%). Drying is lower due to the use of waste heat from the kiln (10%). Electricity is mostly used for body preparation (75%).

The annual output of a wall and roof tile production plant may range from 10 kt/y to 30 kt/y.

Energy market and potential for nuclear pre-heating:

Taking the example of wall and floor tiles (heat represents 95% of energy consumption and is distributed in 60% firing and 40% drying) and the specific energy consumption by ceramic sector, the following heat market for the ceramic industry can be evaluated:

	Total energy consumption (GWh/y)	Total Heat (95%) (GWh/y)	Drying (40%) (GWh/y)	Firing (60%) (GWh/y)
Brick and roof tiles G	35 292	33 527	13 411	20 116
Wall and floor tiles G	38 889	36 944	14 778	22 167
Refractory products G	6 963	6 614	2 646	3 969
Sanitaryware G	3 038	2 886	1 154	1 731
Vitrified clay pipes G	1 017	966	386	580
Table- and ornamentalware	6 275	5 961	2 385	3 577
Technical ceramics G	2 100	1 995	798	1 197
Expanded clay aggregates	1 925	1 829	732	1 097
Inorganic bonded abrasives	62	59	24	35
TOTAL	**95 559**	**90 781**	**36 313**	**54 469**

Table 3.5.4-12 Estimated total energy, total heat and heat for drying and firing by ceramic product

The total heat market is significant and the pre-heating market that represents the heat for drying (maximum 350°C) is a non-negligible market.

It must yet be noted that this large market is distributed over numerous works which make the average kiln consumption very low. The energy consumption for a rather large brick and roof tile kiln producing 100 kt/y would be 64GWh/y (61 for heat only, out of which 24 for drying and 37 for firing).

A production plant may operate several kilns but it would still consume small amounts of heat in comparison to the output of a 500 MWth nuclear reactor.

Conclusion

Ceramic production represents a large heat market split into a pre-heating market for drying up to 350°C and firing market from 800°C up to 1800°C which is significant. As the market is rather dispersed, the site heat consumption would represent as minor part of the thermal output of a high-temperature nuclear reactor and would need to be integrated in an industrial ecosystem.

3.5.4.4. Non-ferrous metals production

Non-ferrous metals industry

Non-ferrous metals, as reported in BREF (2001 and 2009), span a broad range of metals and techniques to produce which include: copper, aluminium (studied separately, see dedicated chapter), lead, zinc, cadmium, antimony, bismuth, precious metals, mercury, refractory metals, ferro-alloys, alkali alkaline earth metals, nickel and cobalt, and carbon. Radioactive metals are not considered.

Europe has very low ore deposits so most ores are imported and the recycling of metals is encouraged.

The industry structure is disparate, with small and large companies operating together on one or more market segment.

The data for the most significant non-ferrous metals (production higher than 1 Mt/y) are reported in the following table; it must be noted that accurate data were difficult to find and that they are to be take with some caution:

Metal	EU production and trend	Main production routes in Europe	Usual site capacities	Melting temperature	Heat consumption range (MWh/t)
Copper	2 400 kt (2005) Growing	Pyrometallurgical or hydrometalluical route	5 – 500 kt/y	1 083°C	3,89 – 5,56
Zinc	2 160 kt in 2007 Growing	Primary zinc: Roast-leach-electrowinning processes (RLE) and Imperial Smelting Furnace Secondary zinc: electric arc furnaces	Primary zinc sites: 50 – 300 kt/y Secondary zinc sites : 15 – 40 kt/y	420°C	0 (RLE is principal route and consumes only electricity) 8,18 – 11,42 (ISF, only one plant in Europe)
Lead	1 500 kt in 2006 Decreasing	Pyrometallurgical process	Primary lead : 30 – 210 kt/y Secondary lead: 30 – 110 kt/y	327°C	1,27 – 8,35
Nickel	2 790 kt (2006) Growing	Direct Outotec Nickel process	25 – 80 kt/y	1 453°C	6,94 – 18,06

Table 3.5.4-13 EU production and trend, production routes, usual site capacities, melting temperature and heat consumption range for the main non-ferrous metal (Source: BREF 2009)

Non-ferrous metals heat market

The heat market of the non-ferrous metals can be estimated very approximately from the above data. It must be noted that not all non-ferrous metals are considered. Yet, the production rates of other metals are low and this should not significantly alter the estimate. Assuming the process temperature corresponds to the melting temperature, the heat market is estimated as follows:

Temperature class	Heat market (GWh/y)		Metal
	Min	Max	
250-550	1 908	12 528	Lead
1000-	28 708	63 708	Copper and nickel
TOTAL	**30 617**	**76 237**	

Table 3.5.4-14 Estimation of the heat market related to non-ferrous metals by temperature class

This rapid and approximate calculation shows that the non-ferrous metals industry may represent a significant heat market, mostly in temperatures above 1000°C.

Assuming additionally that heat is required to melt the metals, a simplistic hypothesis, the pre-heating market at 550°C would represent around 37% to 50% of the heat market, depending on the process temperature (around 1100°C for copper or 1500°C for nickel), nuclear pre-heating may represent 10 625 to 31 764 GWh/y .

3.5.4.5. Conclusions and recommendations

- Glassmaking, cement, ceramic and non-ferrous industries operate mostly high temperature production processes, but also interestingly medium temperature processes. These high temperature processes necessitate heat to 1/ heat up the burden and 2/ sustain the production reactions.

- These sectors are rather neutral towards the heating source (except ceramic firing and specific non-ferrous metals production processes): the heating source may be replaced easily by any viable alternative (glassmaking being a typical example)

- These industrial sectors could therefore be a viable market for nuclear pre-heating, especially glassmaking and ceramics (drying).

- It is therefore recommended to analyse the potential of these sectors more in-depth and to liaise with key companies (e.g. Saint Gobain for glassmaking, LaFarge for cement), the related European professional associations (Glass for Europe, CEMBUREAU, Cerame Unie, Eurometaux) and the technology platforms or assimilated organisation when they exist (European Construction Technology Platform).

3.6. Market evaluation via the direct calculation

Introductory remarks

The direct calculation from the detailed analysis by industrial sector adds several advantages. First, it enables to verify the estimations of the indirect calculation from declared CO2 emissions. Second, it describes more precisely how energy, especially heat, is used in industry. Third, it makes possible to investigate the potential of the two hypothetical markets of polygeneration of hydrogen and oxygen and of pre-heating.

It is recalled that the markets for polygeneration and pre-heating are partially real markets:

- The polygeneration market relates to the current hydrogen market (the uptake of a future hydrogen economy is not considered); yet, the technologies for the production of hydrogen from nuclear energy are still to be demonstrated. Similarly, the market of oxygen production relates to high temperature production processes which are currently being developed but considers only the current estimated oxygen market (e.g. the future additional oxygen consumption from clean coal technologies is not considered).
- The pre-heating market is a part of the real extended market, which could possibly be supplied by nuclear steam at 550°C. This would require some reengineering

Results from the heat market direct estimation

The results of the direct calculation are reported in the table below:

	Plug-in	Polygeneration	Extended market	TOTAL
Direct calculation (GWh/y)	783 969	116 636 *Of which :* *O2: 30 421 GWh/y* *H2: 86 215 GWh/y*	2 190 828 *Of which pre-heating market 361 113 GWh/y*	3 091 432
Equivalent thermal power (GWth)	89	13	250 *Of which pre-heating: 41 GWth*	353
Equivalent number of 500 MWth reactors	179	27	500 *Of which pre-heating: 82*	706
Share of total	25%	4%	71%	100%

Table 3.6-1Heat market estimation from the direct calculation

The results of the direct calculation compare very well with the ones from the indirect calculation:

- The plug-in market is found to be almost the same (784 TWh/y direct, 759 TWh/y indirect).

- The extended market is found to be slightly larger (2 191 TWh/y direct, 1 771 TWh/y indirect); this could be expected since the ETS scope is only partial and excludes industrial facilities with production capacities below a given threshold or using biomass.
- The pre-heating market at 550°C is already a large market, almost half of the current plug-in market; the market would also grow with higher output steam temperatures.
- The polygeneration market is the smallest but offers many attractive advantages.

As a result, the share of externalisation of energy production (cogeneration of steam and electricity) is found to be similar with the indirect calculation (25% / 71% direct, 30% / 70% indirect).

These results can therefore be considered as robust.

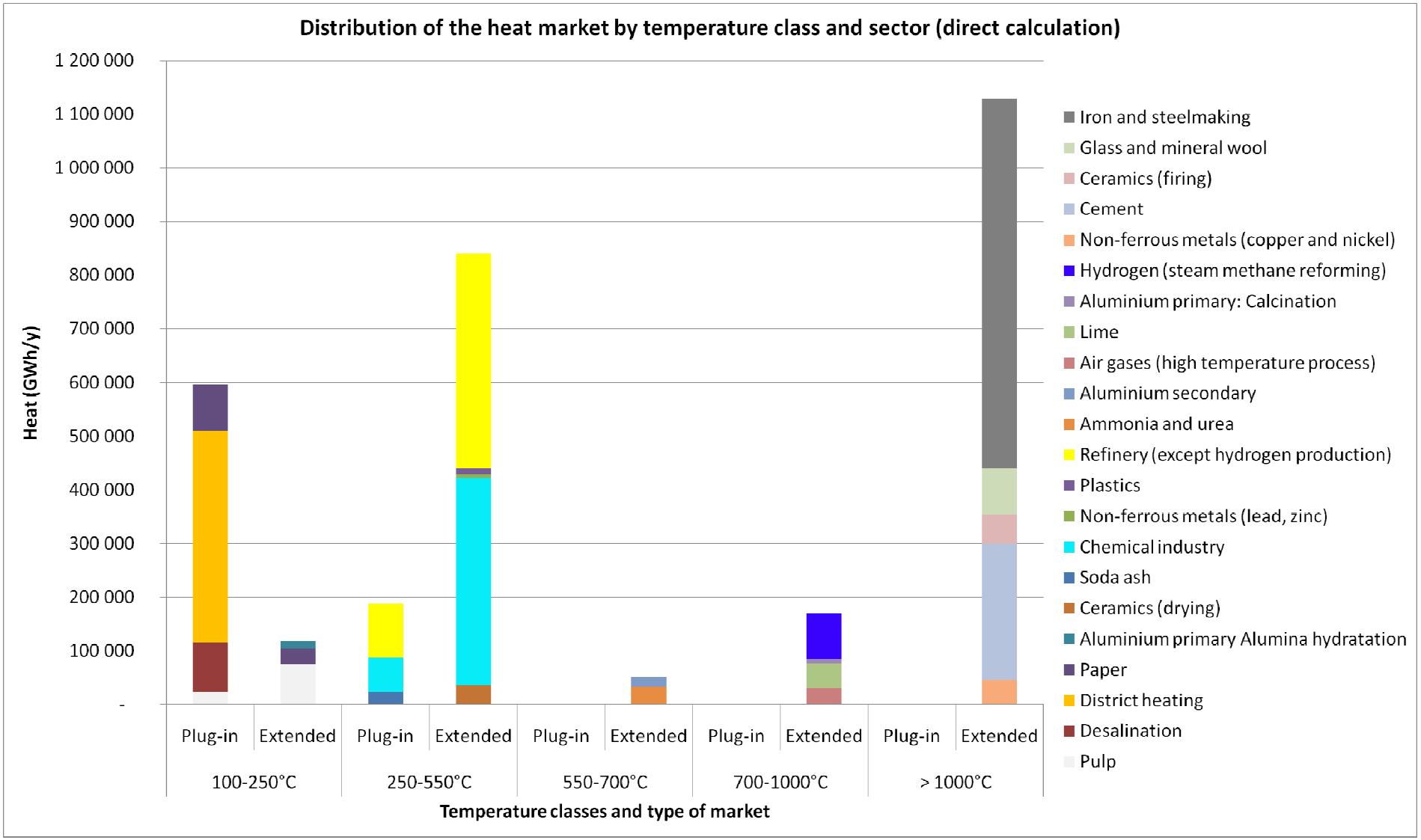


Figure 3.6-1 Distribution of the heat market by temperature class and sector from the direct calculation

The distribution of the heat market by temperature classes and sector demonstrates the same shape than the one from the indirect calculation. The heat market is most significant below 500°C and above 1000°C.

Small but yet higher heat markets are found in the temperature classes 550-1 000°C due to two main reasons

- Although the ammonia production process operates at temperature in the range 550-700°C, production units are always integrated into chemical clusters which operate steam networks at temperature below 550°C so the separation of this heat market is theoretical only. It is simply to be considered in a view to polygenerate ammonia, together with hydrogen and oxygen.
- The production of air gases relates to the high temperature processes which are not deployed industrially yet.

Impacts of the pre-heating and polygeneration markets

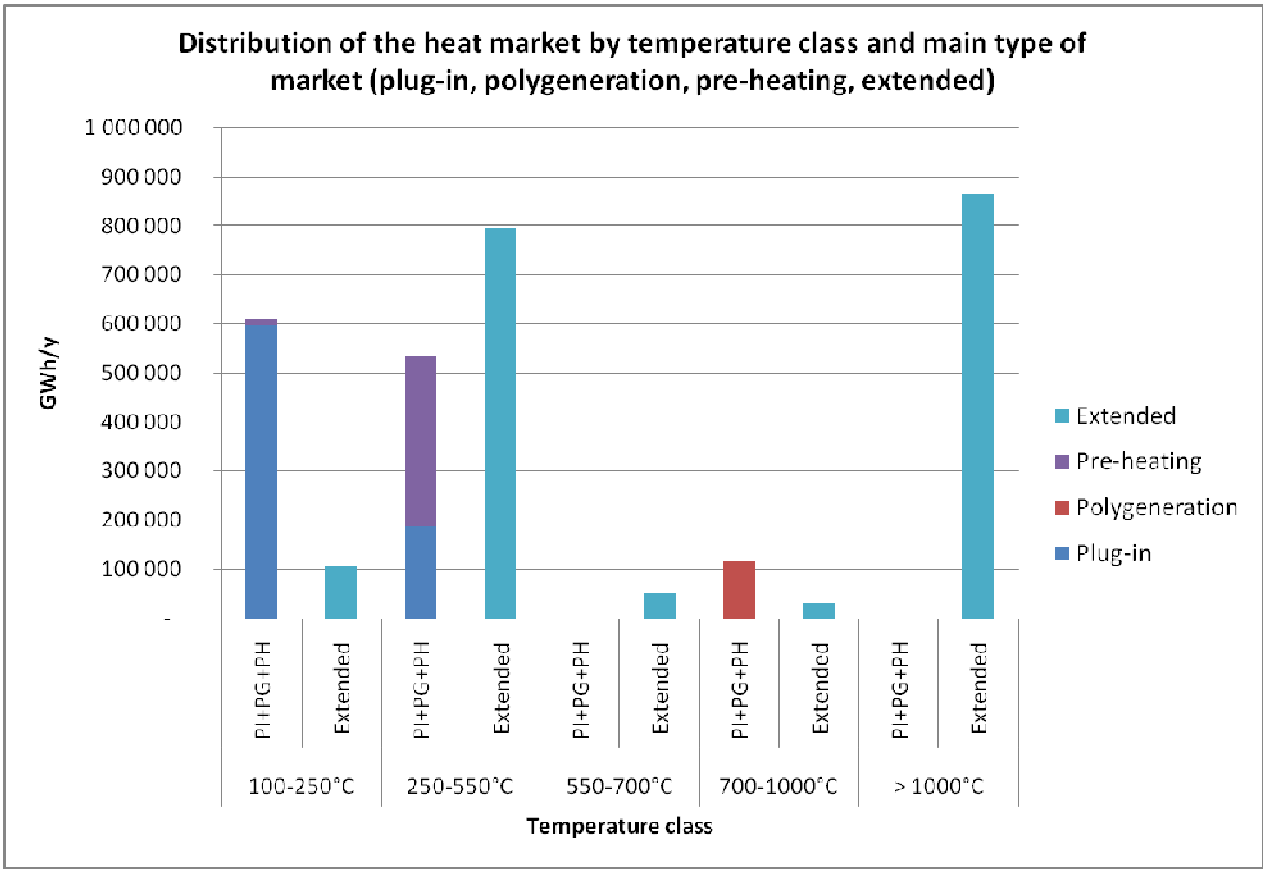


Figure 3.6-2 Distribution of the heat market by temperature class and man type of market (plug-in, polygeneration, pre-heating, extended)

The pre-heating market brings a part of the high temperature processes back to temperatures below 550°C. This market is already large (almost half of the total plug-in market) and is to grow with a higher output steam temperature.

Polygeneration is a more modest market segment and requires 1/ to reach output temperatures higher than 700°C and 2/ to develop and demonstrate the production technologies.

4. Conclusions, market analysis and recommendations

4.1. General conclusions

This study focuses on quantifying and qualifying the European heat market. It was necessary to palliate the absence of data in Europe up to now. It is a pre-requisite before recommending a best market approach for the introduction and deployment of high temperature nuclear cogeneration, and estimating the market potential of this technology.

The dual approach of calculating the heat consumption indirectly from declared CO2 emissions and directly through a detailed analysis by industry sector has given coherent results and therefore makes it possible to draw robust conclusions.

1) The European heat market is large, ranging from 2 526 to 3 091 TWh/y, as compared to the 3 337 TWh/y of electricity production in Europe in 2007; this corresponds to an equivalent 289 to 353 GWth, as compared to an equivalent 381 GWe for electricity production
2) 25% to 30% of the market is externalised in the form of cogeneration, equivalent to 87 to 89 GWth; the remaining 70% to 75% is consumed in embedded process burners and boilers
3) The heat market is most significant at process temperatures below 550°C (60% to 66% of the heat market) and above 1 000°C (28% to 36% of the heat market)
4) The plug-in market (i.e. cogeneration plants) is restricted to temperatures below 550°C only
5) The main fuel for cogeneration today is natural gas, and combined cycle gas turbines are the reference technology for cogeneration
6) The average thermal capacity per site is 34 MWth for the “plug-in” market and 66 MWth for the “extended” market
7) Each sector has a very specific usage of its internal and external energy which demands a tailored energy supply; large consuming sectors are not necessarily the simplest ones to enter
8) The distribution of the European heat market by temperature may change in the future with the introduction of new industrial technologies operating at lower temperatures and with pre-heating which would supply a share of the energy consumed in high temperature processes
9) A competitive, low-carbon production of base raw materials, in particular hydrogen and oxygen, would be welcome by many industries; this would represent an additional polygeneration market.
10) Europe is an attractive market; it has a commercial experience in nuclear cogeneration and good industrial infrastructures with strong companies; and the European energy policy context is favourable to introducing new low-carbon competitive energies.
11) Europe has several industrially dense regions where several customers could be supplied with nuclear steam, electricity and/or base raw chemicals at the same time: Benelux, Western Germany, Northern and Southern France, Northern Italy, Northern Spain and Central UK. Isolated industrial clusters exist in Central and Eastern Europe.

4.2. The potential market of nuclear cogeneration

The plug-in, polygeneration and pre-heating markets could be supplied by nuclear cogeneration. The remaining extended market may be considered as impossible to supply in the medium term, except if a revolutionary technology is introduced in the heat end-user.

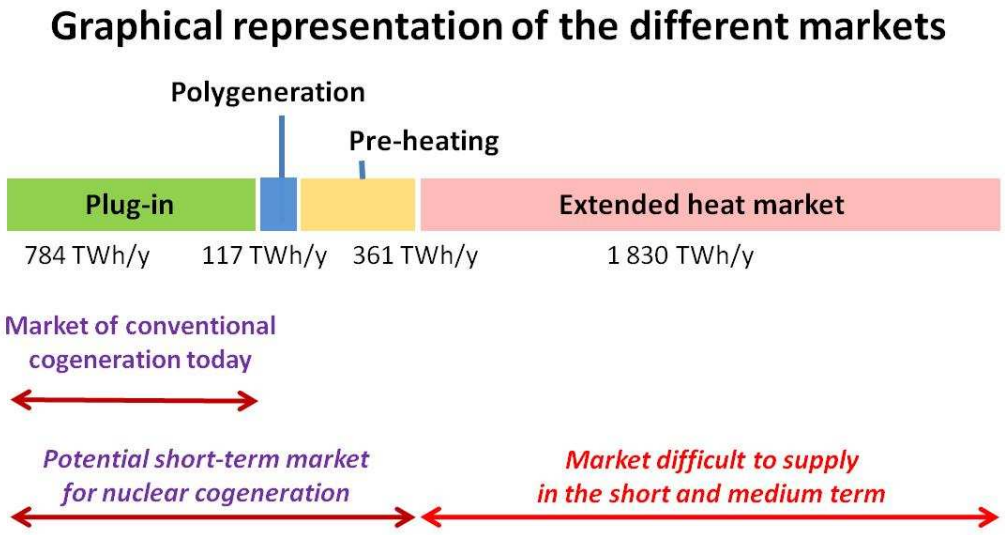


Figure 4.2-1 Graphical representation of the markets for conventional and nuclear cogeneration

As depicted in the figure above, the potential market for nuclear cogeneration is larger than the current market for cogeneration because of the higher steam output temperatures and the possibility to polygenerate base raw materials, in particular hydrogen, via production processes tailored to nuclear energy. Estimating this potential market has been the objective of this study.

A further analysis is required to determine the part of the market which would be technically and economically viable to supply with nuclear energy. All costs and benefits of nuclear energy must be balanced with the reference technology for cogeneration today (reactor engineering, construction, operation and financing costs, coupling development, adaptation to end-user processes, reengineering, safety and security measures, fuel cost neutrality, security of supply, CO2 emissions, etc.). The final demand would represent only a share of this economically viable market.

Considering the low average thermal capacities per site, especially for the plug-in market (34 MWth), the size of a high temperature reactor will determine the number of sites where it could fit. A large reactor of 500 MWth would have fewer customer sites and thus a lower probability to enter the market.

Alternatively, a large reactor could supply several individual customers, establishing an “industrial ecosystem”. However, a centralised heat production for several end-users may reveal technically and economically difficult to demonstrate and would add a further risk. A conceivable scheme would be to supply one large end-user and to use the excess heat for polygeneration.

4.3. Opportunities and challenges for the plug-in, polygeneration and pre-heating markets

The opportunities and challenges relative to each market are summarised in the table below:

Market	Opportunities	Challenges
Plug-in	– Good infrastructures available in Europe *cogeneration, back-up capacities and steam networks in place* – Operational compatibility of European industrial parks *long lifetime, experience of cogeneration, risk sharing, energy systems* – EU context favouring low-carbon energies *Climate policies and concerns on energy supply and costs* – Industrial density in several European regions – Sector specific opportunities	– End-users stringent operational requirements *flexibility, availability* – Low average thermal capacity installed per site – Nuclear acceptability, risks of contamination and safety demonstration – Industrial uncertainty over the long term *eroding competitiveness of the European industry, EU industrial policies* – Sector specific issues
Poly-generation	– On-site added value to nuclear heat – Economies of scale possible for large integrated production units – New markets accessible *H2: fuel cells, ammonia synthesis, iron reduction* *O2: existing market (today supplied by cryogenic ASU), clean coal technologies and H2 production* – Distant supply of final consumers via industrial gases pipelines *Europe operates the world's largest pipeline network and works toward a super European integrated network* – Ongoing R&D in Europe and worldwide making nuclear polygeneration realistic	– Production technologies still to be developed and demonstrated – Competitiveness against today's reference technologies (steam methane reformers, cryogenic air separation units...) to be proven – Safety of co-producing inflammable or explosive raw materials (e.g. hydrogen, oxygen, ammonia) to be demonstrated
Pre-heating	– Neutrality of many high temperature sectors towards the heating source – Heat and CO2 intensity of high temperature industries opening them to any competitive alternative energy – Several high temperature industries with sub-processes at low temperature classes	– Significant reengineering required – Economics of nuclear pre-heating, taking into account all costs and benefits, to be proven

Table 4.3-1 Opportunities and challenges by type of market

4.4. Engineering effort for adaptation and sector brief summaries

All industrial sectors have a specific energy usage although some common features can be observed: pulp and paper mills are often integrated, the chemical, soda ash, plastics, ammonia, petrochemical and oil refining sectors may have similar energy consumption patterns, lime and cement operate resembling processes. Sectors standing apart are ceramics, glass, non-ferrous metals and iron and steel.

In the plug-in market, steam production is clearly the first priority while electricity generation is the second. Indeed, whereas electricity can be drawn from the grid at any time, steam must be supplied by the cogeneration plant (or the back-up capacities). Steam production must therefore fit the end-users' demand at any time and whatever the variations.

The three main dimensions in the development of nuclear cogeneration are:

- Develop and size the nuclear reactor (core, materials, primary circuit...)
- Develop the coupling scheme (heat exchangers, steam turbines, electrical generators...) and ensure the quality and safety of steam supply (availability, flexibility, reactor trips, unexpected drop in end-users energy consumption, water management, contaminant removal, etc.)
- Possibly reengineer the end-users' processes to accommodate nuclear cogeneration (palliative measures against nuclear contamination, nuclear accidents / incidents, maintenance breaks...)

The two last bullets - and possibly the first one in relation to them - require an engineering effort which is mostly specific to the end-user sector. This effort is not only a matter of end-user process temperatures. It depends also on the way energy is consumed and the service quality required.

This effort may best be carried out in partnership with end-users or specialised engineering companies and consultancies.

This necessary engineering effort for adaptation by sector can be interpreted as a sector specific risk since the expected construction of reactors remains uncertain.

The heat market is therefore to be approached as a portfolio of sectors with a risk and a return.

The figure below maps graphically each industrial sector with its heat consumption against the maximum process temperature and the estimated engineering effort for introducing nuclear cogeneration.

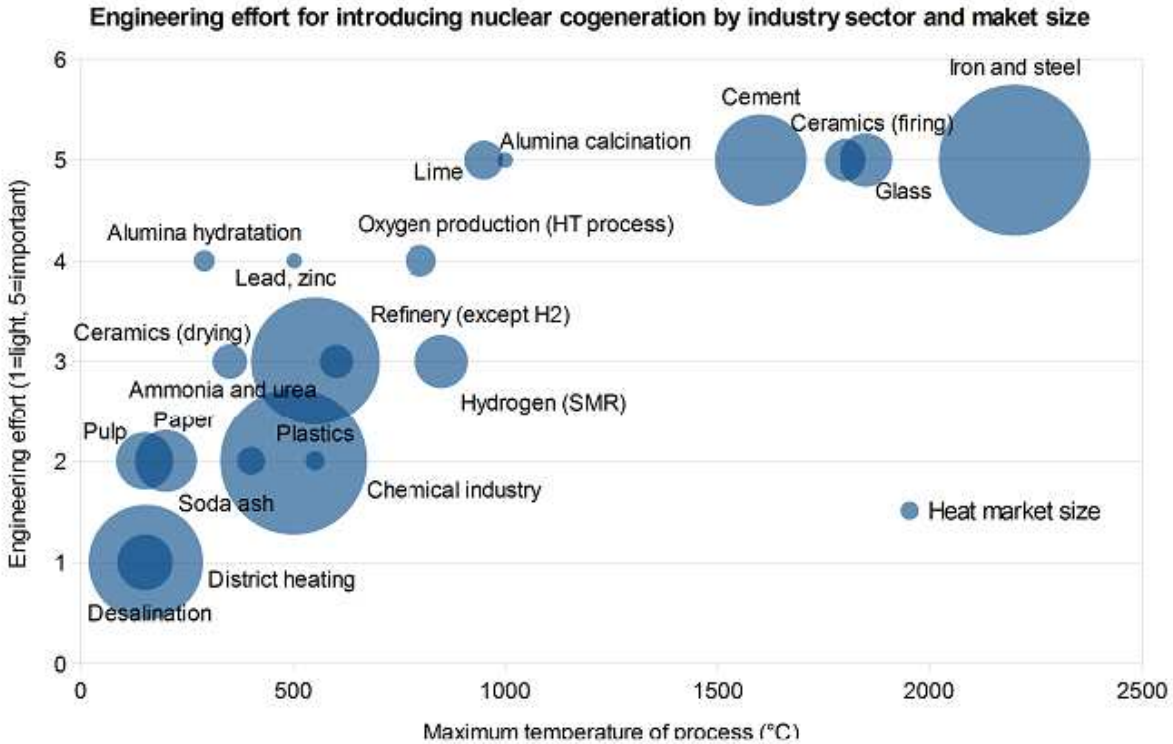


Figure 4.4-1 Engineering effort for introducing nuclear cogeneration by industry and heat consumption

The ranking of the engineering effort to adapt by sector, the effort and feature of the market segment, and the synthesis by sector are reported in the table below.

As regards the market feature, “uniform” means that several technologies can be employed in the sector but the implementation is rather generic; on the contrary, “site specific” indicates that each site is very specific not because one site operates one technology but because the production site is a complex set of many interrelated processes, which demands to approach the market site by site.

Sectors	PI	PG	PH	Effort / market feature	Short summary
Desalination and district heating	X			Proven / Uniform	Nuclear desalination and district heating are proven. Both are low temperature, low risk sectors which could be coupled with any nuclear reactor easily. District heating is a seasonal business. High temperature nuclear reactors could supply a larger region than current reactors. Nuclear acceptance would yet be an issue.
Pulp and paper	X			Feasible / Site specific	Heat for pulp production is mostly locked by biomass. Papermaking could be a low temperature, achievable market. Sudden unexpected web breaks in paper machines is an issue to be addressed.
Chemical industry, plastics, soda ash	X	X		Feasible / Site specific	The chemical industry is a large heat market, organised in clusters. Energy systems are well developed. Availability and load follow are key issues. The competitive polygeneration of industrial gases would be welcome by the industry. European clusters are well connected by gases pipelines. Within the chemical industry, soda ash could be a relevant early adopter.
Refineries	X	X		Feasible / Site specific	Oil refining is a large heat end-user. Most energy is yet derived from by-products. The economic rationale of cogeneration depends on local conditions (e.g. balance of calorific off-gases, economic incentives).
Industrial gases (H2, O2)		X		R&D phase / Uniform	Hydrogen production is a viable and potentially large market. The hydrogen economy is actively pursued in Europe. Hydrogen production by nuclear energy is under active research and looks realistic. Oxygen is a booming market. It is currently produced by cryogenic air distillation but high temperature processes are being developed and would create a new heat market if the high temperature membrane technology can compete with the cryogenic process..
Ammonia		X		Feasible / Uniform	Ammonia is the basis of N fertilisers, a market growing worldwide. Should nitrogen and hydrogen be produced competitively by nuclear energy, ammonia synthesis would resume to a phase of compression and reaction and would improve its competitiveness dramatically.
Ceramics			X	Feasible / Site specific	Ceramics drying is a low temperature, heat intensive process which aims at removing the moisture in just shaped ceramics before firing.
Lime			X	Possible? / Uniform	The lime production process aims at bringing limestone up to 900°C, when it naturally splits into lime and CO2. A high temperature nuclear reactor may pre-heat the limestone and decrease the consumption of fossil fuels.
Iron and steel		X	X	Possible? / Site specific	Iron and steel is a large heat and CO2 intensive sector. It would welcome the competitive production of syngas to replace coke. Air (or pure oxygen) could be pre-heated in hot stoves. Steel scraps could also be pre-heated in electric arc furnaces. HTRs may fit well in new production concepts.
Glassmaking		X	X	Possible? / Uniform?	Glassmaking is a heating neutral sector. It interestingly operates combined fossil fuel and electric heating processes and could probably accommodate a combined nuclear pre-heating, oxy-fuel combustion and nuclear electric heating boost.

Table 4.4-1 Feasibility, applicable market and short summary by sector

Each sector is very different but none can be definitively excluded from the list of potential customers of nuclear cogeneration. The risk, as defined above, ranks from low (desalination, district heating), medium-low (pulp and paper, chemical industry, oil refining, ammonia), medium high (industrial gases, ceramics) and high (lime, iron and steel, glassmaking).

4.5. Market approach

Three, mutually non-exclusive, strategies for entering the market may therefore exist with an increasing level of risk:

- Precautionary strategy: Enter the simplest sector - not automatically a large one - in order to demonstrate the feasibility of coupling a large-scale nuclear reactor with an industrial facility and deploy incrementally to other sectors with increasing difficulty
- Segment approach: Select and customise a cogeneration reactor for a large sector with many expected potential customers, which may require some upfront generic engineering to adapt and target all potential consumers in the sector before entering other sectors
- Aggressive strategy: Enter any sector interested in nuclear cogeneration, whatever the upfront adaptation engineering effort required

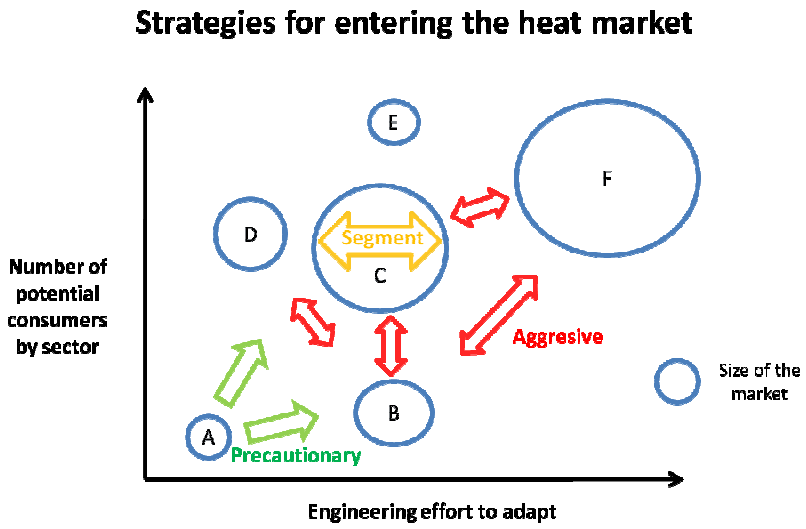


Figure 4.5-1 Strategies for entering the heat market

Early moving organisations will support nuclear cogeneration following the decision of prominent personality (e.g. CEO). This personalisation of the decision making implies that networking is key and that the support to nuclear cogeneration may only be temporary (e.g. the replacement of CEO may change the strategy).

Therefore, a mixed approach would probably be the best. A mixed approach could be to:

a) demonstrate in the short term the coupling of a large-scale high temperature reactor with an accessible sector (e.g. desalination, soda ash) so the experience feedback will probably be encouraging and supports the marketing in other sectors
b) network and identify prominent personalities in heat end-users susceptible to adopt nuclear cogeneration
c) develop in parallel a plant adapted to a large market segment with many potential customers and several early adopters (e.g. chemical clusters) and build on the first experience to market new reactors

4.6. Technology competition

Nuclear cogeneration will compete with gas cogeneration. It must be noted that gas is the reference technology and has many competitive advantages:

- The technology is proven and has a long operational experience
- Gas cogeneration plants can be sized from 10 to several 100s of MWth
- Capital costs are low and the amortization period is short
- Operating costs depend mainly on fuel costs; the discovery of shale gas in the United States and the development of liquefied natural gas are expected to regulate the gas prices downwards and to increase the European security of supply in the next decades
- Natural gas has a low CO2 content and cogeneration is supported in many European Member States in a way which limits the impact of emissions reduction targets (since cogeneration is considered as a measure for energy efficiency).
- Gas cogeneration plants demonstrate low safety issues, high flexibility and high availability since maintenance breaks do not require to stop totally the steam production (gas can be burnt in the gas turbine, heating the steam boilers or directly in any of the steam boilers when the other parts of the plant are maintained).
- Heat end-users' steam networks are already adapted to gas cogeneration.

In some sectors, like oil refining, the excellent operational feedbacks from gas cogeneration are even not sufficient to prove the economic rationale of installing a cogeneration plant so they may have to be completed by economic or fiscal incentive schemes, which depend on each Member States.

Nuclear cogeneration will therefore enter a very competitive market. It will have to demonstrate in all cases its competitive advantage as compared to gas cogeneration, while managing the regulatory context for nuclear safety, radiological protection, in addition to the general cogeneration regulatory framework.

A final remark, it must be noted that in most sectors (as it is the case in nuclear energy), heat end-users are operators only. Technology providers are different organizations, which develop the design of the industrial facilities and possibly manage their construction. In particular, they own the intellectual property rights of the production machines. These stakeholders are therefore important for the deployment of nuclear cogeneration.

4.7. Recommendations

Based on the conclusions and the remarks above, a list of general recommendations is suggested to support the development and deployment of high temperature nuclear cogeneration in Europe.

Detailed recommendations by sector can be found in the related sub-chapters of chapter 3.

1. Liaise with organisations having an operational experience in nuclear cogeneration (in Europe, Canada, Russia, Japan, Kazakhstan) and with the International Atomic Energy Agency in order to benefit from their experience feedback

2. Focus in the short term on the market below 550°C, where the “plug-in” market concentrates

3. Limit the reactor thermal capacity (to a few hundred MWth) to increase the number of potential customers

4. Identify prominent personalities in heat end-user industries susceptible to adopt nuclear cogeneration and determine a structured market approach (precautionary, segment, aggressive)

5. Launch a detailed analysis for each priority segment in order to identify the most relevant sites (size compatibility, flat consumption, long-term industrial visibility, balance of calorific off-gases or by-products, cogeneration plant to be replaced, nuclear acceptance, water availability...)

6. Trigger potential synergies with the technological development carried out in industrial sectors (e.g. steel, industrial gases), coordinate with ongoing RD&D initiatives and possibly launch common projects

7. Partner with industrial gases producers and research organisations to develop hydrogen and air gases production technologies and the coupling with a nuclear reactor, as polygeneration may offer many advantages in terms of siting, acceptance, coupling, economics, and large-scale heat consumption

8. Analyse the regulatory, economic and fiscal contexts for cogeneration and nuclear energy in relevant Member States in order to identify potential host countries for nuclear cogeneration

9. Develop the business case of nuclear cogeneration in order to prove the competitiveness of the technology in each priority market segment (against the reference technology)

10. Identify early potential adopters, specialised engineering companies and consultancies in each sector and collaborate to develop technically and economically the coupling concepts; relevant professional associations, European Technology Platforms and European R&D projects should also be approached

11. Investigate the potential of nuclear pre-heating with a detailed sector analysis, in particular for glassmaking, iron and steel, and lime

Annexes

Annex 1 List of sectors of the Emissions Trading Scheme

	Description of NACE code	No of sites	Emissions verified 2007 (CO2eq)	Included in the market study?
1.11	Growing of cereals and other crops n.e.c.	2	15 379	
1.12	Growing of vegetables, horticultural specialities and nursery products	112	479 786	
1.24	Farming of poultry	1	43 835	
5.02	Fish farming	3	83 502	
10.1	Mining and agglomeration of hard coal	7	170 941	
10.3	Extraction and agglomeration of peat	2	114 639	
11.1	Extraction of crude petroleum and natural gas	178	14 228 975	
11.2	Service activities incidental to oil and gas extraction, excluding surveying	12	230 353	
12	Mining of uranium and thorium ores	1	6 596	
13.1	Mining of iron ores	2	34 388	
14.1	Quarrying of stone	1	11 359	
14.22	Mining of clays and kaolin	3	132 891	
14.3	Mining of chemical and fertilizer minerals	2	164 901	
14.4	Production of salt	5	169 282	X
14.5	Other mining and quarrying n.e.c.	3	38 933	
15	Manufacture of food products and beverages	14	154 074	
15.1	Production, processing and preserving of meat and mea products	2	8 796	
15.11	Production and preserving of meat	26	352 353	
15.12	Production and preserving of poultrymeat	2	19 881	
15.13	Production of meat and poultrymeat products	17	131 240	
15.2	Processing and preserving of fish and fish products	6	94 070	
15.3	Processing and preserving of fruit and vegetables	7	68 192	
15.31	Processing and preserving of potatoes	13	203 730	
15.32	Manufacture of fruit and vegetable juice	17	312 808	
15.33	Processing and preserving of fruit and vegetables n.e.c.	55	623 037	
15.4	Manufacture of vegetable and animal oils and fats	1	6 793	
15.41	Manufacture of crude oils and fats	25	427 012	
15.42	Manufacture of refined oils and fats	29	1 073 902	
15.43	Manufacture of margarine and similar edible fats	5	62 785	
15.5	Manufacture of dairy products	1	4 698	
15.51	Operation of dairies and cheese making	90	2 119 412	

15.61	Manufacture of grain mill products	6	108 062	
15.62	Manufacture of starches and starch products	34	1 737 722	
15.71	Manufacture of prepared feeds for farm animals	15	143 128	
15.72	Manufacture of prepared pet foods	5	46 625	
15.81	Manufacture of breadmanufacture of fresh pastry goods and cakes	1	7 382	
15.82	Manufacture of rusks and biscuits,manufacture of preserved pastry goods and cakes	1	12 357	
15.83	Manufacture of sugar	151	8 948 217	
15.84	Manufacture of cocoa,chocolate and sugar confectionery	14	118 070	
15.85	Manufacture of macaroni, noodles, couscous and similar farinaceous products	5	77 061	
15.86	Processing of tea and coffee	11	176 493	
15.87	Manufacture of condiments and seasonings	2	19 721	
15.88	Manufacture of homogenized food preparations and dietetic food	7	121 624	
15.89	Manufacture of other food products n.e.c.	20	321 688	
15.9	Manufacture of beverages	4	32 200	
15.91	Manufacture of distilled potable alcoholic beverages	17	199 014	
15.92	Production of ethyl alcohol from fermented materials	6	443 851	
15.93	Manufacture of wines	1	108 004	
15.94	Manufacture of cider and other fruit wines	1	3 915	
15.95	Manufacture of other non-distilled fermented beverages	2	11 519	
15.96	Manufacture of beer	72	857 907	
15.97	Manufacture of malt	7	79 594	
15.98	Production of mineral waters and soft drinks	6	42 315	
16	Manufacture of tobacco products	6	65 788	
17	Manufacture of textiles	2	12 557	
17.1	Preparation and spinning of textile fibres	5	44 761	
17.11	Preparation and spinning of cotton-type fibres	3	38 550	
17.13	Preparation and spinning of worsted-type fibres	1	53 893	
17.14	Preparation and spinning of flax-type fibres	1	3 360	
17.17	Preparation and spinning of other textile fibres	1	8 609	
17.2	Textile weaving	5	72 164	

17.21	Cotton-type weaving	4	53 806	
17.23	Worsted-type weaving	1	5 108	
17.24	Silk-type weaving	2	26 711	
17.25	Other textile weaving	2	24 078	
17.3	Finishing of textiles	27	331 946	
17.4	Manufacture of made-up textile articles, except apparel	4	33 998	
17.5	Manufacture of other textiles	2	40 923	
17.51	Manufacture of carpets and rugs	5	30 183	
17.53	Manufacture of non-wovens and articles made from nonwovens, except apparel	2	58 351	
17.54	Manufacture of other textiles n.e.c.	4	23 230	
17.6	Manufacture of knitted and crocheted fabrics	1	4 882	
17.72	Manufacture of knitted and crocheted pullovers, cardigans and similar articles	2	10 323	
18.22	Manufacture of other outerwear		2) 8 781	
19.1	Tanning and dressing of leather	2	7 479	
20.1	Sawmilling and planing of wood,impregnation of wood	19	215 108	X
20.2	Manufacture of veneer sheets,manufacture of plywood, laminboard, particle board, fibre board and other panels and boards	92	1 978 710	X
20.3	Manufacture of builders' carpentry and joinery	6	64 892	
20.41	NACE code does not exist	2	61 522	
20.5	Manufacture of other products of wood, manufacture of articles of cork, straw and plaiting materials	1	-	
20.51	Manufacture of other products of wood	4	120 648	
20.52	Manufacture of articles of cork, straw and plaiting materials	1	3 402	
21.1	Manufacture of pulp, paper and paperboard	1	11 611	X
21.11	Manufacture of pulp	1	137 063	X
21.12	Manufacture of paper and paperboard	21	1 621 306	X
21.21	Manufacture of corrugated paper and paperboard and of containers of paper and paperboard	6	263 633	X
21.22	Manufacture of household and sanitary goods and of toilet requisites	5	120 549	

21.25	Manufacture of other articles of paper and paperboard n.e.c.	1	190	
22.13	Publishing of journals and periodicals	2	38 192	
22.21	Printing of newspapers	1	11 396	
22.22	Printing n.e.c.	8	187 572	
23.1	Manufacture of coke oven products	3	658 870	X
23.2	Manufacture of refined petroleum products	22	787 352	X
23.3	Processing of nuclear fuel	3	59 790	
24	Manufacture of chemicals and chemical products	1	-	
24.1	Manufacture of basic chemicals	5	940 379	X
24.11	Manufacture of industrial gases	3	484 098	X
24.12	Manufacture of dyes and pigments	6	551 200	
24.13	Manufacture of other inorganic basic chemicals	36	4 798 232	X
24.14	Manufacture of other organic basic chemicals	81	10 769 424	X
24.15	Manufacture of fertilizers and nitrogen compounds	27	3 682 877	X
24.16	Manufacture of plastics in primary forms	24	1 241 678	X
24.17	Manufacture of synthetic rubber in primary forms	1	-	
24.2	Manufacture of pesticides and other agro-chemical products	5	104 162	
24.3	Manufacture of paints, varnishes and similar coatings, printing ink and mastics	2	15 008	
24.4	Manufacture of pharmaceuticals, medicinal chemicals and botanical products	1	6 019	
24.41	Manufacture of basic pharmaceutical products	32	444 417	
24.42	Manufacture of pharmaceutical preparations	39	683 292	
24.5	Manufacture of soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	1	15 326	
24.51	Manufacture of soap and detergents, cleaning and polishing preparations	7	451 735	
24.52	Manufacture of perfumes and toilet preparations	2	53 695	
24.61	Manufacture of explosives	3	56 292	
24.62	Manufacture of glues and gelatines	7	113 685	
24.64	Manufacture of photographic chemical material	1	48 080	
24.65	Manufacture of prepared unrecorded media	1	2 772	

24.66	Manufacture of other chemical products n.e.c.	21	671 407	
24.7	Manufacture of man-made fibres	17	1 114 865	X
25.1	Manufacture of basic chemicals	2	4 795	
25.11	Manufacture of rubber tyres and tubes	25	969 351	
25.12	Retreading and rebuilding of rubber tyres	1	48 160	
25.13	Manufacture of other rubber products	7	141 312	
25.2	Manufacture of pesticides and other agro-chemical products	2	31 081	
25.21	Manufacture of plastic plates, sheets, tubes and profiles	7	109 743	
25.22	Manufacture of plastic packing goods	6	210 391	
25.23	Manufacture of builders' ware of plastic	1	4 631	
25.24	Manufacture of other plastic products	5	49 874	
26.12	Shaping and processing of flat glass	1	12 184	X
26.13	Manufacture of hollow glass	1	17 815	X
26.14	Manufacture of glass fibres	1	35 413	X
26.22	Manufacture of ceramic sanitary fixtures	1	23 623	X
26.23	Manufacture of ceramic insulators and insulating fittings	1	7 682	X
26.25	Manufacture of other ceramic products	2	11 271	X
26.26	Manufacture of refractory ceramic products	3	454	X
26.4	Manufacture of bricks, tiles and construction products, in baked clay	1	3 299	X
26.51	Manufacture of cement	1	2 473	X
26.61	Manufacture of concrete products for construction purposes	2	9 829	X
26.7	Cutting, shaping and finishing of ornamental and building stone	1	8 775	
26.81	Production of abrasive products	1	3 021	
26.82	Manufacture of other non-metallic mineral products n.e.c.	35	2 995 482	X
27.1	Manufacture of basic iron and steel and of ferro-alloys	38	18 622 588	X
27.22	Manufacture of steel tubes	5	5 227	
27.32	Cold rolling of narrow strip	1	33 336	X

27.34	Wire drawing	1	7 253	
27.42	Aluminium production	9	313 841	X
27.43	Lead, zinc and tin production	2	26 021	X
27.44	Copper production	1	9 653	X
27.45	Other non-ferrous metal production	1	1 446 979	X
27.51	Casting of iron	3	60 569	X
27.54	Casting of other non-ferrous metals	1	13 617	X
28.11	Manufacture of metal structures and parts of structures	2	14 261	
28.22	Manufacture of central heating radiators and boilers	1	47 510	
28.3	Manufacture of steam generators, except central heating hot water boilers	4	16 186	
28.4	Forging, pressing, stamping and roll forming of metal powder metallurgy	4	63 540	
28.51	Treatment and coating of metals	4	15 491	
28.63	Manufacture of locks and hinges (the emissions of one of 4 installations is disproportionally large suggesting that it is wrongly classified)	4	4 618 609	
28.7	Manufacture of other fabricated metal products	3	15 876	
28.75	Manufacture of other fabricated metal products n.e.c.	2	78 430	
29.11	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	7	38 657	
29.13	Manufacture of taps and valves	2	23 824	
29.14	Manufacture of bearings, gears, gearing and driving elements	3	36 666	
29.2	Manufacture of other general purpose machinery	3	11 138	
29.22	Manufacture of lifting and handling equipment	3	47 390	
29.23	Manufacture of non-domestic cooling and ventilation equipment	1	20 884	
29.24	Manufacture of other general purpose machinery n.e.c.	3	17 175	
29.31	Manufacture of agricultural tractors	1	9 590	
29.32	Manufacture of other agricultural and forestry machinery	2	6 666	
29.5	Manufacture of other special purpose machinery	1	27 951	

29.52	Manufacture of machinery for mining, quarrying and construction	4	16 186	
29.54	Manufacture of machinery for textile, apparel and leather production	1	28 316	
29.6	Manufacture of weapons and ammunition	11	165 321	
29.7	Manufacture of domestic appliances n.e.c.	1	6 051	
29.71	Manufacture of electric domestic appliances	4	32 586	
30.02	Manufacture of computers and other information processing equipment	1	3 021	
31.1	Manufacture of electric motors, generators and transformers	3	73 032	
31.2	Manufacture of electricity distribution and control apparatus	4	15 099	
31.3	Manufacture of insulated wire and cable	3	18 180	
31.5	Manufacture of lighting equipment and electric lamps	1	7 204	
31.6	Manufacture of electrical equipment n.e.c.	1	6 030	
31.61	Manufacture of electrical equipment for engines and vehicles n.e.c.	3	35 324	
31.62	Manufacture of other electrical equipment n.e.c.	2	3 134	
32.1	Manufacture of electronic valves and tubes and other electronic components	8	162 459	
32.3	Manufacture of television and radio receivers, sound or video recording or reproducing apparatus and associated goods	2	6 567	
34.1	Manufacture of motor vehicles	64	1 329 004	
34.2	Manufacture of bodies (coachwork) for motor vehicles, manufacture of trailers and semi-trailers	2	26 917	
34.3	Manufacture of parts and accessories for motor vehicles and their engines	18	178 264	
35	Manufacture of other transport equipment	1	2 578	
35.11	Building and repairing of ships	5	15 732	
35.2	Manufacture of railway and tramway locomotives and rolling stock	11	112 886	
35.3	Manufacture of aircraft and spacecraft	21	157 281	
35.41	Manufacture of motorcycles	2	21 278	
35.5	Manufacture of other transport equipment n.e.c.	1	5 058	
36.4	Manufacture of sports goods	1	2 907	
36.6	Miscellaneous manufacturing n.e.c.	1	-	
36.63	Other manufacturing n.e.c.	2	21 719	
37.2	Recycling of non-metal waste and scrap	1	10 210	X

40	Electricity, gas, steam and hot water supply	145	53 321 630	X
40.1	Production and distribution of electricity	184	62 248 967	
40.11	Production of electricity	990	1 059 446 622	
40.12	Transmission of electricity	1	52 602	
40.13	Distribution and trade of electricity	6	347 464	
40.2	Manufacture of gas,distribution of gaseous fuels through mains	2	71 406	
40.21	Manufacture of gas	39	1 089 599	
40.22	Distribution and trade of gaseous fuels through mains	62	2 017 781	
40.3	Steam and hot water supply	2192	129 359 714	X
41	Collection, purification and distribution of water	7	43 646	
45.21	General construction of buildings and civil engineering works	1	-	
45.23	Construction of motorways, roads, airfields and sport facilities	5	12 477	
45.25	Other construction work involving special trades	3	8 104	
45.34	Other building installation	1	3 950	
51.34	Wholesale of alcoholic and other beverages	1	4 216	
51.51	Wholesale of solid, liquid and gaseous fuels and related products	1	-	
51.52	Wholesale of metals and metal ores	1	-	
51.53	Wholesale of wood, construction materials and sanitary equipment	1	117 118	
51.9	Other wholesale	1	12 259	
55.1	Hotels	1	2 252	
60.1	Transport via railways	4	33 310	
60.22	Taxi operation	1	16 173	
60.3	Transport via pipelines	42	849 083	
62.1	Scheduled air transport	3	29 473	
63.1	Cargo handling and storage	1	26 783	
63.11	Cargo handling	1	3 736	
63.12	Storage and warehousing	8	37 032	
63.23	Other supporting air transport activities	8	141 931	
65.12	Other monetary intermediation	2	781	
65.23	Other financial intermediation n.e.c.	1	801	

67.13	Activities auxiliary to financial intermediation n.e.c.	1	517	
70.11	Development and selling of real estate	1	38 883	
70.2	Letting of own property	4	26 486	
70.32	Management of real estate on a fee or contract basis	11	207 330	
73.1	Research and experimental development on natural sciences and engineering	2	18 884	
74.11	Legal activities	1	-	
74.8	Miscellaneous business activities n.e.c.	2	-	
74.82	Miscellaneous business activities n.e.c.	1	36 951	
74.87	Other business activities n.e.c.	3	34 249	
75.12	Regulation of the activities of agencies that provide health care, education, cultural services and other social services, excluding social security	2	43 855	
75.22	Defence activities	9	90 703	
80.3	Higher education	16	296 759	
85.11	Hospital activities	78	845 112	
90.01	Collection and treatment of sewage	5	44 054	
90.02	Collection and treatment of other waste	8	239 676	
91.31	Activities of religious organizations	1	9 498	
92.2	Radio and television activities	2	6 142	
	TOTAL	5 899	1 412 804 882	
	Total of selected sectors	2 806	235 212 171	

Annex II: refinery sector

Distribution of technologies by application (BREF 2003b)

Process		Technique used	%
Coking		Delayed coking	82%
		Other	18%
		Fluid coking	0%
Thermal operations		Visbreaking	82%
		Thermal cracking	18%
Catalytic cracking		Fluid	94%
		Other	6%
Catalytic reforming		Semiregenerative	55%
		Continous regenerative	27%
		Cyclic	14%
		Other	4%
Catalytic hydrocracking	Used for	Distillate upgrading	68%
		Other	27%
		Residual upgrading	5%
		Lube oil manufacturing	0%
	Severity	*conventional*	64%
		mild to moderate hydrocracking	36%
Catalytic hydrorefining (*)		mid distillate	46%
		Heavy gas oil desulfurisation	32%
		catalytic cracker and cycle stock treatment	13%
		Residual desulfurization	6%
		Other	3%
Catalytic hydrotreating (*)		Naphtha desulfurizing	28%
		Straight-run distillate	24%
		Pretreatment cat reformer feeds	24%
		Lube oil "polishing"	7%
		Naphtha olefin or aromatic saturation	5%
		Other distillates	5%
		Other	5%
		Pretreating cat cracker feeds	3%
Alkylation		hydrofluoric acid	77%
		sulphuric acid	20%
		Other	3%
Polymerisation Dimerisation		Polymerisation	79%
		Dimerisation	21%
Aromatics (*)		BTX	59%
		Hydrodealkylation	28%
		Cyclohexane	10%
		Cumene	3%
Isomerization		C5 and C6 feed	80%
		C5 feed	11%
		C4 feed	9%
Etherification		MTBE	79%
		TAME	11%
		ETBE	7%
		Other	4%
Hydrogen	Production	Steam methane reforming	57%
		Steam naphtha reforming	32%
		Partial oxidation	11%
	Recovery	*Pressure swing adsorption*	52%
		Membrane	29%
		Cryogenic	19%

Capacity of the various processes in EU refineries (BREF 2003b)

Process	Maximum	Average	Minimum
	Charge capacity, Mm^3/yr		
Crude	23.21	7.96	0.46
Vacuum distillation	10.73	3.03	0.26
Coking	3.95	1.72	0.78
Thermal operations	3.50	1.45	0.39
Catalytic cracking	5.22	2.33	0.52
Catalytic reforming	3.08	1.26	0.08
Cat hydrocracking	3.77	1.63	0.05
Cat hydrorefining	6.96	1.48	0.23
Cat hydrotreating	8.01	1.78	0.02
	Production capacity, Mm^3/yr		
Alkylation	1.89	0.45	0.14
Pol./Dim.	0.67	0.22	0.02
Aromatics	1.49	0.36	0.04
Isomerization	1.18	0.55	0.11
Base Oil production	1.03	0.33	0.03
Etherification	0.50	0.11	0.01
Hydrogen (MNm^3/day)	3.23	1.54	0.003
Coke (t/d)	2300	869	173
Sulphur (t/d)	650	130	2
Bitumen	1.16	0.41	0.07
For definitions of processes see bottom of Table 1.2 in pg. 4			

Number and type of refinery processes by country (BREF 2003b)

Country	Number of refineries	Crude	Vacum distillation	Coking	Thermal operations	Catalytic cracking	Catalytic reforming	Catalytic hydrocraking	Catalytic hydrorefining	Catalytic hydrotreating
Austria	1	2	2		1	1	2	2	3	2
Belgium	5	5	4		2	2	4		3	5
Denmark	2	2	1		2		2		1	3
Finland	2	3	5		2	2	2	1	6	8
France	15	14	14		8	12	14	1	7	29
Germany	17	14	15	5	10	9	18	5	14	28
Greece	4	6	4		2	2	4	1	5	11
Ireland	1	1					1		1	1
Italy	17	17	15	1	15	7	18	6	13	26
Netherlands	6	6	6	1	4	2	5	3	1	15
Norway	2	2		1	1	1	3		2	5
Portugal	2	2	2		1	1	3	1	1	6
Spain	10	10	10	2	5	6	9	1	25	17
Sweden	5	5	4		2	1	3	1	3	7
Switzerland	2	2	1		2		2	1	1	4
UK	13	10	11	1	3	7	9	1	7	13
EU+	**104**	**101**	**94**	**11**	**60**	**53**	**99**	**24**	**93**	**180**

Country	Number of refineries	Alkylation	Polymerisation Dimerisation	Aromatics	Isomerization	Base Oil production	Etherification	Hydrogen	Coke	Sulphur	Bitumen
Austria	1				1		2			1	1
Belgium	5	2	1		1		1	2		4	3
Denmark	2				1						1
Finland	2	1	1	1		1	2	1		3	4
France	15	4	2	2	7	5	4	4	3	6	6
Germany	17	3	2	13	6	5	5		4	10	9
Greece	4	1	2		3	1	2	5		3	2
Ireland	1									1	
Italy	17	6	1	4	12	2	5	11	1	7	5
Netherlands	6	2		1	2	2	2	4		3	3
Norway	2		1		1				1	1	
Portugal	2	1		1						1	
Spain	10	3		5	2	4	5	7	2	18	7
Sweden	5		1		3	1		3		4	2
Switzerland	2				2						1
UK	13	6	3	3	4	4	2	2	1	4	7
EU+	**104**	**29**	**14**	**30**	**45**	**25**	**30**	**39**	**12**	**66**	**51**

European refineries by configuration and country

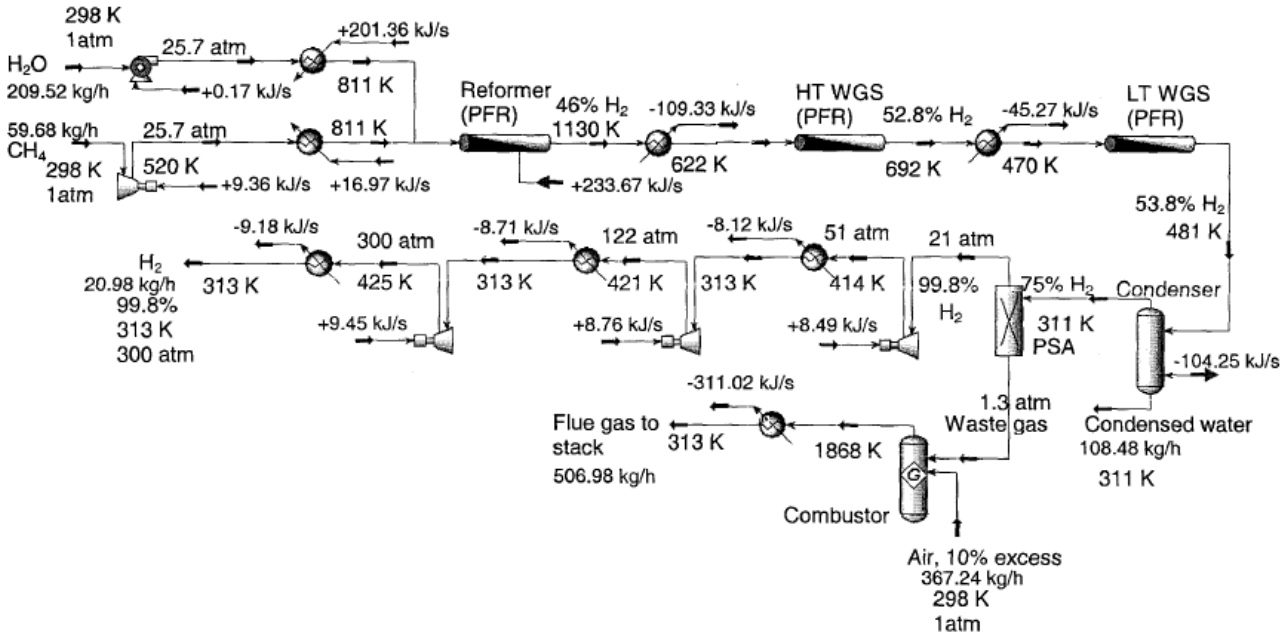
COUNTRY	No. refineries	Base oil and bitumen refineries	Configuration 1 hydroskimming + isomerisation Unit	Configuration 2 catcracker configuration	Configuration 3 hydrocracker configuration	Configuration 4 very complex refinery with catcracking
Austria	1			1		
Belgium	5		1	2	1	1
Denmark	2		2			
Finland	2			1		1
France	15		4	10		1
Germany	17	3	2	8	3	1
Greece	4		2	1		1
Ireland	1		1			
Italy	17		6	4	4	3
Netherlands	6	1	1	1	2	1
Norway	2		1	1		
Portugal	2		1		1	
Spain	10	1	2	6	1	
Sweden	5	2	2			1
Switzerland	2		1		1	
UK	13	3		7	1	2
TOTAL	104	10	26	42	14	12

Process consumption of fuel, electricity, steam consumed and produced, CO2 emissions and H2 consumption

	Fuel (MJ/t)			Electricity consumed (kWh/t)			Steam consumed (kg/t)			Steam produced (kg/t)			CO2 emission (kg/t)			H2 consumption (kg/t)		
	Min	Max	Ave.	Min	Max	Ave.	Min	Max	Ave.	Min	Max	Ave.	Min	Max	Ave.	Min	Max	Aver age
Crude distillation	400	680	**540**	4	6	**5**	25	30	**28**			-	26	36	**31**			-
Vacuum distillation	400	800	**600**	2	5	**3**	20	60	**40**			-	31	41	**36**			-
Coking	800	1 200	**1 000**	20	30	**25**	50	60	**55**	50	125	**88**			-			-
Thermal opeartions	400	800	**600**	10	15	**13**	5	30	**18**			-	17	50	**33**			-
Catalytic cracking	120	2 000	**1 060**	8	50	**29**	30	90	**60**	40	60	**50**	207	212	**210**			-
Catalytic reforming	1 400	2 900	**2 150**	25	50	**38**			-			-	133	146	**140**			-
Catalytic hydrocracking	400	1 200	**800**	20	110	**65**			-	30	300	**165**			-	23	36	**31**
Catalytic hydrorefining	300	500	**400**	10	30	**20**	60	150	**105**			-	10	36	**23**	1	12	**6**
Catalytic hydrotreating	300	500	**400**	10	30	**20**	60	150	**105**			-	10	36	**23**	1	12	**6**
Alkylation	1 000	3 000	**2 000**	20	65	**43**	100	1 000	**550**			-			-			
Polymrisation			-	20	28	**24**	1	1	**1**			-			-			
Aromatics	862	862	**862**	5	5	**5**	8	8	**8**			-			-			
Isomerisation			-	20	30	**25**	300	600	**450**			-			-			
Base oil	490	540	**515**	44	76	**60**	166	900	**533**			-			-			
Etherification			-	12	20	**16**	1 000	2 000	**1 500**			-			-			
Hydrogen	35 000	80 000	**57 500**	200	800	**500**	2 000	8 000	**5 000**			-	710	710	**710**			
Coke			-			-			-			-			-			
Sulphur			-			-			-			-			-			
Bitumen			-	15	35	**25**			-	100	200	**150**			-			

Annex III: Hydrogen production

Process description for Steam Methane Reforming (source: Posada and Manousouthakis)



Annex IV: Aluminium production

Typical plant, process and parameters for secondary aluminium smelting plants

Parameter	Unit	Rotary drum furnace	Tilting rotary furnace	Closed well or Hearth furnaces			Blast furnaces	Crucible furnaces (a) fuel-heated, (b) resistance-heated, (c) inductively heated	Channel induction furnace
				Single chamber		Multiple-chamber, hearth furnace with melting bridge			
Preferred application		Secondary aluminium	Secondary aluminium	Generation of Secondary aluminium, foundries		Generation of secondary aluminium	Moulding shops	Moulding shops	secondary aluminium
Purpose		Melting	Melting	Melting	Holding, casting	Melting	Melting, holding	Melting (M), holding (H)	Melting (M), Holding (H)
Preferred feedstock		New scrap (thin-walled, in small pieces), old scrap, dross	Old scraps, dross	Ingots, old scrap, new scrap	Molten metal	Thin-walled new/old scraps (painted/coated)	Ingots, new scraps, (recycled material)	Ingots, new scrap	Ingots, new scraps, old scraps
Preferred melt treatment		Salt flux	Salt flux	Flux cover, chlorination		Fluxcover	Salt cover	Flux cover	Flux cover, chlorination
Capacity	t	Up to 150	Up to 30	Up to 180		Up to 180	0.5 - 4 (possibly up to 15)	0.1 - 0.6 (b), 0.5 - 6 (c), 0.1 - 1.2 (a)	Approx. 50
Melting efficiency	t feedstock/h	Up to 20	Up to 7	Up to 30	-	3 - 28	Up to 2.5 (typically 1.5)	0.075 - 0.26 (b), 0.25 - 3 (c), 0.1 - 0.43 (a)	Approx. 7 (melting efficiency)
Preferred fuels		Natural gas, light fuel oil, medium/heavy fuel oil	Natural gas, extra-light fuel oil	Natural gas, extra-light fuel oil		Natural gas, extra-light fuel oil	Natural gas, extra-light fuel oil	Natural gas, extra-light fuel oil or electrically heated	Electrically heated
Energy use [b])	GJ/t metal	2 - 4.7	2 - 2.5	2.5 - 4.4	No details	2.4 - 4.3	2.1 - 3.3 (depending on the mode of operation)	5.1 - 7.4 (M, a), 1.7 - 3.5 (H, a), 2.7/1.9 - 2.1 (M, b/c), 0.4/0.9 - 1.2 (H, b/c)	Approx. 3.6 (M/H)
Waste gas rate [c])	m³/t metal	9000 - 18000,	9000 - 13000,	5000 - 13000	No details	10000 - 15000	2000 - 4000	2000 - 4000 (M, a)	Max. 14500
Dust generation [a])		+++	+++	++	+	++	N.R.	N.R.	+
Nitrogen oxides [a, c])		+ (Assuming optimised combustion conditions), ++ (For fuel/oxygen-heated furnaces)						N.R.	N.R.

Annex V: Pulp and paper production

Average energy consumption for the production of 243 000 air dried ton of unbleached Kraft pulp and an integrated production of 250 000 t/a paperboard (source: BREF 2001f)

Department	Process heat [MJ/t]	Electric power [kWh/t]
Wood handling	200	45
Cooking	1700	64
Washing and screening	0	45
Evaporation	4000	21
Recovery boiler	600	48
Auxiliary boiler	0	23
Causticizing	0	14
Lime kiln	1500	7
Miscellaneous, pulp mill	2600	133
Total pulp mill	**10600**	**400**
Stock preparation	0	200
Paper machine	5800	350
Total paper mill	**5800**	**550**
Effluent treatment	**0**	**9**
Total per tonne of paper	**16400**	**959**

Energy balance for the production of 243000 ADt/a unbleached Kraft pulp, and integrated production of 250000 t/a paperboard (source: BREF 2001f)

Department	Process heat [MJ/t]	Electricity [kWh/t]
Pulp mill		
Recovery boiler, process steam	+14500	
Auxiliary boiler, process steam (only own bark)	+2050	
Turbine generator	-2050	+571
External supply (heat for lime kiln)	+1500	0
Consumption (including lime kiln)	-10600	-400
Effluent treatment	0	-9
Excess energy from pulp mill	**+5400**	**+162**
Paper mill		
Consumption	-5400	-550
External supply	0	+388
Total external supply	**1500**	**388**

Energy consumption for non-integrated 250000 ADt/a bleached Kraft pulp (source: BREF 2001f)

Department	Process heat [MJ/ADt]	Electric power [kWh/ADt]
Wood handling	150	55
Cooking	2050	65
Washing and screening	0	55
Oxygen delignification	400	45
Bleaching	500	83
Bleach chemical preparation	70	6
Bleached stock screening	0	40
Pulp drying	2850	105
Evaporation	4100	30
Recovery boiler	610	60
Power boiler	0	30
Causticizing	0	20
Lime kiln (direct heat)	1500	10
Miscellaneous, pulp mill	2170	136
Total pulp mill	**14400**	**740**
Effluent treatment	**0**	**20**
Total per ADt of pulp	**14400**	**760**

Energy balance for non-integrated 250000 ADt/a bleached Kraft pulp (source: BREF 2001f)

Department	Process heat [MJ/ADt]	Electric power, [kWh/ADt]
Recovery boiler, process steam	+17500	
Power boiler, process steam (only own bark)	+3000	
Turbine generators	-2600	+650
External supply	+1200	0
Consumption (including lime kiln)	-14400	-630
Effluent treatment	0	-20
Excess energy from pulp mill (including waste heat)	**+4700**	**0**
Total external supply	**1200**	**0**

Energy consumption for an integrated bleached Kraft mill with 250000 t/a of surface-sized uncoated fine paper (source: BREF 2001f)

Department	Process heat [MJ/t]	Electric power [kWh/t]
Wood handling	230	46
Cooking	1800	55
Washing and screening	0	46
Oxygen delignification	400	38
Bleaching	500	70
Bleach chemical preparation	70	5
Bleached stock screening	0	34
Pulp drying	0	0
Evaporation	3600	25
Recovery boiler	600	51
Power boiler	0	25
Causticizing	0	17
Lime kiln	1300	8
Miscellaneous. pulp mill	1900	115
Total pulp mill	**10400**	**535**
Stock preparation	0	250
Paper machine	7100	420
Total paper mill	**7100**	**670**
Effluent treatment	**0**	**13**
Total per tonne of paper	**17500**	**1218**

Energy balance for an integrated bleached Kraft mill with 250000 t/a of surface-sized uncoated fine paper (source: BREF 2001f)

Department	Process heat [MJ/t]	Electric power [kWh/t]
Pulp mill		
Recovery boiler, process steam	+13800	
Power boiler, process steam (Only own bark)	+2300	
Turbine generator	-2100	+512
External supply (incl. lime kiln)	+1300	+36
Consumption	-10400	-535
Effluent treatment	0	-13
Excess energy from pulp mill	**+4900**	**0**
Paper mill		
Consumption	-7100	-670
External supply	+2200	+670
Total external supply	**3500**	**706**

Energy consumption in an integrated mill with a production capacity of 500000 t/a newsprint from TMP (source: BREF 2001f)

Department	Process heat [MJ/t]	Electric power [kWh/t]
Wood handling	150	50
Refining	0	2110 [1]
Washing and screening	0	50
Bleaching	0	75
Bleach chemical preparation	0	5
Bleached stock screening	0	35
Power boiler	0	25
Total pulp mill	**150**	**2350**
Stock preparation	0	235
Paper machine	5300 [1] [2]	350
Total paper mill	**5300**	**585**
Effluent treatment	**0**	**39**
Total per tonne of paper	**5450**	**2974**

Notes:
1) From a Finnish integrated TMP mill higher electricity consumption in the range of 2400 kWh/t was reported for the refining stage (including reject refining) and a lower value of 4800 MJ/t process heat consumption for the paper machine respectively [Finnish comments].
2) A Swedish newsprint mill reports a heat demand of about 4 GJ/t for drying paper, a need that will be reduced by about 10% with a future shoe-press installation.

Energy balance for an integrated Swedish mill manufacturing 500000 t/a of newsprint from TMP (source: BREF 2001f)

Department	Heat [MJ/t]	Electric power [kWh/t]
Pulp mill		
Recovered steam, only for process use [1]	+1500	
Power boiler, process steam (only own bark)	+1500	
Turbine generator		+100
External supply	0	+2289
Consumption	-150	-2350
Effluent treatment	0	-39
Excess energy from pulp mill	**+2850**	**0**
Paper mill		
Consumption	-5300	-585
External supply [1]	+2450	+585
Total external supply	**2450**	**2874**

Notes:
1) From the Finnish paper maker point of view the heat recovery of TMP process is significantly higher. For an integrated 250000 t/a newsprint mill based on TMP a heat recovery value (recovered steam) of 3450 MJ/t was reported. Thus, in this case there is no need for external supply of heat [Finnish comments]

Energy balance for a non-integrated Finnish CTMP mill (CSF 400 ml) (source: BREF 2001f)

Department	Heat [MJ/t]	Electric power [kWh/t]
Pulp mill		
Recovered steam, only for process use	+ 2700	
External supply	0	+1650
Consumption	0	-1600
Effluent treatment	0	-50
Excess energy from pulp mill	**+2700**	**0**
Pulp dryer		
Consumption	-5600	- 150
Steam boiler (wood residuals & fuel oil)	+2900	+ 150
Total external supply	**2900**	**1800**

Energy consumption in an integrated Swedish mill with a production capacity of 500000 t/a of newsprint from deinked pulp (source: BREF 2001f)

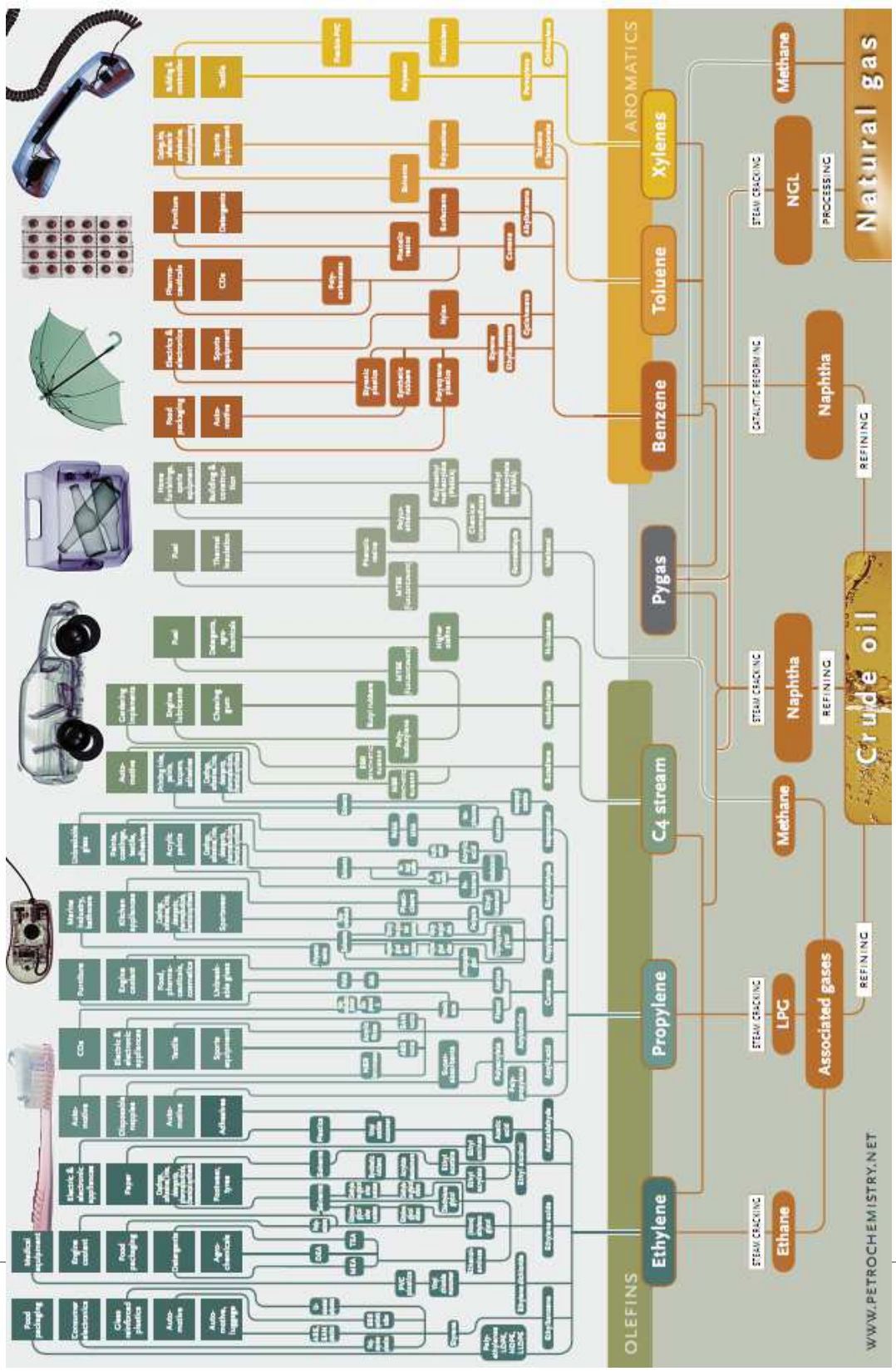
Department	Process heat [MJ/Adt]	Electric power [kWh/Adt]
Pulp mill		
Deinking	200	175
Washing and screening	0	50
Bleaching	0	75
Total pulp mill	**200**	**300**
Stock preparation	0	235
Paper machine	5300	350
Total paper mill	**5300**	**585**
Effluent treatment	**0**	**32**
Specific energy consumption per t/paper	**5500**	**917**

Energy balances of two integrated RCF newsprint mills with a production capacity of 500000 t/a and 250000 t/a respectively (source: BREF 2001f)

Department	Heat [MJ/Adt]	Electric power [kWh/Adt]
Pulp mill		
Turbine generator	0	0
External supply	+ 200	+ 332
Consumption	- 200	- 300
Effluent treatment	0	- 32
Excess energy from pulp mill	**0**	**0**
Paper mill		
Consumption	- 5300	- 585
External supply	+ 5300	+ 585
Total external supply	**5500**	**917**

Annex VI: Chemical industry

Flowchart of petrochemicals from crude oil and gas to end-products (Source: communication from Association of Petrochemicals Producers in Europe)



List of naphtha cracker in EU+ countries (Source: APPE website)

AUSTRIA	Schwechat	OMV	500
BENELUX	Antwerp	FAO1	255
	Antwerp	FAO1	550
	Antwerp	FAO1	610
	Antwerp	BASF	1050
	Geleen	Sabic Europe	1310
	Moerdijk	Shell	900
	Terneuzen	Dow	580
	Terneuzen	Dow	580
	Terneuzen	Dow	650
BULGARIA	Burgas	Lukoil Neftochim	150
CZECH Republic	Litvinov	Chemopetrol	525
FINLAND	Porvoo	Borealis2	380
FRANCE	Berre	LyondellBasell	470
	Carling	TOTAL	570
	Dunkerque	Polimeri	380
	Feyzin	A.P. Feyzin3	250
	Gonfreville	TOTAL	525
	Lavera	Naphtachimie4	740
	NDG	ExxonMobil	425
GERMANY	Boehlen	Dow	565
	Burghausen	OMV	450
	Gelsenkirchen	BP	1050
	Heide	Shell	100
	K-Worringen	Ineos Olefins	1100
	Ludwigshafen	BASF	220
	Ludwigshafen	BASF	400
	Munchmunster	LyondellBasell	400
	Wesseling	LyondellBasell	305
	Wesseling	LyondellBasell	735
	Wesseling	Shell	500
HUNGARY	Tiszaujvaros	TVK	620
ITALY	Brindisi	Polimeri Europa	440
	Gela	Polimeri	245
	Priolo	Polimeri	745
	Porto Torres	Polmeri	250
	Porto Marghera	Polimeri	490

NORWAY	Rafnes	Ineos Olefins	568
POLAND	Plock	Polski Koncern Naftowy ORLEN	700
PORTUGAL	Sines	Repsol2	410
ROMANIA	Pitesti	Arpechim	200
SLOVAKIA	Bratislava	Slovnaft	225
SPAIN	Puertollano	Repsol	250
	Tarragona	Repsol	660
	Tarragona	Dow	675
SWEDEN	Stenungsund	Borealis2	620
UK	Fawley	ExxonMobil	126
	Grangemouth	Ineos Olefins	1050
	Fife	ExxonMobil / Shell	830
	Wilton	Sabic UK	865
	TOTAL		27,539,000

Annex VII: Iron and steel industry

Input data from blast furnaces in different EU member states (Source: BREF 2009b; in working draft status)

Inputs	Units	Maximum	Minimum	Weighted average value
Raw materials				
Sinter	kg/tHM	1621	116	1088
Iron ore	kg/tHM	684	0	180
Pellets	kg/tHM	972	0	358
Coke	kg/tHM	515	282	359
Returned material	kg/tHM	106	0	20.1
Limestone/Lime	kg/tHM	80	0	25.7
Tuyère injection				
Oil	kg/tHM	116	0	30.1
Coal	kg/tHM	232	0	162
COG	kg/tHM	46.9	0	1.1
Natural gas	kg/tHM	5.6	0	2.2
Oxygen	kg/tHM	85.1	0	54.4
Others [1)]	kg/tHM	73.5	0	3.6
To stoves				
BF gas	MJ/tHM	2287	1.2	1536
COG	MJ/tHM	817	0.024	284
Natural gas	MJ/tHM	819	0	168
BOF gas	MJ/tHM	259	0.124	213
Energy				
Electricity	MJ/tHM	850	107	268
Others				
Oxygen	m³/tHM	67	4.6	43
Nitrogen	m³/tHM	59	33	46
Steam	MJ/tHM	435	14.8	48
Compressed air	m³/tHM	35	0.008	9.1
Cooling water [2)]	m³/tHM	22.9 [4)]	0.37 [4)]	--
Process water [3)]	m³/tHM	13	0.28	3.4

Note: Blast furnace input data for 2004, based upon production of 73.4 Mt HM. HM: hot metal

1) Others could include plastic, recovered oils, fats, emulsions, etc.

2) Water that does not have direct contact in the process.

3) Process water is an integral part of the process and is not contained in a defined cooling system, e.g. slag pit water.

4) Differences reflect once-through systems and closed systems. Weighted averages are not calculated since once-through systems should not be compared to closed systems.

Output data from blast furnaces in different EU member states for 2004 (Source: BREF 2009b; in working draft status)

	Units	Maximum	Minimum	No.	Tonnage HM
Energy					
BF gas	MJ/t HM	6061	3377	16	62956753
Electricity	MJ/t HM	91	40	6	31160302
Production residues (waste/by-products)					
Slag	kg/t HM	346.6	150.0	18	69223393
Top gas dust	kg/t HM	18.0	3.4	13	61044562
Top gas sludge	kg/t HM	22.3	2.0	15	66268056
Dust from cast house dedusting	kg/t HM	5.1	0.6	8	41197012
Production residues (waste/by-products)					
Used refractory, etc.	kg/t HM	5.9	0.3	8	48063570
Waste water	m^3/t HM	13.736 [2)]	0.096 [2)]	12	54428253

Notes: Data based based upon:
Tonnes of hot metal = 73459787 [1)]
Tonnes of BF slag = 19562299
HM: hot metal; No: Number of EU installations that have reported; Tonnage of hot metal: Amount of hot metal produced by the installations that have reported data for each item.

1) No single output has been reported for all installations. This is the reason why this figure is higher than any other in the column. Tonnare hot metal

2) Differences reflect once-through systems and closed systems.

Input/output data from four existing basic oxygen steelmaking plants in four different EU Member States (Source: BREF 2001e)

Input				Output		
Raw materials				Products*3	kg/t LS	1000.0
pig iron*1	kg/t LS	820 – 980		Slabs)		
scrap	kg/t LS	170 – 255		Blooms)		
iron ore	kg/t LS	7 – 20		Billets)		
other Fe-material	kg/t LS	7 – 10		Ingots)		
coke	kg/t LS	0.02 – 0.48				
lime	kg/t LS	30 – 55		Energy		
dolomite	kg/t LS	1.5 – 4		BOF gas*4	MJ/t LS	(0)-650 – 840
alloys*2	kg/t LS	3 – 9		Steam*5	MJ/t LS	(0)-20 – 270
				Gas. Emissions		
Oxygen	m3/t LS	45 – 55		Dust	g/t LS	15 – 80
				Cr*6	g/t LS	0.01 – 0.36
				Cu*6	g/t LS	0.01 – 0.04
Energy				Pb*6	g/t LS	0.13 – 0.9
natural gas	MJ/t LS	20 – 55		Mn*6	g/t LS	<0.01 – 1.2
electricity	MJ/t LS	38 – 120		NO_x	g/t LS	5 – 20
				CO	g/t LS	1500 – 7960
				CO_2*7	kg/t LS	11.2 – 140
Steam	MJ/t LS	30 – 140		PAH*8	mg/t LS	0.08 - 0.16
				PCDD/F	µg I-TEQ/t LS	<0.001 – 0.06
Compressed air	Nm3/t LS	4 – 18				
				Residues/ By-products		
				Desulphur. slag	kg/t LS	2.2 – 19.2
Water	m3/t LS	0.4 – 5		BOF-slag	kg/t LS	85 – 110
				Slag from second. Metallurgy	kg/t LS	2 – 16
				Spittings	kg/t LS	4 – 5
				Dusts	kg/t LS	1.5 – 7
				Slag from contin. Casting	kg/t LS	4 – 5
				Mill scale	kg/t LS	1.2 – 6
				Rubble	kg/t LS	0.8 - 5
				Wastewater	m^3/t LS	?

Legend: LS = liquid steel (crude steel)

*1 distinction can be drawn between high phosphorus (1.5-2.2% P) and low phosphorus hot metal (0.08-0.25% P)

*2 important alloying additions are: Fe-Ti, Fe-W, Fe-Ni, Fe-V, Fe-Si and Fe-Mo

*3 sum of products (slabs, blooms, billets or ingots)

*4 zero in case of non-recovery of BOF gas

*5 high value in case of non-suppressed combustion and heat recovery from flue gases in form of steam; zero in case of quantitative recovery of BOF gas without any heat recovery (no steam generation)

*6 higher value in case of less sufficient secondary de-dusting

*7 high value in case of partial to full combustion of the BOF gas

*8 PAH as Borneff 6; data available from two plants only

Input/output data for electric arc furnaces within the EU (Source: BREF 2009b, working draft status)

Input			Output		
Raw materials			Products		
metallic input:			Liquid steel (LS)	kg	1000.00
Scrap	kg/t LS	1039 - 1232			
Pig iron	kg/t LS	0 - 153			
Liquid hot metal[1]	kg/t LS				
DRI (HBI)	kg/t LS	0 - 215			
Lime/dolomite[2]	kg/t LS	25 - 140	Air emissions		
Coal (incl. anthracite and coke)	kg/t LS	3 - 28	Offgas flow	Million Nm^3/h	1 - 2
	kg/t LS			Nm^3/t LS	8000 - 10000
Graphite electrodes	kg/t LS	2 - 6			
Refractory lining	kg/t LS	4 - 60	Dust	g/t	4 - 300
Alloys:				mg/m^3	0.5 - 52
Carbon steel	kg/t LS	11 - 40	Hg	mg/t	2 - 200
High alloy and stainless steel	kg/t LS	23 - 363	Pb	mg/t	75 - 2850
			Cr	mg/t	12 - 2800
Gases			Ni	mg/t	3 - 2000
Oxygen	m^3/t LS	5 - 65	Zn	mg/t	200 - 24000
Argon	m^3/t LS	0.3 - 1.45	Cd	mg/t	1 - 148
Nitrogen	m^3/t LS	0.8 - 12	Cu	mg/t	11 - 510
Steam[3]	kg/t	33 - 360	HF	mg/t	0.04 - 15000
			HCl	mg/t	800 - 25000
Energy			SO_2	g/t	5 - 210
Electricity	kWh/t LS	404 - 748	NO_x	g/t	13 - 460
	MJ/t LS	1454 - 2693	CO	g/t	50 - 4500
			CO_2	kg/t	72 - 180
Fuels (natural gas & liquid fuels)	MJ/t	50 - 1500	TOC	g C/t	35 - 260
			Benzene	mg/t	30 - 170
			Chlorobenzenes	mg/t	0.2 - 12
			PAH[4]	mg/t	9 - 970
Water	m^3/t	1 - 42.8	PCB[5]	mg/t	0.01 - 5
			PCDD/F	µg I-TEQ/t	0.04 - 6
			Production residues (waste/ by-products)		
			Slag from furnace	kg/t	60 - 263
			Slag from ladle	kg/t	10 - 80
			Dusts	kg/t	10 - 30
			Waste refractories	kg/t	1.6 - 22.8
			Noise	dB(A)	90 - 133

Legend: LS = liquid steel

1) Hot metal is only used in very special cases (about 275 kg/t LS), then the quantity of scrap is lower.
2) Typically lime is not used but in few cases dolomite alone is used or combinations of dolomite and lime (e.g. weight proportion 63/37).
3) Steam is generally not used withing the EAF steelmaking, except for plants with secondary metallurgy with vacuum treatment DRI (direct reduced iron); hot metal are only used in special cases.
4) No consistent database, some results represent the total of 16 EPA PAH, others only a section of them.
5) No consistent database, values represent different selections of PCBs (32 of them refer to the above-mentioned Ballschmiter PCBs, 2 to WHO-TEQ, 1 to SUM-WHO and 2 without further indication).

Notes: Some measuring methodologies might vary importantly from country to country and from plant to plant. Not all the emitted substances are measured at all plants. The measuring programmes vary greatly depending on permit requirements.

Data has been compiled from information provided by EAF melt shop operators (carbon steel, alloy steel and stainless steel) representing 37.4 Mt of steel produced. This represented close to 50 % of the total EAF steel production in the EU in 2004 in 11 different EU countries

Annex VIII: Nuclear cogeneration, desalination and district heating

Reactors having non electric applications worldwide (IAEA 2007)

TABLE 1.2. Reactors having non-electric applications

Country	Reactor		Type	Capacity MW(e)			Operator	NSSS Supplier	Construction Start	Grid Connection	Commercial Operation	Load Factor % (1) to 2005	Unit Capacity Factor % (1) to 2005	Non-electric Applications (2)
	Code	Name		Net	Gross	Thermal								
BULGARIA	BG -5	KOZLODUY-5	PWR	953	1000	3000	KOZNPP	AEE	1980-7	1987-11	1988-12	50.0	64.0	DH
	BG -6	KOZLODUY-6	PWR	953	1000	3000	KOZNPP	AEE	1982-4	1991-8	1993-12	58.0	72.0	DH
CZECH REP.	CZ -23	TEMELIN-1	PWR	930	975	3000	CEZ	SKODA	1987-2	2000-12	2002-6	70.0	72.0	DH
	CZ -24	TEMELIN-2	PWR	930	975	3000	CEZ	SKODA	1987-2	2002-12	2003-4	69.0	68.0	DH
HUNGARY	HU -2	PAKS-2	PWR	441	468	1375	PAKS RT.	AEE	1974-8	1984-9	1984-11	79.0	78.0	DH
	HU -3	PAKS-3	PWR	433	460	1375	PAKS RT.	AEE	1979-10	1986-9	1986-12	87.0	86.0	DH
	HU -4	PAKS-4	PWR	444	471	1375	PAKS RT.	AEE	1979-10	1987-8	1987-11	89.0	87.0	DH
INDIA	IN -5	MADRAS-1	PHWR	202	220	801	NPCIL	NPCIL	1971-1	1983-7	1984-1	49.0	58.0	DS
	IN -6	MADRAS-2	PHWR	202	220	801	NPCIL	NPCIL	1972-10	1985-9	1986-3	55.0	62.0	DS
	IN -3	RAJASTHAN-1	PHWR	90	100	693	NPCIL	AECL	1965-8	1972-11	1973-12	21.0	28.0	PH
	IN -4	RAJASTHAN-2	PHWR	187	200	693	NPCIL	AECL/DAE	1968-4	1980-11	1981-4	53.0	60.0	PH
	IN -11	RAJASTHAN-3	PHWR	202	220	801	NPCIL	NPCIL	1990-2	2000-3	2000-6	77.0	88.0	PH
	IN -12	RAJASTHAN-4	PHWR	202	220	801	NPCIL	NPCIL	1990-10	2000-11	2000-12	77.0	91.0	PH
JAPAN	JP -45	GENKAI-3	PWR	1127	1180	3423	KYUSHU	MHI	1988-6	1993-6	1994-3	86.0	85.0	DS
	JP -46	GENKAI-4	PWR	1127	1180	3423	KYUSHU	MHI	1992-7	1996-11	1997-7	86.0	85.0	DS
	JP -23	IKATA-1	PWR	538	566	1650	SHIKOKU	MHI	1973-6	1977-2	1977-9	77.0	78.0	DS
	JP -32	IKATA-2	PWR	538	566	1650	SHIKOKU	MHI	1978-2	1981-8	1982-3	81.0	81.0	DS
	JP -47	IKATA-3	PWR	846	890	2660	SHIKOKU	MHI	1986-11	1994-3	1994-12	87.0	85.0	DS
	JP -15	OHI-1	PWR	1120	1175	3423	KEPCO	WH	1972-10	1977-12	1979-3	66.0	66.0	DS
	JP -19	OHI-2	PWR	1120	1175	3423	KEPCO	WH	1972-12	1978-10	1979-12	72.0	72.0	DS
	JP -29	TAKAHAMA-3	PWR	830	870	2660	KEPCO	MHI	1980-12	1984-5	1985-1	84.0	83.0	DS
	JP -30	TAKAHAMA-4	PWR	830	870	2660	KEPCO	MHI	1981-3	1984-11	1985-6	86.0	84.0	DS
PAKISTAN	PK -1	KANUPP	PHWR	125	137	433	PAEC	CGE	1966-8	1971-10	1972-12	26.0	43.0	DS
ROMANIA	RO -1	CERNAVODA-1	PHWR	655	706	2180	SNN	AECL	1982-7	1996-7	1996-12	86.0	87.0	DH

TABLE 1.2. Reactors having non-electric applications (cont'd)

Country	Reactor		Type	Capacity MW(e)			Operator	NSSS Supplier	Construction Start	Grid Connection	Commercial Operation	Load Factor % (1) to 2005	Unit Capacity Factor % (1) to 2005	Non-electric Applications (2)
	Code	Name		Net	Gross	Thermal								
RUSSIAN FEDERATION	RU -96	BALAKOVO-1	PWR	950	1000	3000	REA	FAEA	1980-12	1985-12	1986-5	62.0	68.0	DH,PH
	RU -97	BALAKOVO-2	PWR	950	1000	3000	REA	FAEA	1981-8	1987-10	1988-1	61.0	67.0	DH,PH
	RU -98	BALAKOVO-3	PWR	950	1000	3000	REA	FAEA	1982-11	1988-12	1989-4	66.0	73.0	DH,PH
	RU -99	BALAKOVO-4	PWR	950	1000	3200	REA	FAEA	1984-4	1993-4	1993-12	71.0	78.0	DH,PH
	RU -21	BELOYARSKY-3(BN-600)	FBR	560	600	1470	REA	FAEA	1969-1	1980-4	1981-11	74.0	75.0	DH,PH
	RU -141	BILIBINO-1	LWGR	11	12	62	REA	FAEA	1970-1	1974-1	1974-4	58.0	80.0	DH
	RU -142	BILIBINO-2	LWGR	11	12	62	REA	FAEA	1970-1	1974-12	1975-2	57.0	81.0	DH
	RU -143	BILIBINO-3	LWGR	11	12	62	REA	FAEA	1970-1	1975-12	1976-2	59.0	81.0	DH
	RU -144	BILIBINO-4	LWGR	11	12	62	REA	FAEA	1970-1	1976-12	1977-1	58.0	78.0	DH
	RU -30	KALININ-1	PWR	950	1000	3000	REA	FAEA	1977-2	1984-5	1985-6	71.0	71.0	DH,PH
	RU -31	KALININ-2	PWR	950	1000	3000	REA	FAEA	1982-2	1986-12	1987-3	71.0	73.0	DH,PH
	RU -36	KALININ-3	PWR	950	1000	3200	REA	FAEA	1985-10	2004-12	2005-11	77.0	77.0	-
	RU -12	KOLA-1	PWR	411	440	1375	REA	FAEA	1970-5	1973-6	1973-12	65.0	76.0	DH,PH
	RU -13	KOLA-2	PWR	411	440	1375	REA	FAEA	1973-1	1974-12	1975-2	65.0	76.0	DH,PH
	RU -32	KOLA-3	PWR	411	440	1375	REA	FAEA	1977-4	1981-3	1982-12	72.0	82.0	DH,PH
	RU -33	KOLA-4	PWR	411	440	1375	REA	FAEA	1976-8	1984-10	1984-12	71.0	81.0	DH,PH
	RU -17	KURSK-1	LWGR	925	1000	3200	REA	FAEA	1972-6	1976-12	1977-10	57.0	60.0	DH,PH
	RU -22	KURSK-2	LWGR	925	1000	3200	REA	FAEA	1973-1	1979-1	1979-8	60.0	63.0	DH,PH
	RU -38	KURSK-3	LWGR	925	1000	3200	REA	FAEA	1978-4	1983-10	1984-3	71.0	73.0	DH,PH
	RU -39	KURSK-4	LWGR	925	1000	3200	REA	FAEA	1981-5	1985-12	1986-2	75.0	76.0	DH,PH
	RU -15	LENINGRAD-1	LWGR	925	1000	3200	REA	FAEA	1970-3	1973-12	1974-11	68.0	69.0	DH,PH
	RU -16	LENINGRAD-2	LWGR	925	1000	3200	REA	FAEA	1970-6	1975-7	1976-2	68.0	69.0	DH,PH
	RU -34	LENINGRAD-3	LWGR	925	1000	3200	REA	FAEA	1973-12	1979-12	1980-6	69.0	71.0	DH,PH
	RU -35	LENINGRAD-4	LWGR	925	1000	3200	REA	FAEA	1975-2	1981-2	1981-8	71.0	73.0	DH,PH

TABLE 1.2. Reactors having non-electric applications (cont'd)

Country	Reactor		Type	Capacity MW(e)			Operator	NSSS Supplier	Construction Start	Grid Connection	Commercial Operation	Load Factor % (1) to 2005	Unit Capacity Factor % (1) to 2005	Non-electric Applications (2)
	Code	Name		Net	Gross	Thermal								
	RU -23	SMOLENSK-1	LWGR	925	1000	3200	REA	FAEA	1975-10	1982-12	1983-9	70.0	73.0	DH,PH
	RU -24	SMOLENSK-2	LWGR	925	1000	3200	REA	FAEA	1976-6	1985-5	1985-7	73.0	76.0	DH,PH
	RU -67	SMOLENSK-3	LWGR	925	1000	3200	REA	FAEA	1984-5	1990-1	1990-10	78.0	81.0	DH,PH
SLOVAKIA	SK -13	BOHUNICE-3	PWR	408	440	1375	SE,plc	SKODA	1976-12	1984-8	1985-2	75.0	80.0	DH
	SK -14	BOHUNICE-4	PWR	408	440	1375	SE,plc	SKODA	1976-12	1985-8	1985-12	77.0	82.0	DH
SWITZERLAND	CH -1	BEZNAU-1	PWR	365	380	1130	NOK	WH	1965-9	1969-7	1969-9	82.0	87.0	DH
	CH -3	BEZNAU-2	PWR	365	380	1130	NOK	WH	1968-1	1971-10	1971-12	87.0	87.0	DH
	CH -4	GOESGEN	PWR	970	1020	2900	KKG	KWU	1973-12	1979-2	1979-11	88.0	89.0	DH
UKRAINE	UA -40	KHMELNITSKI-1	PWR	950	1000	3000	NNEGC	PAIP	1981-11	1987-12	1988-8	72.0	72.0	DH
	UA -27	ROVNO-1	PWR	381	420	1375	NNEGC	PAIP	1973-8	1980-12	1981-9	80.0	81.0	DH
	UA -28	ROVNO-2	PWR	376	415	1375	NNEGC	PAIP	1973-10	1981-12	1982-7	79.0	81.0	DH
	UA -29	ROVNO-3	PWR	950	1000	3000	NNEGC	PAIP	1980-2	1986-12	1987-5	69.0	73.0	DH
	UA -44	SOUTH UKRAINE-1	PWR	950	1000	3000	NNEGC	PAA	1977-3	1982-12	1983-10	66.0	66.0	DH
	UA -45	SOUTH UKRAINE-2	PWR	950	1000	3000	NNEGC	PAA	1979-10	1985-1	1985-4	61.0	62.0	DH
	UA -48	SOUTH UKRAINE-3	PWR	950	1000	3000	NNEGC	PAA	1985-2	1989-9	1989-12	72.0	73.0	DH
	UA -54	ZAPOROZHE-1	PWR	950	1000	3000	NNEGC	PAIP	1980-4	1984-12	1985-12	61.0	64.0	DH
	UA -56	ZAPOROZHE-2	PWR	950	1000	3000	NNEGC	PAIP	1981-1	1985-7	1986-2	64.0	68.0	DH
	UA -78	ZAPOROZHE-3	PWR	950	1000	3000	NNEGC	PAIP	1982-4	1986-12	1987-3	66.0	70.0	DH
	UA -79	ZAPOROZHE-4	PWR	950	1000	3000	NNEGC	PAIP	1983-4	1987-12	1988-4	71.0	75.0	DH
	UA -126	ZAPOROZHE-5	PWR	950	1000	3000	NNEGC	PAIP	1985-11	1989-8	1989-10	72.0	74.0	DH
	UA -127	ZAPOROZHE-6	PWR	950	1000	3000	NNEGC	PAIP	1986-6	1995-10	1996-9	77.0	80.0	DH

(1) Performance factors Load Factor (LF) and Unit Capacity Factor (UCF) calculated only for period of full commercial operation, and only through 2005.

(2)The column Non-Electrical Applications indicates the use of the facility to provide:- DS desalination, DH district heating, PH process heat.

District heating and process heat in 2006 per reactor worldwide (IAEA 2007)

Country	Reactor	District heating (GWh)	Process heat (GWh)	Total (GWh)	Equivalent thermal power (MWth)
Bulgaria	Kozloduy-5	142	N/A	142	18
	Kozloduy-6	21	N/A	21	3
Czech Republic	Temelin-1	49	N/A	49	6
	Temelin-2	6	N/A	6	1
Hungary	PAKS-2	3	N/A	3	0
	PAKS-3	30	N/A	30	4
	PAKS-4	249	N/A	249	31
India	Rajasthan-1	N/A	-	-	-
	Rajasthan-2	N/A	115	115	14
	Rajasthan-3	N/A	131	131	16
	Rajasthan-4	N/A	25	25	3
Romania	Cernavoda-1	32	N/A	32	4
Russia	Balakovo-1	56	-	56	7
	Balakovo-2	-	-	-	-
	Balakovo-3	1	-	1	0
	Balakovo-4	3	-	3	0
	Beloyarsky-3	325	-	325	41
	Bilibino-1	53	N/A	53	7
	Bilibino-2	48	N/A	48	6
	Bilibino-3	58	N/A	58	7
	Bilibino-4	57	N/A	57	7
	Kalinin-1	393	4	397	50
	Kalinin-2	261	4	265	33
	Kola-1	8	2	10	1
	Kola-2	9	2	12	1
	Kola-3	13	2	15	2
	Kola-4	7	2	9	1
	Kursk-1	70	73	143	18
	Kursk-2	112	118	230	29
	Kursk-3	149	135	284	35
	Kursk-4	252	196	448	56
	Leningrad-1	255	-	255	32
	Leningrad-2	31	-	31	4
	Leningrad-3	283	-	283	35
	Leningrad-4	213	-	213	27
	Novovoronezh-3	98	-	98	12

	Novovoronezh-4	158	3	161	20
	Novovoronezh-5	-	2	2	0
	Smolensk-1	65	40	105	13
	Smolensk-2	324	26	350	44
	Smolensk-3	290	25	315	39
Slovakia	Bohunice-3	261	-	261	33
	Bohunice-4	225	-	225	28
Switzerland	Beznau-1	0	N/A	0	0
	Beznau-2	0	N/A	0	0
	Goesgen	N/A	73	73	9
Ukraine	Khemlnitski-1	220	N/A	220	28
	Rovno-1	96	N/A	96	12
	Rovno-2	78	N/A	78	10
	Rovno-3	150	N/A	150	19
	South Ukraine 1	114	N/A	114	14
	South Ukraine 2	151	N/A	151	19
	South Ukraine 3	159	N/A	159	20
	Zaporozhe-1	104	N/A	104	13
	Zaporozhe-2	107	N/A	107	13
	Zaporozhe-3	51	N/A	51	6
	Zaporozhe-4	75	N/A	75	9
	Zaporozhe-5	145	N/A	145	18
	Zaporozhe-6	147	N/A	147	18
TOTAL		**6 204**	**978**	**7 182**	**15**

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