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The natural gas chain

Toward a global life cycle assessment

Report

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Preface

The International Gas Union's (IGU) Programme Committee A decided in 2004 to make a Life Cycle Analysis (LCA) of the entire gas chain. The reason for this decision was that, although numerous LCA's on fossil fuels have been made, a full LCA of the gas chain on a worldwide scale was not available. Nowadays accurate figures and analyses become more and more important, because data on fossil fuels are used for all kind of studies like studies on global warming, emission scenario's, etc.
Therefore IGU felt the need to have a basic set of LCA data of the gas chain, that could serve as the basis for whatever other study or analysis in the future.

This report presents the initiation of this LCA project. A methodology is presented for an industry database and available data are structured. The data set that results from this study is first step toward a proper life-cycle analysis. This partly results from the complexities of assessing data at a global level, which means many processes are not physically connected. Despite these drawbacks, the exercise has been promising in view of the intentions of the IGU.

Veenstra, Gasunie

Contents

Summary

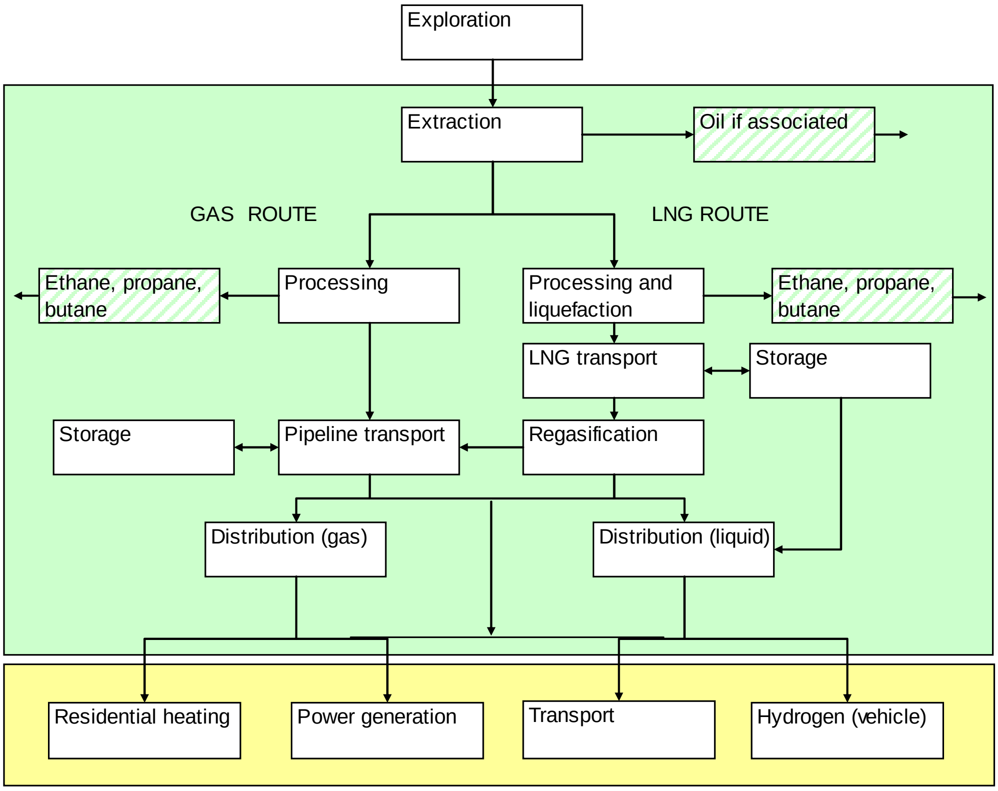
The International Gas Union (IGU) started a life-cycle initiative for the natural gas chain. The aim was to collect and structure industry data on consumptions and emissions along the life cycle of natural gas. This report describes the initiation of the life-cycle inventory.

Costs and environmental impact are important drivers for investigating the natural gas life cycle. Environmental impact will more and more become an important subject in industry policy and strategy. While natural gas is now performing well in terms of environmental profile with respect to other fossil energy sources, continued efforts will be essential to keep this position in a changing market and with other fossil fuels working on their environmental impacts. In order to identify the – most attractive – options for improvement, further expansion of the life-cycle database is desirable. Nevertheless, the data collected in this project do cover a fair fraction of the global volume and give useful first insight into issues as well as options along the gas chain.

One of the main issues in the natural gas chain is the loss of product through fugitive emissions and venting or flaring. Natural gas – methane – has a high global warming impact and therefore product loss and climate impact are closely related. This means that reducing losses leads to improved economic as well as environmental performance.

While venting, or flaring, may not easily be avoided, the fugitive emissions could in principle be reduced significantly, as is shown in the USA Gasstar programme. Also, the energy efficiency of processing, may be improved. Most of this energy is provided by the natural gas itself and thus results in a loss of product as well.

Figure 1 Schematic representation of the scope of the study (dashed cells indicate by-products)



In Figure 1, an overview of processes along the life cycle of natural gas is shown.The "gas" route with pipeline transport is most prone to fugitive losses, whereas in the "LNG" route the use of product as an energy source is relatively high. In LNG processing, though, the overall efficiency is improving, as comparison of existing plants with capacity under construction shows. This is important, as the share of LNG will increase as the globalizing market is demanding more flexibility.

The focus of industry data collection in this report is on the first part of the chain (green background). Some data on specific applications of natural gas (yellow background) have been taken from available literature.

Confidentiality of some of the industry data may limit the scope or detail of such a database. Nevertheless, there are several ways to proceed, depending on the possibilities and on the intended goal. A global data inventory, such as initiated in this project, would yield a general basis that could be used in a great variety of applications, such as input for specific life-cycle analyses, benchmarking or identifying improvement potential.

As such a project would be very ambitious, another option is to construct such data inventories at a regional level. In Europe, the Marcogaz project is already underway. Such an initiative could provide a more coherent life-cycle inventory, focussing on e.g. consumption (what is the environmental profile of 1 m^3 of natural gas consumed in Europe?). If detailed insight in the life cycle and comparison with other fuels is important, an option would be to make some case studies of actual life cycles, that would then also include the utilization phase.

In all cases, the IGU could assume a coordinating role to ensure progress, whether the data are intended for internal or external use, and also in using the data for strategic purposes.

1 Introduction

1.1 Project background

The International Gas Union's (IGU) Programme committee A (sustainable development) decided during the Dutch presidency to make a Life Cycle Analysis (LCA) of the entire gas chain.

Currently, many sources of life-cycle information on natural gas exist, but they do not follow the same methodology and quality standards and many studies are based on assumptions and estimates as actual industry data are not publicly available. Moreover, not all of global production is covered by existing life cycle studies. A framework database that allows the progressive collection of complete and consistent (industry) data could provide solid backing for several purposes, both internal and external to the IGU.

High quality life-cycle data could be used to show and prove the benefits of natural gas, with respect to alternative energy sources. Alternatively, potential improvement areas along the gas chain might be identified. A continuously updated data base might be used to monitor progress toward sustainability. Regardless of the specific purpose, having reliable – and transparent – life-cycle data at hand will prove essential in political discussions around the world.

In the current project, such a database is initiated. Two earlier, large-scale life-cycle projects are closely related to the current project:

- Global energy sources: World Energy Council LCA study group, that the IGU was represented in, reported in 2004 (WEC, 2004).
- European natural gas: Eurogas-Marcogaz (ongoing).

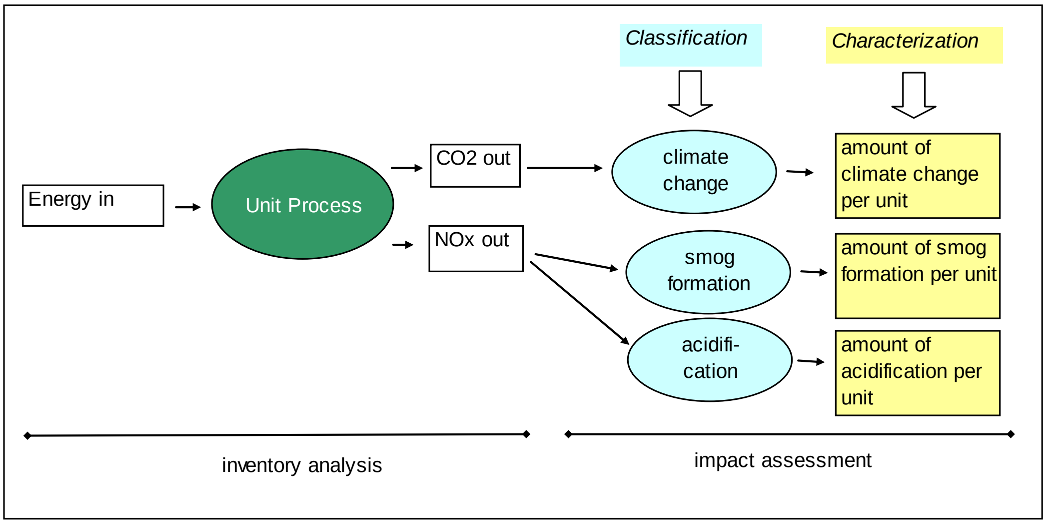
Some data sources are shared with these two projects, but the structure of this IGU project is independent.

1.2 Project definition

LCA is defined as the "compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040). A product system in this sense is a "collection of unit processes that are connected by energy or material flows and fulfill one or more well-defined functions".

In practice, an LCA basically consists of a data inventory step, called inventory analysis, and calculation step, called impact assessment. In Figure 2, this is schematically illustrated for one 'unit process'. Data, for each unit process, on for instance energy consumption, are translated into emissions, those are translated into qualitative impacts (classification) and finally into quantitative impacts (characterization).

Figure 2 Simplified illustration of steps involved in an LCA



The definition given above of the ‘product system’ in LCA terminology has some consequences for the study at hand. Global gas, even if narrowed down to one particular utilization, does not strictly comprise a product system, because many of its unit processes are not connected by a physical flow of energy or material. A cubic meter of gas in Japan, imported as LNG from Indonesia, has absolutely no physical connection to a cubic meter of gas in the Netherlands. Adding (environmental) data for these two gas chains would not yield a result that is in any way qualitatively representative of a real situation. Adding to this is the fact that the two chains – and many others – are very different in their associated environmental impacts, so that the average is also not representative in a quantitative manner.

This means that an ultimate goal of making an LCA of a global average cubic meter of gas is not desirable. Such aggregation level is simply too high to be meaningful. This precaution is of importance mainly for future applications of the database that is initiated in this project. For the data collection carried out in this project – the life-cycle *inventory* (LCI) for global gas – it means data are recorded at an aggregation level as close to reality as feasible (see section 3.5.2).

At a regional scale, LCA results are meaningful. In this report, some results will be presented for regions that may be considered to be one well-defined market for natural gas. The Northern American region (USA, Canada, Mexico) for instance is an almost entirely separate system of production and consumption. Within this region, averaging data over several production and long-distance transport systems represents a real mixing of the physical gas.

The resulting database may in principle be used to construct a global average as well as an LCA for e.g. gas supply in a single country, provided the composition of the gas supply in that country is known. Neither is done in this project, the former for the reasons outlined above, the latter as this is simply too complex on a global scale. For the same reason, compositions of gas supply per country are not part of the database. However, the database will be structured in a way to allow such flexibility of application.

In short, the goals of this project are:

- Initiation of LCA by constructing a database that provides:
    - Framework to collect industry data (instead of generic public data).
    - Flexibility with respect to later LCA applications.
- First overview of natural gas per region.
- Recommendations for way forward for IGU LCA project.

1.3 Outline of this report

An non-technical overview of the life cycle of and the global market structure for natural gas are given in Chapter 2. A detailed methodological background, describing assumptions and choices as well as the consequences thereof, are given in Chapter 3. An analysis of data, focusing on regional variations and effect of utilization, is given in Chapter 4. In Chapter 5, the achieved level of quality and completeness of the database, and consequences for its application, are briefly discussed. Finally, in Chapter 6 conclusions and recommendations of this study are put forward.

The technical descriptions of processes in the life cycle as well as the actual inventory data are covered in a separate document (CE, 2006).

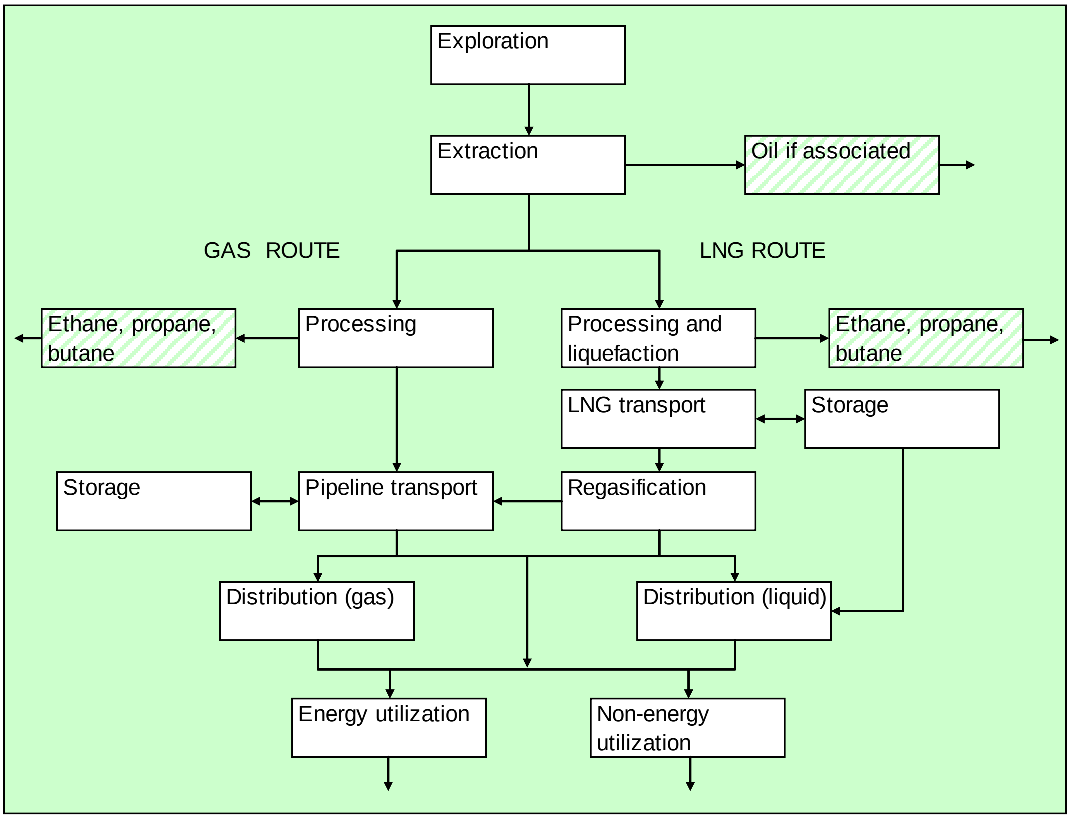
A limited use of jargon is inevitable in this study. While mostly “extraction” and “processing / treatment” are distinguished in the life cycle, the term “production” will be loosely used to mean the combination of those two steps. This is a common term, for instance in naming the “exploration and production” industry. When using a m^3 as a unit, standard temperature and pressure (Nm^3) are implied.

2 Natural gas around the world

2.1 Introduction to the life cycle

In the gas life cycle, we can distinguish the following main stages: exploration, extraction, processing (treatment), transport, storage, distribution and application (utilization). An overview of the chain is given in Figure 3, with a mention of co-products at several steps in the chain.

Figure 3 Overview of the gas chain (dashed cells indicate by-products)

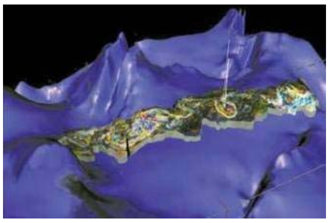


In the above figure, the chain splits in parallel "routes" several times. End products may be divided into energy and non-energy applications. At an intermediate stage, there is a distinction between gas and liquefied natural gas (LNG), primarily different modes of transport of natural gas.

At the stage of extraction and processing, parallel routes may be distinguished as well. These are mostly determined by – natural – circumstances: onshore versus offshore and associated versus non-associated gas. The latter indicates whether or not the gas is produced in conjunction with oil or not.

In this chapter, a description of the stages of the life cycle is given, as well as an overview of the global market for gas and current developments (2.10, 2.11).

2.2 Exploration and drilling



In the search for natural gas reservoirs, the subsoil is analysed essentially by geophysical methods (magnetic, gravimetric, seismic). Seismic surveying is the main tool and has undergone a considerable development in recent years. Earlier, explosives were used to generate the seismic waves. This method was harmful to the environment and fish were normally killed in the vicinity. This method has now been discarded and today the most common method for generating seismic waves is to use air guns, that discharge compressed air into the water. This method has reduced the environmental impact substantially compared to the use of explosives.

Upon discovery of a reservoir, exploration and development wells are drilled. Clearly, these activities are more complex when performed offshore than when performed onshore, especially in deeper waters. The drilling techniques used for exploration and developing boreholes are essentially the same as for oil. In the exploration phase, either jack-up or floating drilling rigs are used, depending on the water depth and environmental sensitivity. A drilling fluid (mud) is pumped into the drill pipe. This fluid consists of water, clay, polymers and suspended materials for density control.

Traditionally, the return drilling fluid was dumped at the seafloor near the rig. As different types of chemicals are added to the drill fluid, this caused pollution. Recently, there has been a continuous improvement to reduce the environmental impact from drill fluids. Risk-based analysis methods have been developed to quantify the pollution gradients and in sensitive areas, the drill fluid is collected and transported to the shore for disposal.

After drilling, a well casing is installed and to prepare the final well for production, it must be “completed” and a well head is installed. At this stage, production may start. Some further steps may be necessary, especially in the case of production together with oil.

In developing offshore gas fields, the first generation platforms are standing at the sea floor. Still today, the majority of offshore natural gas production platforms are of this type. As field development over time moved to larger seawater depths, a new generation of floating drilling- and production platforms was developed.
An even newer development has been to drill the production wells by dedicated floating drilling rigs, and the wells are completed by installing the required equipment at the seafloor. The wells are then tied back through flow-lines to a gas processing platform or ship. Further development of sub-sea production

facilities, automating the installations, improving reliability and reducing the environmental impact, are major development guidelines for the future.

Although exploration is core business for gas producing companies, it cannot be directly linked to production. Some exploration will lead to production, some will not. These means that it is hard to include exploration in a life cycle approach that tries to assess environmental impacts associated with a unit of natural gas. It would be feasible to allocate yearly impacts associated to exploration to the yearly production of gas, for instance, but it is not immediately obvious at which level this should occur – per company, per region, per country? An additional complication is that exploration for gas is often tied in with exploration for oil. At the exploration stage, there is no knowledge of the yield of either gas or oil; if it so happens that only oil is found, allocation to gas is impossible, although the exploration was targeting gas as well as oil. Therefore, it is common practice to exclude exploration from the life cycle inventory and assessment (not only for fossil fuels, but also for mineral ores, see e.g. MSD, 2001).

This is not to say that the exploration and drilling stage should be viewed as causing no impacts (see e.g. OIL, 2002), but that these impacts are hard to integrate in a life-cycle approach.

In this project, the exploration stage (including drilling, well preparation and closure) will not be included (Chapter 3).

2.3 Extraction

Details of equipment used in extraction may depend partly on whether the production site is on- or offshore (in the latter case there may e.g. be extra compression) and whether the gas is associated to oil or not. Extraction of non-associated natural gas – after establishment of the well and well head (see section 2.2) – requires little more than letting the gas flow from the reservoir. The only operations conducted concern maintenance. For maintenance operations on the well head the well is ‘killed’ by injection of a fluid with a specific density high enough to counterbalance reservoir pressure.

In all maintenance operations anti-corrosion agents and other chemicals are added to the fluids to prevent damage to the well casing and well head.
Reproduced fluid is generally discharged into the sea in offshore production, although it may also be injected, and re-injected together with formation water in onshore production. The well fluid may consist of expensive chemicals and is therefore reused if possible.

The infrastructure needed for extraction is generally more complex in the case of offshore production. Especially as deeper and deeper sea beds are being explored and developed, demands on platforms and lines from the well head to the platform become more stringent.

As this study does not assess higher-order effects (see Chapter 3) of the life cycle, this does not show up as a difference in the data for extraction, except in the possibly higher energy use.

2.4 Processing

Extraction of non-associated natural gas gives a mixture of raw gas, condensed higher hydrocarbons, free water and carried along particles. The raw gas is isolated from solids and fluids by flashing, the so-called primary separation. The isolated raw gas will have an elevated temperature due to the higher temperatures in the reservoirs and a pressure of several to several hundreds of bars. It does not yet have sufficient quality to allow transportation to the consumer for application.

Further processing basically involves the separation of the methane fraction (CH_4) in the raw gas from co-products or pollutants such as:
- Water vapour.
- Acid gases (CO_2, sulphurous compounds).
- Nitrogen (N_2).
- Condensable hydrocarbons (C_{5+}).
- Ethane, propane, butane.

Which processes are applied depends on raw gas quality as well as required standard for the processed gas. In the Netherlands, for instance, a high percentage of N_2 is still present after processing. Ranges in hydrogen sulphide are large (sweet to sour gas), as is the case for CO_2. Gas from fields yielding low calorific gas may be mixed with high calorific gas to match required market standards. The hydrocarbons heavier than methane but lighter than pentane do not necessarily have to be separated, except for the production of some chemicals. They may be separated for economic reasons, as ethane and LPG (propane/butane) are excellent naphtha cracker feedstock and LPG (as well as C_{5+}) may be sold as automotive fuels. Isolation of these so-called Natural Gas

Liquids (NGL) can be economically viable in certain regions with a high demand and low (alternative) supply.
In the case of associated gas, the natural gas may already be separate from the oil (free gas) or it may be dissolved in the oil (dissolved gas). Extra steps are involved in either case to separate the gas before processing takes place.

There are no major differences in the processing that takes place onshore or offshore, but the remarks made for extraction hold for processing as well. In some cases, there may only be pre-processing offshore, with subsequent transport – after compression – of the gas for further onshore treatment.

Most treatment processes require electricity for valves, pumps, etc. The electricity is often produced on site in case of off shore production and treatment or in case of fields located in remote area's. Otherwise electricity may be taken from the grid. Other inputs are methanol, which may be added before dehydration, but is mostly recovered and recycled, and activated carbon and glycol, involved in the desulphurization and dehydration steps.

As fields mature, more and more water are produced together with the oil and gas. This produced water can cause environmental impact when dumped, depending on what content of hydrocarbons and other chemicals are present in the produced water.

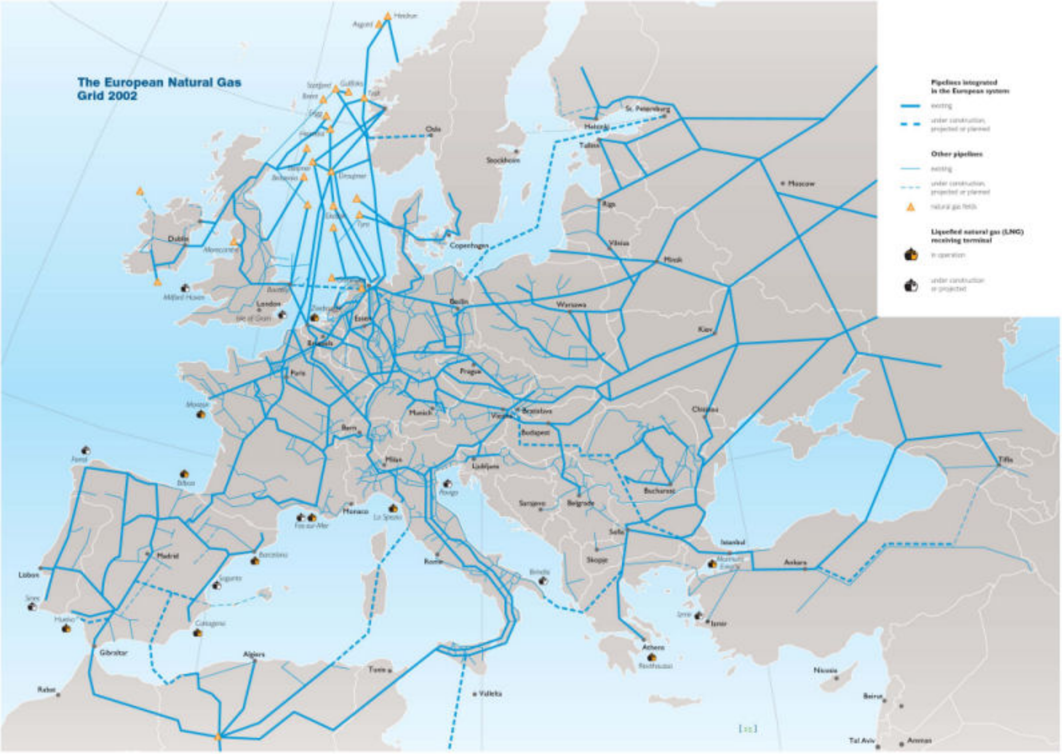
2.5 Pipeline transport

After processing, gas is often transported over very large distances. Most of this transport takes place through pipelines. In 2002, almost 80% of international trade concerned pipeline transport (IEA) (the other possibility is transport by LNG tankers as a liquid, this is discussed in the next section). Pipelines may run between two fixed locations, but are also frequently linked by "crosspipes" as may be seen in Figure 4.

The total pipeline "system" may consist of the pipeline, compression stations, import/export stations and metering. Normally, pipeline diameters range from 25 to 150 cm. Before transport, gas is compressed to pressures of approximately 70 bar. In the case of subsea pipelines, the initial pressure may be higher (more than 200 bar) due to the impossibility of transfer compression.

Pressure loss due to friction of gas along the pipeline wall is compensated by intermediate compressor stations along the pipeline. Compressors are almost always driven by natural gas, as this is obviously easily available.

Figure 4 Existing and planned pipelines in Europe and neighbouring countries



Source: Eurogas.

Upon “arrival” at the receiving end, blending stations, metering and pressure-regulation stations as well as export/import stations take care of the connection between the long-distance transmission grid and the regional distribution grid. Quality control, pressure (and temperature) control and odorization take place at these points.

Apart from energy consumption for the transport itself, maintenance and check-up activities – especially in remote areas – may require energy. Another source of gas ‘consumption’ during transport is leakage. As the gas, methane, is a powerful greenhouse gas (see section 3.7), leaks may have a significant environmental effect.

2.6 LNG

Liquid natural gas (LNG) is natural gas cooled to a low temperature (-162^{o}C) so it becomes a liquid that hence occupies a much smaller volume. It can be transported over long distances without the need for a fixed infrastructure. The

LNG process consists of several steps: processing, liquefaction, transport, storage, and regasification.

The processing step for LNG is essentially the same as previously described (section 2.4). The undesirable components are removed (water, CO_2, etc.). The hydrocarbon fractions are removed during the liquefaction process. Liquefaction of LNG means cooling the natural gas to below its condensation temperature of –162°C. The heavier hydrocarbon components in the natural gas condense at higher temperatures and are therefore liquefied – and removed – during the process. LNG often consists of both methane and ethane, the latter re-added to fluid methane after methane liquefaction (ethane liquefying before methane does). By-products of LNG production are LPG and gasoline, the heavier fractions of the raw natural gas.

Cooling down to condensation temperature is done in industrial installations that could be described as gigantic refrigerators. Current benchmark technology stands at a production capacity of approximately 5 Mton/a of LNG. The different technologies differ in the use of cascading, number of cooling stages applied and the type of refrigerant used.

The LNG is stored in full containment tank normally consisting of a concrete outer tank and an inner tank of 9% nickel steel. The boil-off gas and pre-cooling and loading vapours are compressed and used as fuel gas for the liquefaction units or flared. Transportation to and from storage is driven by pumps. Storage may also take place at other stages in the LNG chain (after international transport or before regasification). Again, boil-off gas is mostly put to use, but may be vented in emergencies.

Long-distance transport of LNG takes place primarily by cargo ships with an insulation system to keep the temperature at -162^{o}C. The LNG is often carried in separate tanks. Boil-off gas provides a large fraction of the fuel need for the ship, also on the return journey when some LNG is left in the tanks to ensure that the gas concentration in the tanks is above the upper explosion limit (UEL).

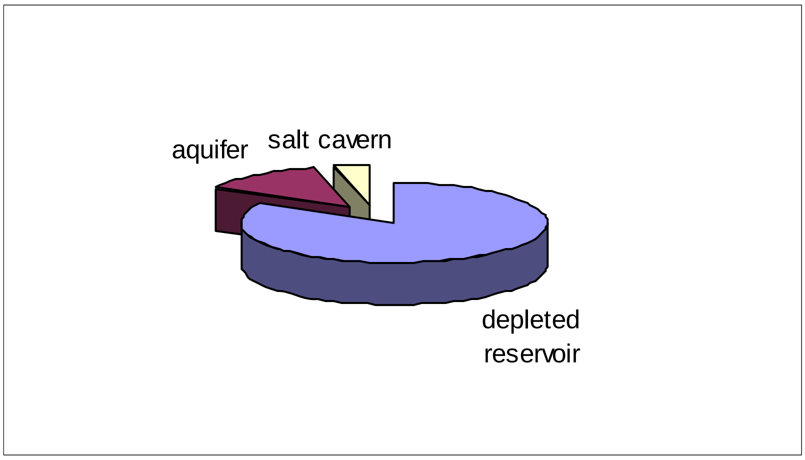
Regasification consists of increasing the LNG temperature by heat exchange with (sea) water at roughly ambient temperature or heated. The gas is then ready to be transported in the regular regional distribution network (section 2.8) after quality control.

2.7 Storage

As natural gas demand is variable over the year, there is a need for storage between production and consumption. As enormous volumes are involved in the storage of a gas, the main option is to use geological structures. Such structures may be aquifers, salt cavities, (depleted) oil or gas reservoirs or (empty) mines. The gas has to be compressed to be pumped into the geological structures. After storage, treatment may be necessary along the same lines as described in section 2.4, as the gas may once more have been contaminated with water (in all cases) and sulphurous compounds (aquifer, depleted reservoir). A fairly new technique for storage is the so-called “Lined rock cavern” (LRC).

In practice, all options are used. Figure 5 shows that depleted oil and gas reservoirs are the main storage options, providing more than 80% of world-wide storage capacity. LRC and mined caverns are not yet widely used, but considered as future options.

Figure 5 Underground storage of natural gas in the world



Source: (IGU, 2003).

2.8 Distribution

The last link in the chain to deliver the natural gas to the end user is (local) distribution. While some large customers (industrial, power generation) receive natural gas directly from high capacity gas pipelines (usually contracted through natural gas marketing companies), most other users receive natural gas from a local distribution company (LDC). LDCs are companies involved in the delivery of natural gas to consumers within a specific geographic area.

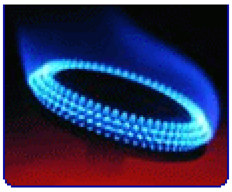
The delivery of natural gas to the end user by a distribution utility is much like the transportation of natural gas discussed in section 2.5. However, there is no compression and distribution involves moving smaller volumes of gas at much lower pressures over shorter distances to a great number of individual users. Small-diameter pipe is used to distribute natural gas to individual consumers and the distribution network is normally operated at a pressure well below 15 bar, much lower than for long-distance transmission.

Hence, before distribution, the natural gas is typically depressurized at a gate station, from as high as 100 bar to as low as 1 bar. When natural gas was not already odorized during transmission, an odorant is added to the natural gas at the gate station for safety reasons, before distribution. Traditionally, rigid steel or cast iron pipes were used to construct distribution networks. However, new technology is allowing the use of flexible plastics for distribution pressures up to some 8 bar. These new types of plastics, mainly polyethylene, allow cost reduction and installation flexibility. The current trend is to use new polyethylene pipes at pressures even above 8 bar and in some countries, polyethylene pipes are already operated at a pressure up to 10 bar.

Distribution networks are equipped with a high number of valves (safety valves and operating valves). Meters and customer lines are also part of the distribution network. Another innovation in the distribution of natural gas is the use of electronic meter-reading systems. The natural gas that is consumed by any one customer is measured by on-site meters, which essentially keep track of the volume of natural gas consumed at that location. Traditionally, in order to bill customers correctly, meter-reading had to be installed to record these volumes.

Supervisory control and data acquisition (SCADA) systems, similar to those used by large pipeline companies are also used by local distribution companies. These systems can manage gas flow control and measurement with other accounting, billing, and contract systems to provide a comprehensive measurement and control system for the LDC. This allows accurate, timely information on the status of the distribution network to be used by the LDC to ensure efficient and effective service at all times.

2.9 Utilization



The consumption phase has a separate status in the gas chain. Technical details of gas consumption are extremely diverse, due to a large variety of applications and for each of those a variety of technologies. The following applications can be distinguished:

- Transport (LNG, CNG).
- Residential (heating, cooking).
- Electricity (power) or co-generation.
- Industrial (drying, heating, powering, etc.).
- Hydrogen production.
- Material (non-energy use, chemical industry).

World wide, some 35% goes toward power generation (WEO, 2004) and 25% toward residential and commercial heating and cooking. Transport applications only consume some 3% of the gas supply (within OECD, IEA, 2002). The remaining third goes primarily toward energy and non-energy (5 to 10%) applications in industry.
Correspondingly, there is a variety of competing products, depending on the specific application. Some of these are e.g. coal or nuclear fuel (power generation), petrol or bio fuels (transport), bio gas (heating), oil (non-energy uses).

In this study typical technologies for some major (energy) applications are assessed. It is not feasible to generate a generic data base that covers all or even few of the possible circumstances.

Power
Globally, about 20% of power generation and most of the planned new capacity is natural-gas driven. By 2030, almost 30% of global power and heat generation (demand) will be gas driven (WEO, 2004).

The most common technique is combined-cycle power generation (CCPG) by means of a steam-and-gas turbine (STEG), in which waste heat is applied to generate extra electricity (via steam). Another form of waste-heat application is cogeneration (Combined Heat and Power, CHP), where the heat is actually used as heat which results in higher efficiency as there is no loss of energy in the additional power-generation step.

An emerging technology is the so-called micro turbine. With increasing demand for distributed power generation, where e.g. hospitals or large office blocks generate their own power locally, the micro turbine provides a good solution. They may apply waste heat either in the power generation cycle or as an energy carrier in itself.

In this study, we assess BAT for CCPG and micro co-generation.

Heating

Several fossil fuels are used for residential space heating. In countries without traditional gas distribution systems, local (i.e. per room) heating is often oil based in remote areas and may be electricity based in populated areas. In countries with traditional gas distribution systems, local heating is mostly gas based, except in very remote areas. However, local heating is becoming increasingly less common, and central and district heating are taking over.

Central heating (which usually includes heating of water for other purposes) is mostly natural-gas based. For district heating, heat as a by-product from nearby industrial activity (power generation) may be used or, at smaller scale, heat may be generated centrally for e.g. an apartment block, which is often again natural-gas based.

Therefore, there are three main natural-gas residential space heating technologies:

- Local heating, with traditional gas heaters for one room. In this case, water heating and cooking is usually also gas-based, but with separate equipment.
- Central heating, with a hot-water system to heat an entire house. In this case, the equipment may also provide hot water, but cooking is separate although usually gas-based.
- Block heating that serves one or more entire buildings. In this case, the system also provides hot water, but cooking may be electrical, as separate housing units may not be connected to gas distribution.

To keep the focus on space heating, in this study local and central heating, without additional hot water provision, is assessed.

Transport

The most common gaseous transport fuel is LPG, a co-product of oil- and gas production, but demand for CNG (compressed natural gas) as a transport fuel is rising. One of the main drivers is the battle against local air pollution, as polluting emissions are much lower for gas combustion than for other fossil fuels. To be attractive as a transport fuel, the energy content per volume of the natural gas has to increase with respect to standard temperature and pressure. In CNG, this is achieved by compression.

Most cars can be converted to take CNG as well as diesel (primarily) into bi-fuel vehicles. Also, there are dedicated CNG cars, with possibly only an emergency tank for petrol or diesel.

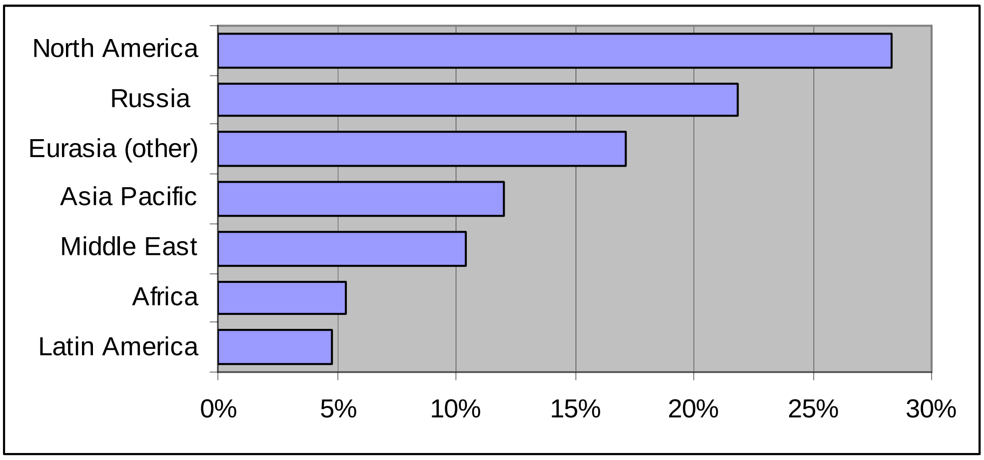
Hydrogen

There are four principal methods for the production of hydrogen: ammonia splitting, methanol steam reforming, natural gas reforming and water electrolysis. Currently, about half of the global hydrogen production takes place by natural gas reforming[1]. The hydrogen is produced and used in a variety of industrial processes and only about 5% of hydrogen is currently sold to third parties, mostly as an energy carrier for transportation (PEW, 2004). Natural gas as an input material for hydrogen production is expected to remain important for some time (PEW, 2004). Hydrogen demand for electricity production is expected to rise after only 2020 or 2030 (WEO, 2002).

2.10 Global gas market

The International Energy Agency (IEA) provides year-by-year data on production, consumption, imports and exports. In Figure 6, the production is given as a percentage of the global production for major regions.

Figure 6 Percentage of global production for different regions (2004)



Source: BP statistical review 2005.

Although gas is produced around the globe, a few countries provide a large percentage of the total volume, such as the USA, Canada, Russia, UK, and Algeria. In Table 1, the most important producers are listed, with production volumes and contribution to the world total. Fifteen countries provide almost 80% of the total world production, although this figure is of course subject to change (see section 2.11).

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[1] www.greencarcongress.com.

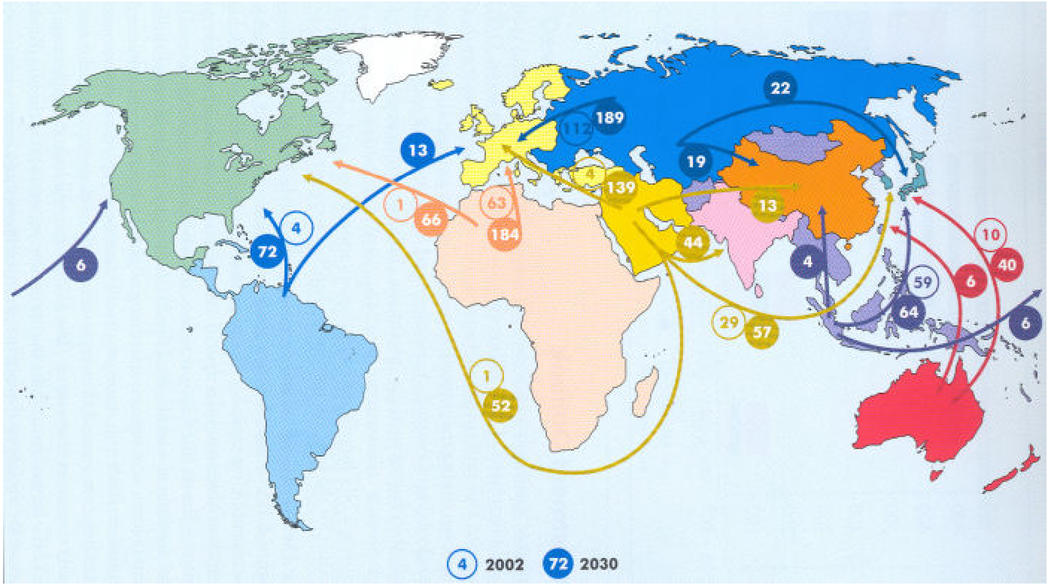
Table 1 Production volumes of largest producers

	Production 2004	
	MTOE	% of global
Canada	164,5	6,8%
USA	488,6	20,2%
Netherlands	61,9	2,6%
Norway	70,6	2,9%
UK	86,3	3,6%
Argentina	40,4	1,7%
Russia	530,2	21,9%
Turkmenistan	49,2	2,0%
Uzbekistan	50,3	2,1%
Algeria	73,8	3,0%
Iran	77	3,2%
Saudi Arabia	57,6	2,4%
United Arab Emirates	41,2	1,7%
Indonesia	66	2,7%
Malaysia	48,5	2,0%
Sum	**1906,1**	**78,7%**
World	2422,4	100,0%

Source: BP statistical review 2005.

Inter-regional trade flows are shown in Figure 7, both for 2002 and a projection for 2030 (WEO, 2004). The largest flows (in 2002) are from the former USSR (Russia) and Africa (Algeria) to Europe and from the Middle East and South-East Asia (Indonesia, Malaysia) to Japan.

Figure 7 Inter-regional trade flows natural gas in 2002 and 2030

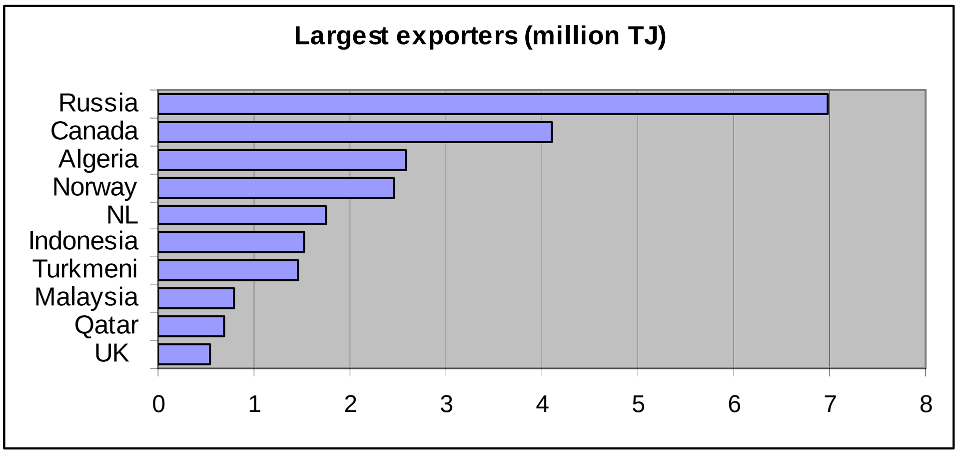


Source: *World Energy Outlook 2004*, © OECD/IEA, 2004.

Many of the large producers are also large exporters. In Figure 8 and Figure 9, the largest exporting and importing countries are shown.

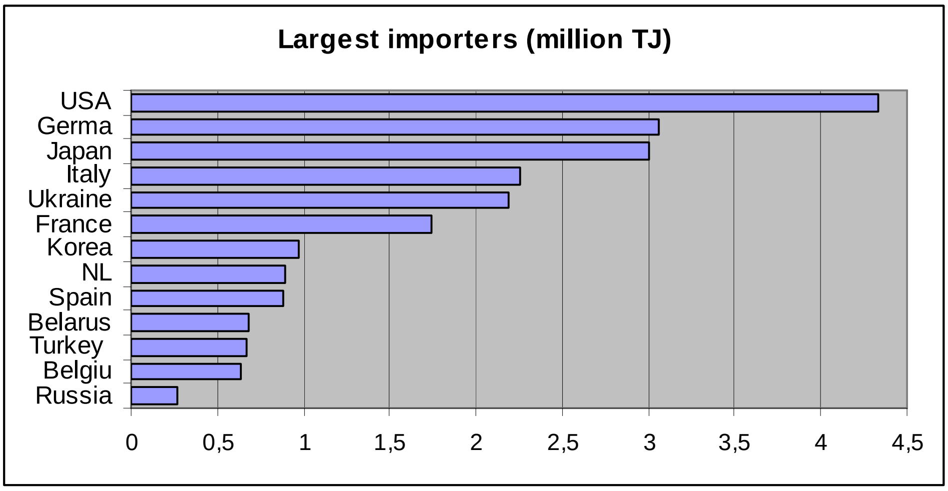
Only the USA, though being the second-largest producers of natural gas after Russia, are in fact the largest importer as well. Almost all of this imported gas originates from neighbouring Canada. Russia and the Netherlands are large exporters as well as fairly large importers.

Figure 8 Largest exporters of gas (data 2002)



Source: IEA.

Figure 9 Largest importers of gas (data 2002)

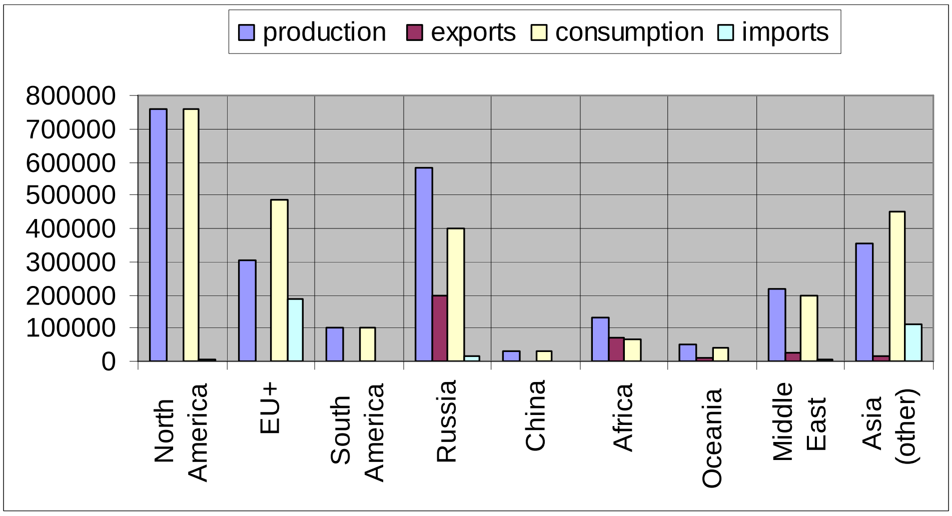


Source: IEA.

In total, about a quarter of the global production is exported to be consumed in a different country. In other words, just under 75% of gas produced is consumed in the same country: many countries primarily use nationally produced gas.

The global gas market thus consists of a number of fairly coherent, separate regions (e.g. Figure 10) that consume natural gas that originates from only a few countries. For this life-cycle study, this means that presenting representative averages for regions may be feasible, if data exist.

Figure 10 Production, exports, consumption and imports for regions (2000)



Source: IEA.

On the scale of global gas consumption LNG is a relatively marginal commodity. It makes up only about 6% of the total global gas market and 26% of international trade flows (2004). LNG is a typical outlet for remote gas fields with no sufficiently large consumer market in the vicinity and with no access to nearby international pipelines. It is a capital intensive activity requiring high investments for both liquefaction plants and tankers. It is therefore currently most competitive for markets at distances larger than some 4.000 kilometres from the nearest gas fields, so in some consumer markets, LNG is the only or most important commodity, especially in e.g. Japan and South Korea. LNG is currently becoming more important, as described in the next section.

2.11 Current developments

In future, the global market may become more complex. With the current trend of de-regulation as well as growing concerns about climate change around the world, the market for natural gas is expected to increase and change considerably.

Most notably, the market for LNG will expand, as it is more flexible with respect to transport, storage and production locations and therefore in supply and demand. Currently, about 75% of international trade is transported by pipeline, but LNG trade is growing each year by more than 5%. For 2030, IEA expects more than half of international gas trade to be in LNG. Another likely development is an increased use of gas storage, to increase flexibility of the supply chain.

Imports to North America are expected to increase by a factor of about 40 between 2002 and 2030 (Figure 7). The Middle East will become a major supplier to several regions, amongst others India and China. Australia will become a significant exporter to China and Japan. Production in Europe will decline, while demand in India and China is growing rapidly because of the fast economic growth in these countries.

Apart from a major expected shift to LNG, the production of “gas to liquids” (GTL) is expected to take off. The technology has existed for several decades, but its economic viability was low and therefore current production is negligible. With decreasing cost and increasing prices of the competing petroleum products, economic viability is now high. Also, increasing pressure on the energy industry to reduce pollution means GTL as a gas-derived liquid fuel is becoming more favourable. Major increase is expected after 2010 to 2020 (OPC, 2002; WEO, 2004) although it will still comprise only a couple of percent of total gas applications.

These developments are not explicitly assessed in this study. A life-cycle inventory is a snapshot in time by necessity, so expected shifts in markets and techniques call for continuous updating of data to remain representative. Data for “best available techniques” might be used to predict the effects of expected developments, but the coverage of BAT in this study is limited.

3 Methodology

3.1 Introduction

In the series of guidelines ISO14040 (details in ISO14041-14043), the requirements on life-cycle analysis (LCA) are laid out. A full LCA is a good deal more complex than suggested by Figure 2, although the basics are illustrated in that figure. This chapter follows the structure of those ISO guidelines, that may seem unusual to readers that are not accustomed to LCA studies. It is necessary to do so, as this makes the methodology used in this study transparent for possible users of the data. All methodological choices described in this chapter are applied in the actual inventory and impact analysis that are covered in a separate document (CE, 2006).

In this study, we will follow those guidelines as much as possible. However, as the aim of the study is to initiate an LCA database rather than to conduct a full LCA, the guidelines are not always applicable.

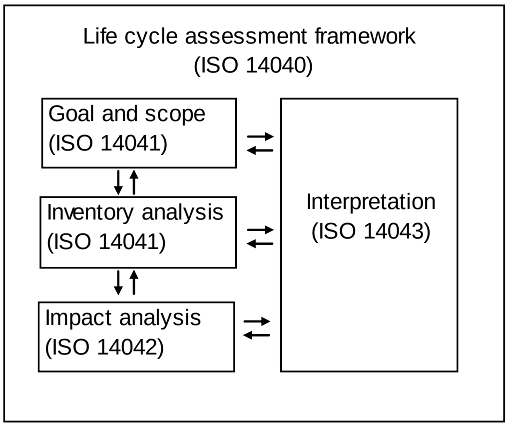
The main points where this study will not be able to follow the guidelines are:

1. Representative and consistent data quality. The selection of input data is mainly driven by data availability, as extra data generation is not currently part of the project.
2. Because of the incomplete coverage of the data, many stages in the life cycle cannot be linked to others. This means there is no single reference flow and data are given for a unit output per process.
3. The status of the utilization phase with respect to the life cycle. The logical reference flow for most of the life cycle would be measured in GJ or m^3. This could be extended to the utilization phase, but this would not yield useful results. Therefore, each application will be related to its own functionality and corresponding reference flow.

These points will be further elaborated in the corresponding sections below. Apart from those points, the ISO guidelines are observed. They concern mostly procedural requirements, such as full description of all essential steps and assumptions made, clear referencing to external sources and consistent approach in data selection and analysis to suit the defined goal and scope.

An important approach to internal consistency according to the ISO guidelines is the iterative character of life-cycle studies (Figure 11). The current study is the result of iterations as well. In this methodology chapter, we indicate what the initial scope was as well as what turned out to be possible in practice.
The chapter follows the regular structure according to the ISO guidelines, which means goal and scope definition and the data selection criteria are described and underpinned first (ISO14041). Details concerned with the so-called allocation (ISO14041) and choice and description of the impact assessment method (ISO14042) follow.

Figure 11 Framework for life-cycle assessments (figure after ISO 14040 guideline)



The guidelines ISO14043 deal with the interpretation of LCA. Interpretation is tied in with all stages of the LCA and therefore discussed in the subsections concerned. It is also closely related to the iterative character discussed before; interpretation does not take place at the end of the life-cycle study, but continuously.

3.2 Goal

The goal of the present study is to initiate a global data base of consumptions and emissions (impacts) that provides an overview of the life cycle of natural gas supply. It is meant to be a first step toward the construction of an inventory database that covers all global flows of natural gas.

3.3 Scope: function and unit

The function that a unit amount of natural gas will be used for depends on the application. Applications of natural gas may be:

- Transport (LNG, CNG).
- Residential (heating, cooking).
- Electricity- or co-generation.
- Industrial (drying, heating, powering, etc.).
- Hydrogen production.
- Material (non-energy use, chemical industry).

Most of the life cycle up to the consumption phase is identical for the various applications. Therefore, it is practical to use a uniform functional unit as a reference for data collection. The data records will in principle be given for a cubic meter[2] (Nm^3), but this unit can always be translated into e.g. GJ by multiplying with the energy content of the gas concerned.
It should be noted that this Nm^3 always refers to the output of the process under consideration. As this inventory is not targeting a specific life cycle and the

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[2] At standard temperature and pressure; STP.

processes are not linked, it is not possible to use a final reference flow (that could be e.g. a Nm^3 gas supplied at the end-user).

3.4 Scope: system definition

The full life cycle of natural gas consists of the following stages:

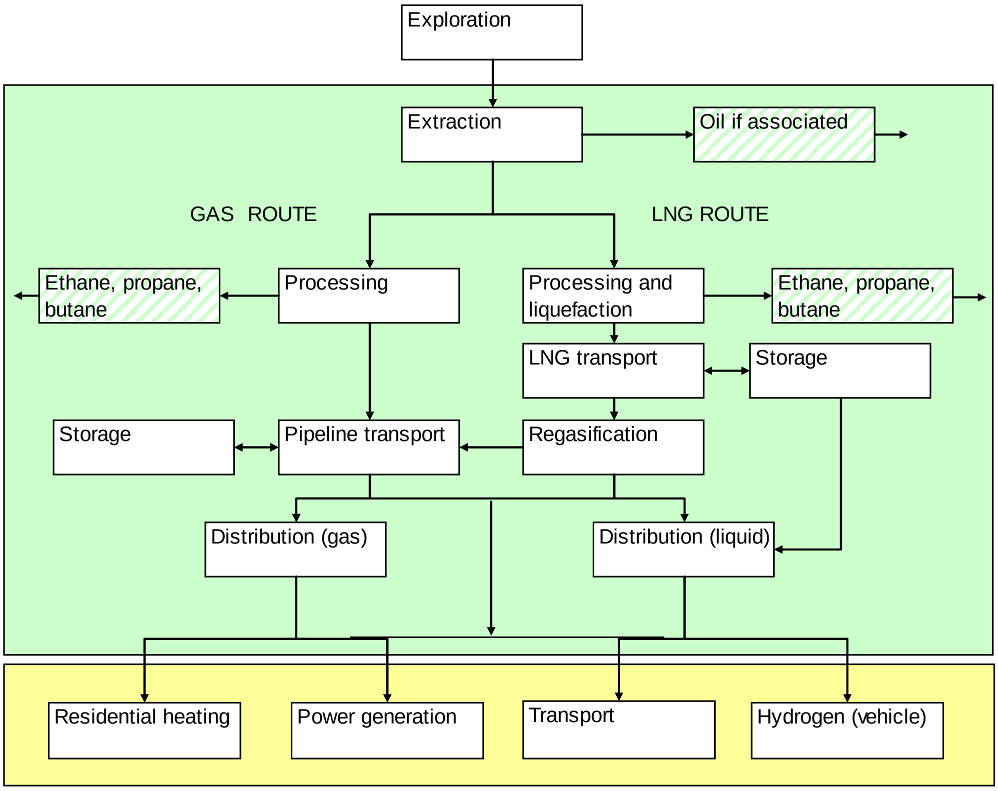
1. Exploration (including well preparation and closure).
2. Extraction.
3. Processing.
4. Transport.
5. Storage.
6. Distribution.
7. Utilization.

Of these stages, the first and the last pose complex problems in terms of allocating impacts to the life cycle of gas. Exploration for gas is often tied in with exploration for oil. The same holds true for extraction, but in this case impacts may be allocated to gas and oil by e.g. energy content or economic value. At the exploration stage, there is no knowledge of the yield of either gas or oil; if it so happens that only oil is found, allocation to gas is impossible, although the exploration was targeting gas as well as oil. Therefore, the exploration stage will not be included in this study. This is common practice, not only for fossil fuels, but also for mineral ores (MSD, 2001).

For utilization, the issue is whether impacts should be allocated to the gas chain or, in the case of cooking, to the life cycle of the food. After all, when the consumer doesn't boil those potatoes, there is no gas consumption. Typically, energy use in the "consumption" phase is allocated to the product that transforms this energy. Hence, impacts of gas use for cooking are allocated to food, for mobility to transport, for electricity generation either to electricity or to electric appliances, etc.

When comparing the life-cycle impacts of gas to life-cycle impacts of alternatives given a certain application, however, it is essential to take the impacts of utilization into account. In this project, figures are included for various applications (section 2.9). The functions of the various applications are too different to have a useful common reference flow and unit. Therefore, each application is treated separately and the utilization phase has a distinct status within the framework of this study. This is illustrated in Figure 12.

Figure 12 Schematic representation of the scope of the study (dashed cells indicate by-products)

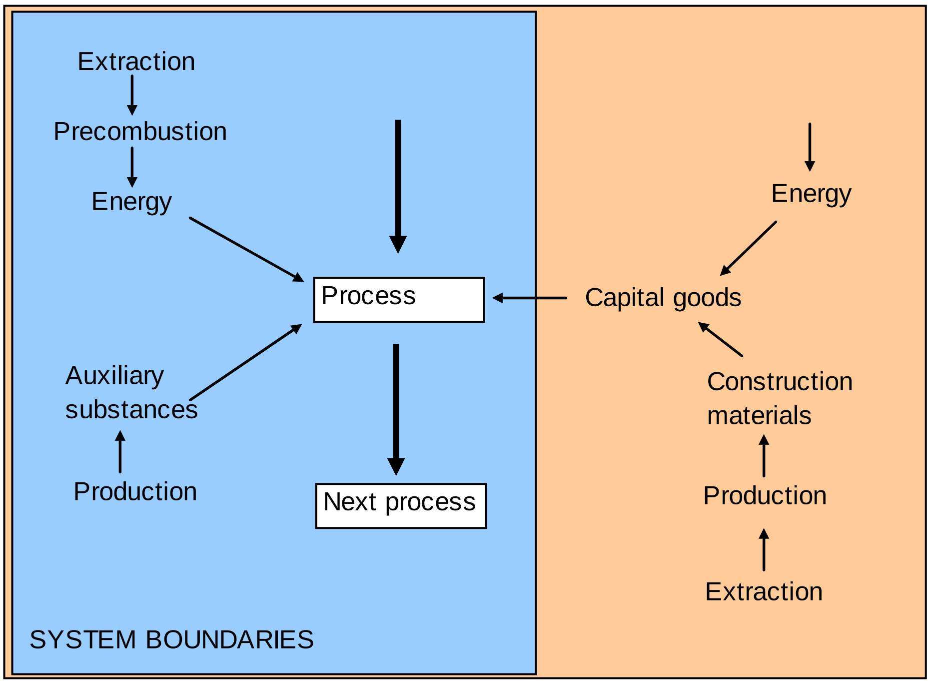


3.5 Scope: data

In the life cycle of a product, several "orders" or levels of detail can be distinguished. The lower orders of the life cycle consists of all processes that are directly involved in the production of substances that are consumed in the production of the product itself. This includes fuels (energy carriers) that may consumed. For instance, for a MJ of electricity used in a process, the energy and related emissions of generating that electricity are also included. It is obvious that this is necessary, because there are no direct emissions involved in the use of electricity. If those upstream effects were not included, the use of electricity to create a product would not lead to any environmental impacts allocated to that product.

Higher orders of the life cycle consist of processes that are involved in supporting those lower-order processes. That means, for example, the building of processing plants or pipelines for gas transport and the construction of the materials in them. Even higher orders might concern the construction of trucks to transport the metals needed to build pipelines, et cetera.

Figure 13 System boundaries include in principle (upstream) effects of all resources that are consumed in the life cycle (if contributing more than 10% to the total effect of the process concerned)



In principle, a quantitative assessment should be made of the significance of the contribution of processes in the different orders of the life cycle. A cut-off criterion might be to exclude orders that contribute less than 10% to the total. This is a very data- and time intensive process, however, and therefore in this study it is decided a priori that only lower-order processes will be included. The resulting system boundaries are drawn schematically in Figure 13. Given the goal of the present study, a lower-order inventory is appropriate.

This means that inputs and outputs will be inventoried for all processes involved in the chain of substances that are either part of the product or are consumed in making it. The sources of emissions considered will be those associated with standard operations, including venting and leakages – in e.g. pipeline transport – in so far available.

Even some of those lower-order processes may not contribute significantly to the total. This is often the case for certain additives that are added to the main product in small quantities. There are also processes that do give significant contributions to the total, but that are simply not covered by the available data. This means that in practice it is not currently feasible to define minimum requirements on the data representativeness in terms of mass, energy or environmental impact covered (see also section 3.5.2). Rather, data collection is driven by availability and representativeness is tracked as a percentage of volume (m^3 or GJ) covered. Hence, data representativeness is known, but no minimum requirement is applied. This is a departure from ISO14041.

In practice, the inventory data are structured as follows:

- Consumptions:
    - Natural gas.
    - Electricity.
    - Heavy fuel oil (LNG transport).
    - Methanol (processing).
    - Glycol (dehydration).
    - Amines (sweetening).
- Emissions:
    - Direct emissions due to fuel combustion, leakages, process emissions.

The indirect emissions (of electricity generation or methanol production, for instance) are *in general not* included in the current database. The reason for this is that those emissions will vary greatly per country of production. It was beyond the possibilities in this project to include those emissions for all processes. In future applications of the database these emissions should be added. In practice this means that not all inputs and outputs have been linked in the current database.

3.5.1 Selection of emissions

In principle, there are many impacts that may be considered in a life cycle assessment. For natural gas, the main impacts - in terms of contribution to the total global impact - are global warming, acidification, marine ecotoxicity and abiotic depletion[3] (see e.g. Table 2). The latter category will be excluded in this study, as it is not considered an environmental problem in itself[4]. Marine ecotoxicity is an important impact category, but there are problems with the exact methodology of this category (TNO/CML). Moreover, in the case of gas production and transport, the impacts in this category, as well as the other toxicity categories, are almost entirely due to the use of steel in the construction of capital goods (wells, pipelines, plants, etc.). In this study, these are not included (Figure 13). Therefore, toxicities will not be targeted in this study. This is not to suggest that these impacts may not be important, but just that they do not match the scope of this study.

Apart from impact categories related to emission of substances, there are also so-called “intervention” impact categories: use of land, use of water, use of energy. The last of these clearly overlaps with emission impact categories, as emissions of CO_2, SO_2, NO_x, etc. directly result from energy consumption. Land use may be an important parameter in comparisons of energy applications of natural gas versus biomass. Without the context of such a comparison, however, the inventory of land use is less meaningful, as the impact of land use are extremely site dependent. The same holds true for the use of water. We therefore believe that those impacts should not be generalized in a global inventory, but should be inventoried in a well-defined LCA case study when appropriate.

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[3] This is when comparing all impact categories of the CML baseline 2000 method, with global normalization.

[4] Abiotic depletion may be used as an indicator for environmental impact over the life cycle, but doesn’t add any information when the environmental impact over the life cycle is already explicitly assessed.

Note that some of the emission impacts may also be site dependent. In section 3.7, we explain how this may be treated.

Table 2 Example of normalized impacts for gas (including capital goods) produced in Russia and transported to Europe by pipeline, ordered by magnitude. (Note: these are not data from this report)

abiotic depletion	1,45E-13
marine aquatic ecotoxicity	3,86E-14
global warming (GWP100)	1,86E-14
Acidification	9,23E-15
fresh water aquatic ecotox.	4,93E-15
photochemical oxidation	2,69E-15
terrestrial ecotoxicity	1,91E-15
Eutrophication	1,59E-15
ozone layer depletion (ODP)	1,09E-15
human toxicity	3,21E-16

Source: (Ecoinvent 1.2), using SimaPro with CML Baseline 2.03/world1995 method.

Looking in more detail at the emissions that lie behind the impacts in the remaining categories, it is obvious that with only a few emissions the bulk of the environmental impacts may be traced.

Table 3 Major contributions to impact categories, grey cells indicate emissions that will be part of the inventory (data and impacts as Table 2)

Impact category	**Emission (air)**	**Contribution to total impact in category**	**Source**
Global warming	CO_2	76%	Processing
	CH_4	21%	Leakages
Smog formation	SO_2	50%	Processing
	CH_4	15%	Leakages
	CO	10%	
	Ethane, propane	24%	
Acidification	SO_2	78%	Processing
	NO_x	22%	Processing
Eutrophication	NO_x	93%	Processing
Ozone depletion	Halon 1211	98%	Fire extinguisher pipeline transport (banned, so no longer valid)

Although for a full life-cycle assessment more categories should be considered, in our current study we will collect data on emissions of CO_2, CH_4, NO_x and SO_2.
This is partly instigated by the availability of data, but, as explained, also by the belief that these emissions cause the priority impacts along the gas chain. In covering those four emissions, roughly 90 to 100% of the global warming, acidification and eutrophication impact is covered, as well as 65% of smog formation.
In Table 3, the contributions of the emissions to total impacts are determined using the impact factors of the CML method (see section 3.7). To assess the sensitivity of the resulting choice of four emissions to the impact method used,

Table 4 lists the contributions for the method “Eco Indicator 99” (PRé consultants).

Table 4 Major contributions to total damage (process data as Table 2; impacts and weighting Eco Indicator 99)

Emission (air)	**Contribution to total damage excluding raw material depletion**
CO_2	18 to 33%
CH_4	12 to 22%
NO_x	4 to 37%
SO_2	21 to 27%
Particulates	7 to 13%
Total of CO_2, CH_4, NO_X, SO_2	*85 to 87%*

The same four emissions are dominant when using the Eco Indicator method, although the relative contributions vary depending on the exact damage assessment and weighting applied[5]. Particulate emissions contribute more to the total damage than NO_x in one of the assessment implementations, but in the others NO_x is the dominant emission.

To conclude, the choice of CO_2, CH_4, NO_x and SO_2 for an initial inventory is fairly independent of the details of the impact assessment method. In practice, unfortunately, data on SO_2 emissions are very hard to find. This means that in the actual inventory, little data on SO_2 are presented. This is an important point for future attention.

3.5.2 Data quality and structure

According to ISO14041, data quality requirements should be specified. The requirements should concern time, geographical and technical coverage of the data. To meet those requirements, one may collect adequate data in several ways:

1 Data from existing literature or data bases.
2 Empirical data, that is, making new measurements.
3 Theoretical data, calculated from models of certain processes.

Given the goal of the project, the data collection is driven by availability. Therefore, national data that cover the representative technical mix and are more recent than 1995 will be collected as available from existing data sources (first option in list above). The national geographical level is chosen as the optimal aggregation level. Data could in theory be generated at the level of individual gas treatment plants. In fact, in most first world countries emission data are registered on individual plant level. However, because the infrastructure is such that gas supply is regulated on regional and national levels, with no direct physical connection between gas well and consumer, this is not necessary.

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[5] Eco Indicator 99 has a variety of damage assessment and weighting methods, the table gives the range of E/E, I/I and H/H results; for more information see (PRé, VROM report 1999).

If such data are not readily available, no additional empirical or theoretical data will be constructed. Rather, the data “record” will be left empty and the geographical coverage will be translated into a “representativeness” (%) of the weighted average compared to the true global average. Also, a minimum and maximum is derived from the collected data. It should be noted that a high representativeness indicates that the calculated average is close to the global average, but there may still be a large spread in the data. A high degree of representation therefore does not mean the average is close to any realistic situation.

Next to the weighted average, data for the “best available technique” (BAT) will be given for each life-cycle stage if possible. This may involve some theoretical calculations if existing data are not found. Also, for some processes, averages or typical techniques may be given at a regional level instead of national.

When using the data for comparative purposes (e.g. LCA of LNG versus petrol in transport) the effect of data quality and representativeness on the comparison should be given proper consideration. Large differences in data quality between two products compared in an LCA will give unreliable outcomes.

3.6 Allocation

Gas production often takes place in association with oil production. For the production of this so-called associated (either free or dissolved) gas, some allocation of impacts to the co-products gas and oil, respectively, has to be made. For non-associated gas (either from gas well or condensate well), allocation may also be necessary as there may be co-products at some stage in the life cycle, such as condensates.

These co-products have energy as well as non-energy (primarily oil) applications. For energy applications, allocation by total energy content could be a logical choice. For the non-energy application, however, allocation by economic value could be more appropriate. Almost all applications and therefore life cycles are driven by economic considerations. The (local) economic value of gas e.g. determines whether it will be flared or captured and processed, in the case of associated gas.

However, economic value is a local, variable and unpredictable quantity. Although in practice it may be feasible to allocate by economic value, allocation by energy content is chosen as the first option. It should be noted, however, that the ISO guidelines prefer economic allocation over allocation based on a physical quantity that has no direct causal relation to the processes that are allocated.
For instance, in the case of extraction of oil and associated gas, one could argue that the energy consumption is primarily driven by the oil. The energy content of gas and oil bear no direct relation to the extraction processes.

3.7 Impact assessment

An impact assessment consists of translating the inventory output data (consisting in our case of only emissions per functional unit) to environmental impacts. As the concept of environmental impact is quite a broad one, there are several implementations or models to make this translation.

The impact models use what are called “characterization factors” that give the environmental impact per unit of emission, e.g. 1 kg of CH_4 emitted to the atmosphere has an effect 23 times stronger than 1 kg of CO_2 (IPPC, 2001). These factors are calculated by means of e.g. atmospheric computer models and may be expressed in several ways. For climate change, this can range from “increased infra-red absorption” (mid-point indicator) to “economic damages due to increased occurrence of malaria” (end-point or damage indicator). All impact models are based on solid scientific and economic research, but some are, as follows from the above, more physics oriented and others are economy or damage oriented.

A full impact assessment consists of:
- Classification, to allocate an emission to a certain impact.
- Characterization, to quantify the particular impact of the emission.
- Normalization, to relate the absolute impact to a reference (optional).
- Grouping, to facilitate interpretation (optional).
- Weighting, to compare different impacts with one another (optional).

An internationally accepted and recognized impact model is the CML model (CML, 2002). It uses mid-point indicators, that are relatively transparent in the underlying physical modelling. This suits the goal of this study: build a structured database and give a first insight in the life cycle of natural gas, rather than compare gas, in a certain application, to comparable products. More importantly, the CML factors are all expressed in terms of “potential” impacts or impact potentials. This means that the model is in principle globally applicable. The actual impacts or damages may vary for different regions, but the impact potential is only determined by the type of substance emitted. This matches the global scale of the current assessment. In a more detailed LCA case study, the practitioner may translate these impact potentials to actual impacts or damages for site-dependent impacts, such as acidification (SO_2) or smog formation (NO_x), by using existing databases with site-dependent factors.

The current assessment inventories only four emissions (section 3.5.1). It is therefore not really necessary to do the impact calculations, except to determine the combined effect of CO_2 and CH_4 (greenhouse effect). When making the impact calculation, emissions are classified and characterized according to the CML model in the present study. Next to the specific emissions (and greenhouse effect), the relative gas consumption will be used as an indicator.

There is certainly no need for further reduction of the number of impact categories, so interpretation will be relatively straightforward, without the use of damage- or other weighting techniques and even normalization. The optional steps of the impact assessment mentioned above are therefore all left out, as this leaves the data more flexible and more closely representative of the global situation.

4 Overall results

4.1 Introduction

The inventory data for the various life-cycle stages are listed and described in a separate document (CE, 2006). Some data are confidential and therefore not listed in this (public) report. In this chapter, aggregated results are presented and the possible applications of the data set are discussed. In the aggregations, confidential data are taken into account when applicable.

The results are aggregated geographically, in order to make comparisons between several (market) regions in the world, or along the average life cycle, in order to make comparisons for different applications. In the latter case, figures are approximate because the reference flow is not well-defined and therefore coupling of life-cycle stages is not possible. The data used in this project, obtained through the IGU, are too patchy to form a true life-cycle inventory database. The data that are available are of variable quality, due to for instance undocumented averaging or lack of allocation to by-products, but in general the quality is promising. The effect of expected shifts in the global market (see sections 2.10 and 2.11) will be briefly discussed. This concerns especially the effects of global de-regulation.

4.2 Overview of regions

4.2.1 Production

Data are available for several European countries, the USA, Russia and Australia. Together, the volumes produced in these countries represent 54% of global annual production of natural gas.

Energy consumption and emissions at the processing stage depend on the quality of the raw natural gas. In Table 5, it is clear that little processing is necessary as the quality of the Russian gas is relatively high (99% CH_4, ExternE) and the energy efficiency of the processing is 99%, higher than in the other regions. In Australia, the energy efficiency of processing is 91%. The range in Australia is large (AGA, 2000), with energy consumption for processing ranging from 1.1% (Northern Territories) to 14.8% (Victoria). However, these figures partly include energy consumption for oil processing and liquefaction, which means the actual efficiency of the gas treatment for non-LNG gas is higher (AGA, 2000), with energy use possibly less than 5%. For these reasons, the figures for Australia are not included in this chapter.

Table 5 Consumption and losses of natural gas (volume percentage) at the production stage (non LNG)

	NW Europe	Russia	USA	Average
Energy	1.2 – 1.5%	0.6 – 1.0%	5.4%	2.7%
Fugitive and venting	0.04 – 0.13%	0.44 – 0.5%	0.81%	0.58%
Flaring	0.12 – 0.29%	unknown	0.55%	0.48%
Total gas consumption and losses	1.3 – 1.7%	1.1 – 1.5%	6.7%	3.5%
Greenhouse effect (g CO_2eq / Nm^3)	25-44	120	250	150

In the United States, about 5% of the natural gas is used for energy in the processing. Methane content of the raw natural gas may be as low as 75%, which explains the relatively high energy consumption. In NW Europe, energy consumption is somewhat higher than for Russian gas processing, but considerably lower than for the USA.

The emissions of methane and the amount flared do not depend on the gas quality but rather reflect the technology used. In NW Europe, the total of fugitive and venting emissions and gas flared may range from 0.16% up to 0.3%, compared to more than 1.3% in the USA (Table 5).

In total, gas consumption and losses in the processing step amount to 1.3-1.7% for EU/RU and almost 7% for the USA. The average total[6] is 3.5%.

In terms of global warming effects of production, the range is 0.025 to 0.46 kg CO_2-eq/Nm^3. The ratio of total gas consumption and losses to global warming effect is mainly influenced by the percentage of fugitive emissions in the total. For USA, the climate impact per amount of methane “used” is twice as high as for NW Europe. For Russia (ExternE data), the climate impact per amount of methane “used” is more than five times higher than for NW Europe (Figure 14).

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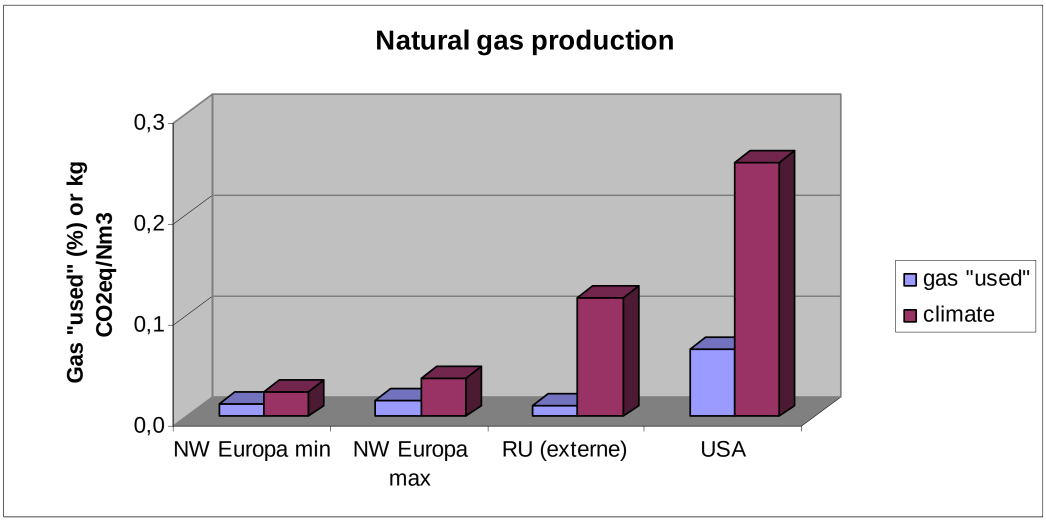
[6] Note that the average total is not the sum of the averages for energy, fugitive and flaring; each of those averages derives from slightly different records, due to gaps in the database.

Figure 14 Effects of the processing stage for different regions (note: data for Australia include effects of liquefaction and oil processing, see text)



Despite the low energy consumption, the greenhouse effect of Russian gas production is still high due to fugitive emissions. The greenhouse effect of USA gas production is even higher.

To conclude, for non-LNG production, the USA have a relatively high energy consumption per unit produced. In determining the greenhouse effect of the processing step, the fugitive emissions are an important factor, as methane itself has a stronger greenhouse impact per kg emitted than the CO_2 resulting from flaring or combustion has.

No data of wide-spread consumption of externally produced electricity during the production phase have been found, but in their annual report of 2004, Statoil (Norway) reports electricity consumption. For the Kollsnes plant, about 80% of the direct energy use is in the form of electricity. The contribution of electricity to overall emissions could be significant, but depends on the emission factor for electricity, which could be argued to be low in Norway due to the prevalence of hydropower.

For LNG, the amount of energy needed for processing is much higher due to the additional liquefaction. In this project, data were collected for several individual existing production locations as well as locations under construction and the Japanese import mix. In Table 6, the relative gas consumption is listed for those. The Japanese mix consists of LNG produced in Brunei, Australia, Malaysia and Indonesia.

Table 6 Gas consumption in LNG processing (data this study, compared to Ecoinvent)

	Capacity under construction	Existing capacity	Japan mix[a] (existing)	Average (existing)	Ecoinvent[a]
Refrigeration cycle	6.2-6.9%		8.8%		14.94%
Auxiliary electricity	1.6-1.4%				
Hot oil system	0-0.3%				
Venting	(0.005%)		0.2%		0.05%
Flaring	--	0.2-0.4%	0.7%	0.5%	
Total	7.9-8.7%	9.9-12.9%	9.6%	10.3%	15%

[a] Includes allocation to byproducts.

Together, the data for existing capacity cover approximately 70% of the global LNG production. The average gas consumption over the capacity covered is 10.3%. For the capacity under construction, this figure is 8.2%. For BAT[7], this figure is about 6% (CE, 2006).

The specific data in this project all show lower consumptions than the more general data from Ecoinvent, that give 15% as the total gas consumption for LNG production. Determining the underlying reasons for this difference in gas consumption between Ecoinvent and the data in Table 6 would require a separate study. The Ecoinvent data are based on relatively old data and are not targeting a specific situation. They also include the effects of capital goods, but this should not be significant for gas consumption.

All in all, there seems to be a trend toward higher efficiency in the LNG production and liquefaction stage. The actual emissions arising from LNG production are listed in Table 7.

Table 7 Emissions and climate impact for LNG production in g/Nm^3 gas (between brackets if only one data record available)

	Capacity under construction	Existing capacity	Japan mix (existing)	Average (existing)
CO_2	214 - 221	202 - 280	299	280
CH_4	(0.036)	(5.9)		
NO_X	0.14 – 0.19	(0.99)		
SO_2	(0.0011)	(0.0029)		
Greenhouse effect of CO_2 + CH_4 (g CO_2eq/Nm^3)	(222)	(377)		

Corresponding to the higher efficiency, the specific CO_2 emissions are also lower for the planned capacity than for the existing capacity. The emission associated with BAT is 116 g/Nm^3 (CE, 2006). More extreme differences can be seen in the NO_x and CH_4 emissions, although it should be noted that these figures are

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[7] With capture and storage of the CO_2 contained in the raw gas.

available for only one existing plant. As a result, there is a potentially large reduction by a factor of 1.7 in total greenhouse effect between existing and future processing plants. As is the case for non-LNG processing, the CH_4 emissions are an important contributor to the total climate impact potential.

When comparing the non-LNG and the LNG processing, it is clear that the LNG processing on average takes more energy. The average gas consumption is 4.1% in the former case and 10.3% in the latter. Looking at individual countries or locations, however, current energy consumption for non-LNG processing may be as high as 7% and for LNG processing at plants currently under construction as low as 8%.

4.2.2 Pipeline transmission

Emission data for pipeline transmission are available for several European countries, Australia, Iran, USA, Canada, Russia, Algeria, Argentina. These countries cover about 80% of the global production volume, hence a similar percentage of global pipeline transportation is covered.

In Table 8, regional averages are shown, as well as the total average and spread per consumption and emission. For Europe, the data are taken from Eurogas-Marcogaz.

Table 8 Regional data for pipeline transmission

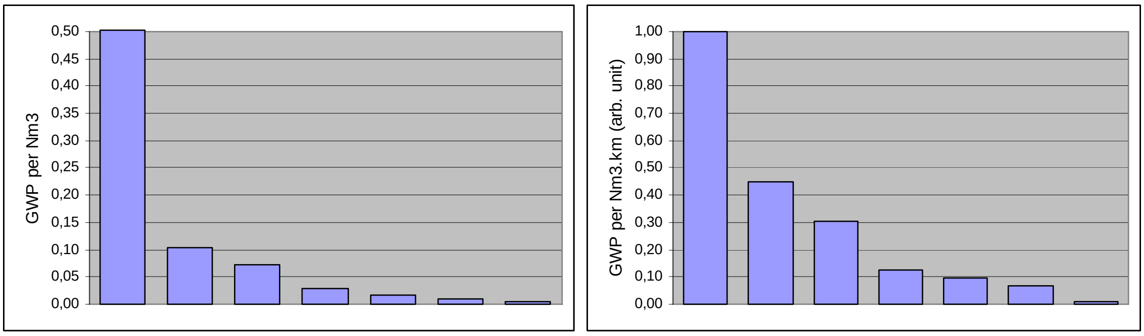
	Europe	North Am	Asia	Other	Average	Max
Gas (energy)	0.39%	2.19%	8.67%	0.96%	4.1%	9.08%
Gas (fugitive & venting)	0.02%	0.35%	0.67%	0.08%	0.4%	0.74%
CO_2 (g/Nm^3)	7.81	51.02	310.59	20.83	132.12	332.77
CH_4 (g/Nm^3)	0.11	2.51	6.67	0.11	3.35	7.39
NO_x (g/Nm^3)	0.02	0.06		0.10	0.05	0.34
Percentage of global gas volume	12%	27%	24%	6%	79%	

Clearly, there is quite a range in consumptions and emissions, but it should be noted that the effect of the distance is not included in the data. The variation in gas consumption for combustion, for instance, is very closely related to the distance of the transmission.

In principle, a comparison between pipeline transmission systems in terms of efficiency and emissions should be based on the total actual Nm^3*km of transport. This would be in line with mobile transport modes, where comparisons are based on e.g. the actual ton*km of transport. However, these data are not available and commonly the comparison is made for the total Nm^3 transported. An approximation of the distance-corrected figure can be obtained by using the total volume of gas transported and the total length of the pipeline system in a country.

In Figure 15, the distribution of resulting total greenhouse gas emissions in some individual countries are shown, both per cubic meter of gas transported and with the approximate correction for the distance as described above. This "distance correction" shows that the differences between countries are probably smaller than suggested by the figures per Nm^3 only. Just like energy consumption, fugitive methane emissions due to leakages are also partly related to the length of the pipeline, but accessibility and state of material play a role as well.

Figure 15 Sum of CO_2 and CH_4 emissions (GWP in kg CO_2-eq) per Nm^3 transported as well as per Nm^3.km (total volume times length total pipeline system) pipeline transmission in seven countries (anonymous)



For LNG transport, the consumptions and emissions are referred to a Nm^3*km of transport. The average gas consumption is 0.4% per 1,000 km (the value is derived for the Japanese market, which represents 43% of the global LNG market). With best available technology, this figure can probably be 0.2% per 1,000 km. It should be noted that both for the average technology and for BAT, there is also consumption of heavy or medium fuel oil.

4.2.3 Overview over the chain

For the various stages in the chain, data were found for a variety of countries and/or regions. All in all, however, there are too many data gaps to link those stages to give results for the full supply chain for a certain regional market, according to true LCA principles.

In this section, we present the resulting global averages, bearing in mind the previous discussions (see section 3.5.2) on the validity of such global averages.

Table 9 A global look at the natural gas chain (empty cells indicate lack of (sufficient) data, not necessarily zero value)

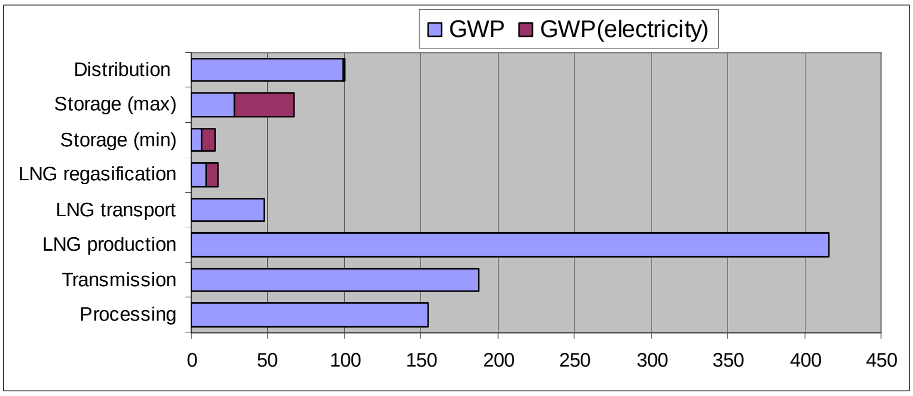
	Production	Transmission	LNG production	LNG transport	LNG regasification	Storage		Distribution
	average	average	average (existing)	BAT (1,000 km)	average	min	max	average
Percentage covered	54%	79%	69%	not applicable	27%	not applicable		34%
Natural gas consumption	3.52%		10.3%					
– energy	2.73%	4.1 %	8.8%	0.21%	0.43%	0.13%	2.00%	0.16%
– fugitive / venting	0.58%	0.4%	0.2%		0.00%	0.00%	0.10%	0.42%
– flaring	0.48%		0.5%					
– other								
Electricity (MJ/Nm^3)					0.042	0.047	0.205	0.003
Fuel oil (kJ/Nm^3)				73.8				
Emissions (g/Nm^3)								
CO_2	62.05	132.12	280.22	9.59	8.88	*3.39*	*10.80*	0.16
CH_4	4.01	3.35	5.90		0.03	*0.16*	*0.75*	4.32
NO_x	0.07	0.05	0.99	0.01	0.004	*0.002*	*0.10*	
SO_2			0.003	0.01				

Once again, we note the following with respect to the data in Table 9:

- Electricity consumption is given as final energy consumption.
- Emissions due to electricity consumption are not included in the emission data.
- Averages do not necessarily add up, as there are small variations in coverage for different sub-data.
- For LNG transport and for storage, data are not given as averages over a number of country-specific data records and therefore there is no “percentage covered”.

It is clear that production and transmission are the most energy-consuming stages of the chain and have the highest climate impact. In Figure 16, the CO_2 and CH_4 emissions (from Table 9) are added to yield the climate impact per Nm^3 per life-cycle stage. Estimates of the climate impact of electricity are also included, assuming a (life-cycle) emission factor of 188 g/MJ final energy consumption.

Figure 16 Climate impact (GWP) in gram CO_2-eq per Nm^3 (for LNG transport, a distance of 5,000 km is assumed)



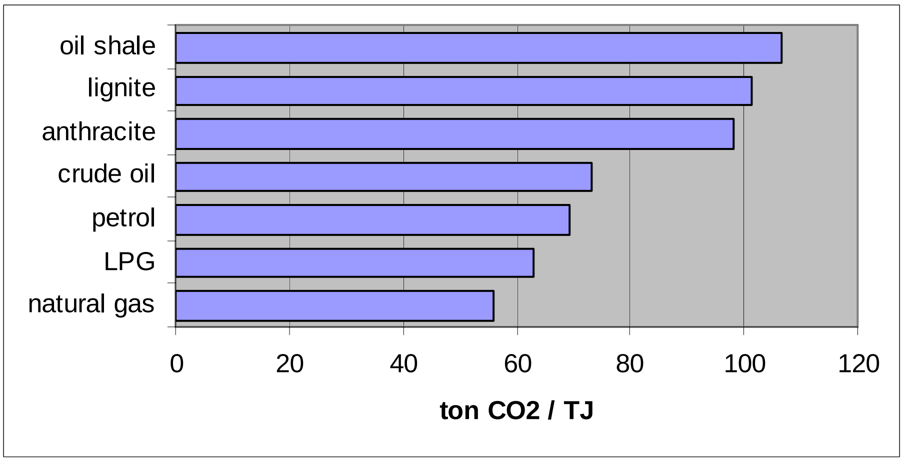
Electricity only has a significant contribution (about 50%) to the total climate impact for regasification and storage. LNG production clearly has a climate impact per Nm^3 that is almost a factor 3 larger than for production of standard natural gas. When looking at the combination of production and transport for the liquid and the gaseous routes along the chain, the impact of LNG is only 35% higher, when assuming a transport distance of 5,000 km.

4.3 Utilization: literature overview

In this section, data from general public literature is used. The data collected in this study is used in section 4.4.

For emissions in the utilization phase, a set of IPCC emissions factors for CO_2 exists, that is used for national greenhouse gas monitoring. Figure 17 shows these factors for a range of fuels. Natural gas has the lowest emission factor for utilization of all solid, liquid and gaseous fossil fuels.

Figure 17 IPCC default emissions factors



Source: ETC/ACC technical paper 2003/10.

From a life cycle perspective, this is of course not the entire story. A myriad of studies comparing the emissions of different fuels for specific applications is available. Results of those studies are in general not suited for a broader comparison, as in each life-cycle study different assumptions are made. Nevertheless, in the recent report of the World Energy Council (WEC, 2004), a compilation of life-cycle assessment results for a variety of applications of fossil fuels is presented.

For power generation, in a range of current techniques, natural gas is very favourable in terms of several emission (greenhouse gases, sulphur dioxide, nitrogen oxides) as can be seen in Figure 18. With respect to coal, specific emissions are 50% or less.

Table 10 Combustion versus upstream emissions according to Wuppertal 2003

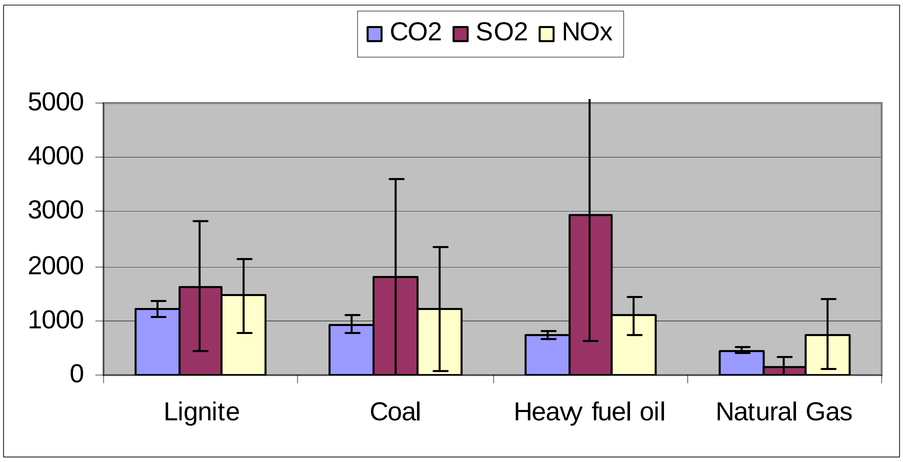
	Combustion (ton CO_2/TJ)	Upstream (ton CO_2/TJ)	Ratio
Natural gas	56	10-25	3.7
Oil	77	10	7.7
Coal	92	15	6.1
Lignite	110	4	27.5

An estimated figure of the ratio of combustion to upstream emissions resulting from this study is given in 4.4.1.

In Figure 18, data are shown for life-cycle emissions for power generation. The data derive from different studies, see (WEC, 2004), so it should be noted that the figures may not be strictly comparable. Clearly, natural gas has the lowest specific emissions of the four fossil fuels shown.

The upcoming technique of CO_2 sequestration may influence these life-cycle emission profiles, as it will be applied to the combustion emissions (primarily power generation). This means that the upstream emissions will become more important and the comparison between fossil fuels may become more favourable for e.g. coal. It could be argued that applying sequestration to coal-powered plants is more efficient, since emissions are much larger. Naturally, CO_2 sequestration does not influence the emissions of SO_2 and NO_x or other substances.

Figure 18 Literature ranges (indicated by vertical bars) of life-cycle emissions for power generation in ton CO_2eq or kg per GWh_{el}

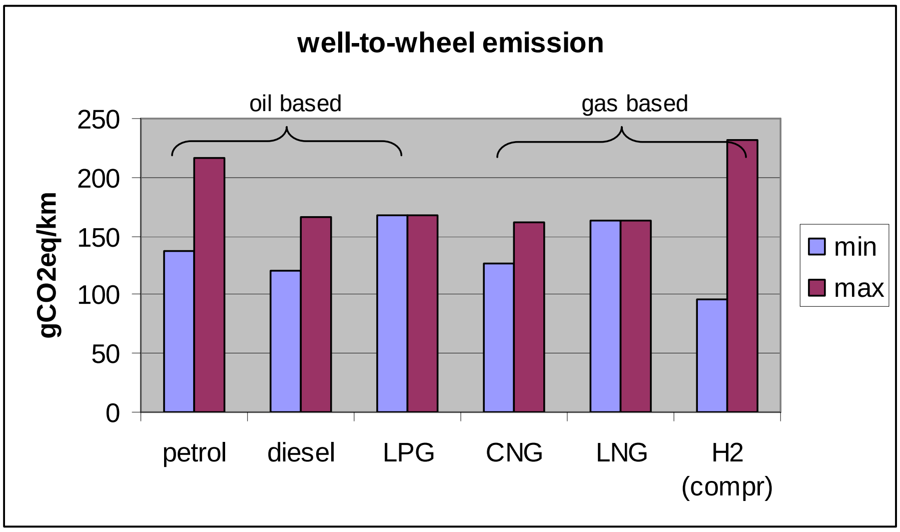


Source: (WEC, 2004).

A study commissioned by the Spanish government (IDAE, 2000) shows that the life-cycle impact (including a wider range of emissions and impacts than considered in this study) of natural-gas power generation is even lower than that of then current production technologies for photovoltaic energy (final “score“ 49 versus 85).

For transport applications, the (WEC, 2004) compilation shows a less clear picture. Firstly, only greenhouse gas emissions are assessed, whereas in the case of transport emissions that cause air pollution are of obvious importance. Secondly, the spread in life-cycle emissions listed is fairly large for both oil-based and natural-gas-based fuel options. The (WEC, 2004) data are shown in Figure 19.

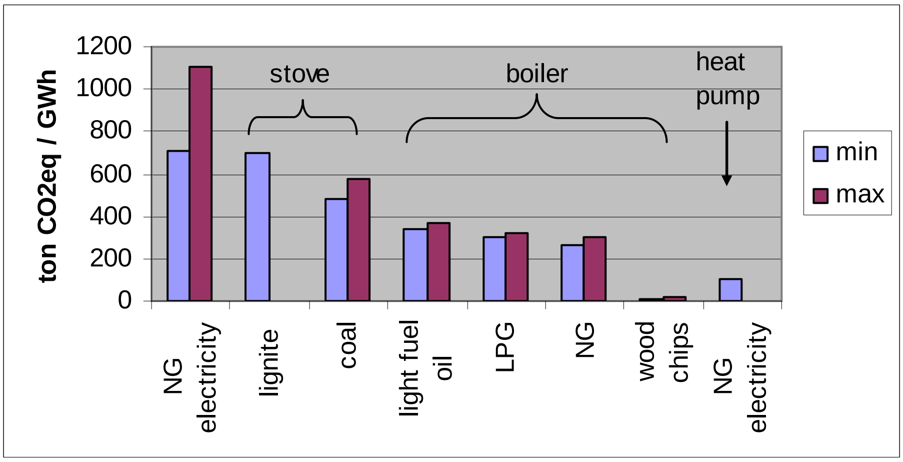
Figure 19 Literature ranges of life-cycle emissions for transport in gram CO_2eq per km



Source: (WEC, 2004).

With the large spread, no clear distinction can be made between different fuels based on greenhouse-gas emissions. A comparison for specific vehicle types, such as described in section 4.4.1, shows clearer trends in this case. It should be noted that the most important factor favoring natural-gas vehicles lies in the much lower local air pollution (NO_x and PM_{10}).

Figure 20 Literature ranges of life-cycle emissions for (local and central) space heating in ton CO_2eq per GWh



Source: (WEC, 2004).

For traditional (local stove or central boiler) space heating, natural gas is one of the best options. Natural gas could also be the basis for electric local heating (minimum shown in Figure 20) but in that case the performance is worse, as electricity is not an efficient way to provide space heating. On the other hand, a gas-driven heat pump has even lower climate impact than the gas-driven boiler.

When using wood chips as an energy source for boilers, net greenhouse gas emissions are very low, as the short-cycle CO_2 – contained in biomass – is not counted in life-cycle assessments. For this example, however, the NO_x emissions are very high (WEC, 2004).

4.4 Utilization: results of current study

In this section, some analysis of the data is made for different applications. The analysis is not meant to be a complete assessment.

4.4.1 Power

The best current technology in terms of gas-fired combined-cycle power generation is demonstrated by the plant in Baglan Bay (UK) that has been operational since 2003. The efficiency is 60% and CO_2 and NO_x emissions are as low as 336 and 0.15 g/kWh, respectively. Compared to the values shown in Figure 18, these are clearly in the lowest ranges. NO_x emissions could be lower, but do conform to the IPPC BREF specifications.

Using these emission values for the utilization phase, the upstream greenhouse gas emissions resulting from this report constitute about 15% to 20% of the full life cycle for electricity generation. The upstream NO_x emissions constitute 10% to 50% of the life cycle emissions. In both cases, the higher value for the upstream emissions is for LNG transported over 5,000 km and the lower for pipeline transmission.

For CO_2 (equivalents), the percentage of emissions occurring upstream as derived here is low compared to the range given in Table 10.

4.4.2 Residential heating

Values for CO_2 and NO_x emissions for the average (based on market share) technology for central heating in the Netherlands are 226 ton/GWh and 65 kg/GWh, respectively. The average efficiency is 89%. The value for CO_2 is lower than the values taken from WEC (2004), that range from 260 to 300 ton/GWh for natural gas central heating (boiler, see Figure 20). This may be due to the fact that natural gas central heating is very advanced in the Netherlands and therefore emissions values are low.

For the most efficient modern gas stoves (local heating per room), emission figures are not too far behind - 237 ton/GWh and 68 kg/GWh, respectively - as efficiency may be as high as 85%. It should be noted that this is “best available technology”, compared to Dutch average installed technology for central heating.

The ratio of upstream to combustion emissions is the same as calculated for power generation, as the same emission factor of 56 kg CO_2 / GJ applies.

4.4.3 Transport

Data were found for the use of compressed natural gas (CNG) in several types of passenger cars. In Table 11, an overview of the upstream emissions is given for CNG.

Table 11 Upstream emissions for several implementations to provide CNG for passenger cars (data not corrected for reference flow)

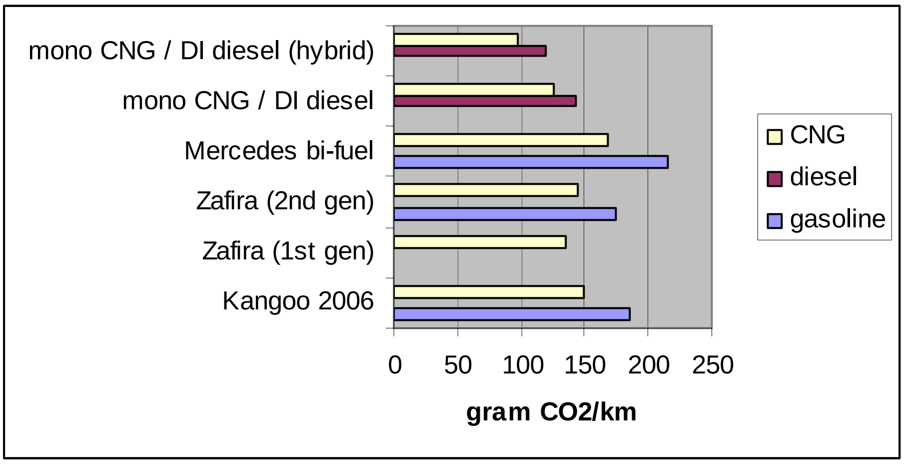
	Average data this study (electricity not included)		Data WTW, 2002 (electricity EU average mix)	
	processing	long distance	distribution	refueling
	gCO_2eq/MJ	gCO_2eq/MJ	$gCO_2eq/MJcng$	$gCO_2eq/MJcng$
high P network	0.17	5.41	0.00	1.40
low P network	0.17	5.41	2.90	4.90
LNG	10.95	0.36[a]	1.20[b]	0.40

[a] LNG long distance transport 1,000 km assumed.

[B] LNG distribution via road.

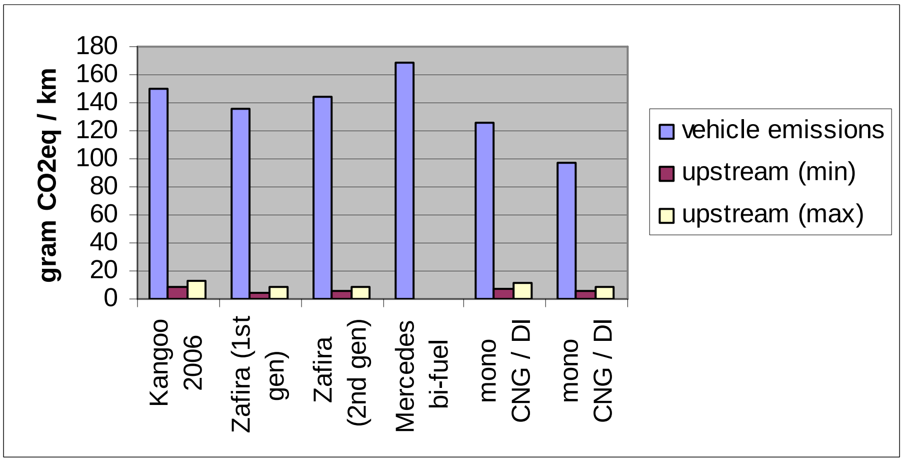
The emissions in the utilization phase are typically known per kilometre travelled, which is a logical functional unit for transport. In Figure 21, these emissions are shown for several types of car (passenger and light commercial van). For each type, the vehicle (combustion) emissions of the CNG variety are lower than the corresponding petrol or diesel variety.

Figure 21 Vehicle emissions for several car types (source www.greencarcongress.com)



Assuming a pressure of 25 MPa for CNG (WTW, 2002), the upstream emissions from Table 10 can be expressed per km. In Figure 22, vehicle and upstream emissions are shown for the CNG vehicles.

Figure 22 Life-cycle CO_2 emissions



The upstream emissions represent a quite low percentages of the total life cycle emissions (approximately 6 to 9%). This is low with respect to other literature sources, but not extreme. Note that the upstream emissions are not properly coupled for a reference flow and are therefore only an approximate figure.

For the various types of passenger cars, only CO_2 emission data are available. Average (partly estimated) data for the use of CNG in buses (AUS, 2000) were found for local polluting emissions. Compared to diesel, local emissions of NO_x and CO are considerably lower for CNG and local emissions of particulate matter (PM) are lower by a factor of 10 (all per km).

4.4.4 Hydrogen production

The most common hydrogen production method is by natural gas steam reforming. Carbon dioxide is the most prominent emission of the natural gas reforming process. The plant emissions of CO_2 from the NREL study (NREL, 2001) are close to those given in the General Motors study (WTW, 2002). For the life cycle emissions, values seem to diverge more between different studies. For the NREL study, life cycle emissions are relatively high, as the US natural gas chain was used in the analysis. In Table 12, the plant emissions are compared to the average upstream emissions (processing and transmission) resulting from this study, assuming that the plant is connected to the high-pressure transmission grid.

Table 12 Emissions for hydrogen production in gram per kg H_2 produced

	NREL2001	This study[a]	
	Plant	Upstream	Percentage upstream
CO_2	8,889	923	9%
CH_4	0.00	35.6	100%
NO_x	0.90	0.63	41%

[a] Emissions of electricity not included; emissions not corrected for reference flow.

The upstream emissions account for a fairly small fraction of CO_2 but all of the CH_4 emitted, according to (NREL, 2001). In terms of total greenhouse effect, the upstream emissions account for about 10%.

The only source that discusses an alternative form of hydrogen production is NTNU. For water electrolysis using nuclear power, they give a climate-change impact of 2.46E+0.3 kg CO_2eq/TJ (HHV) over the chain. This is a factor of 30 less than the figure for natural gas reforming (NTN, 2004, without CO_2 capture).

A comparison between those two forms of hydrogen production in terms of environmental impact is complex, however, as use of nuclear fuel involves radioactive emissions over the life cycle. A more suitable way to compare the methods would be in terms of energy use over the life cycle, or total efficiency of the chains. Data for such a comparison are not available.

5 Status and application of the life cycle data

5.1 Status of the database

In previous paragraphs an overview of the environmental impact data we found for the various steps in the natural gas production and utilization chain have been given. The data coverage is incomplete, meaning that although for a relatively large fraction of global production *some* data were found, the data are not often complete in covering all the inputs and outputs that were defined in Chapter 3 as desirable.

Also, there is no general coverage of physical chains, except for most of the European supply chain. This means that the results - inputs and outputs - cannot easily be linked to form a real life-cycle assessment.

The data that were found, however, are generally of good quality and already give some indications that the effort of trying to improve on public general databases is worthwhile (see Chapter 4). The database can certainly be improved upon, but this was outside the scope of this project.

In the following paragraphs, the potential applications of an 'optimal' database are discussed, along with the applications of the current database.

Generally, the following use of an inventory data base would be possible:

- Overview of the environmental impacts of the production chain (internal strategy, transparency) and identification of possible improvement opportunities.
- Comparison between systems and processes:
    - Between equal processes – e.g. comparison between two glycol dehydration installations or two different dehydration processes (process design).
    - Between systems delivering the same intermediate product – e.g. natural gas supply (LNG supply versus long distance pipeline transmission).
    - Between different systems delivering the same type of end-use product – e.g. coal or gas based electricity (comparison with alternative fuels).

5.2 Overview of the production chain

A thorough overview of energy use and environmental effects along the production chain is becoming increasingly important for industry and industrial sectors. In the Netherlands, industry has entered into an agreement with the government to work on improving life-cycle energy efficiency. The underlying idea is, amongst others, that achieving energy efficiency at a specific location may not always be the most cost effective. Also in Dutch air quality policy (NeR), cost effectiveness is used to determine whether measures have to be implemented or not. In Norway, a law obliges producers and importers of products to make life-cycle environmental impacts publicly available. In annual sustainability reports, more and more focus is put on life-cycle management.

These are only a few individual examples, but they show a beginning trend of life-cycle thinking in policy making and industry. This life-cycle thinking provides many opportunities. Identification of processes in the life cycle where energy (or material) consumption is relatively high gives an immediate potential for energy saving and thus cost reduction. For the natural gas chain, this is even more immediate, as energy consumption and fugitive emissions result in a loss of part of the actual end product. By reducing especially the fugitive emissions, an important environmental gain goes hand in hand with higher productivity. This was one of the drivers behind the US Gas Star program.

This policy for energy conservation and reduction of methane emissions in the gas industry is strongly targeting cost effectiveness. The Gas Star program gives excellent results in methane emission reduction and has given a good insight in highly cost measures for methane emission reduction, often having pay back periods of just a few months or years. It has also resulted in development of cost effective technology.

While energy consumption and total gas “loss” are good quantities to assess when focusing on cost reduction, the translation to emissions of CO_2 and CH_4 and subsequently to total greenhouse impact is very useful to assess priorities and cost effectiveness in terms of environmental impact. As discussed in Chapter 4, the emission of CH_4, typically resulting from fugitive emissions, has much stronger greenhouse effect than the emission of CO_2, typically resulting from energy consumption (combustion). Both reducing energy consumption and reducing fugitive emissions result in a cost reduction as well as a reduction in greenhouse impact. Together with the necessary investments, analysis of these reductions can be used to select the optimal strategy.

When certain measures can be shown to be much less cost effective than other measures that achieve reduction of the same substance, discussions with policy makers (competent authorities) may be entered into.

A next step up is to even combine the effects of very different substances, such as CO_2 and NO_x to yield an overall cost effectiveness, such as shadow pricing or distance-to-target weighting. These methods may prove very useful for strategic decisions but are still the subject of a lot of debate and have to be applied with caution. As an example, the Dutch oil- and gas exploration and production company (NAM) uses an internal system for prioritization that is based on a weighting system developed and updated by an academic environmental centre.

The data inventory constructed in this study does not allow for all the above applications. For most countries, the life cycle is not completely covered. This means that for national strategies, such as the US Gas Star programme, there is not enough information to cover the entire production cycle. Assessing the environmental improvement and cost effectiveness of measures, such as described, requires information in more detail than available in this study.

5.3 Comparisons

5.3.1 Process level

Comparisons at this level may be made for several reasons:

- Benchmarking.
- Decision for purchase or replacement of a specific process.
- How does process compare to BAT.

As stated in previous paragraph the collected data mostly concern overall averages for entire countries, while all those comparisons require detailed information on processes as well as gas quality. The current data therefore do not allow for these applications, given the aggregation at the level of countries. This results directly from the defined goal and scope of this project. As stated earlier, detailed comparisons at process (plant) level will always require a separate life-cycle analysis for that specific situation.

5.3.2 Supply chain level

As described in 1.2, a general comparison between regional supply markets, such as Europe, North America or Japan, was one of the main targets of this study. None of the supply chains is completely covered and many are even largely missing, such as for Latin America and Africa. The completeness of the current data base is therefore not good enough to compare all regional markets, but as shown in Chapter 4, several regional comparisons can be made per life-cycle stage.

The developments in markets and products are of special importance in this regional analysis. As can be seen in Figure 7, Latin America is expected to be the major supplier of natural gas imported into North America (USA) in 2030. This is most likely to be in the form of LNG. Production capacity for this still has to built; currently a plant is under construction in Peru. At an international level, a strategy could be developed as a collaboration between IGU members to optimize those new chains in terms of efficiency. At the production stage, the most efficient technologies could be used in new capacity. At the transport stage, logistics could be optimized, with e.g. Latin America’s east coast supplying North America’s east coast and vice versa. At the utilization stage, attention could be paid to preventing unnecessary regasification by using LNG as much as possible for transport or for application in areas without local distribution.

Obviously, in a liberal market, such structures will not be enforced or easily achieved. However, collaboration between “life cycle partners” is not impossible and this could be an important role for the IGU. The basis for these observations is available in the current data set.

The European market will undergo similar changes, with imports from Latin America, Middle East and increasingly from Africa. Gas from the Middle East could be imported via pipeline or via LNG transport. An assessment as outlined in section 4.2.2 could give insight into the most efficient option, both in terms of minimizing product “loss” and in terms of reducing environmental impacts. The current data set can be used for a first assessment that shows whether further investigation is warranted.

5.3.3 Comparison with other fuels

Comparing end-use applications of natural gas with alternative fuels is obviously an interesting application of life-cycle data. However, as is clear from the data shown in section 4.3, such comparisons are not always useful when using non-specific data, as the variations in environmental performance with end-use technology are large. As explained in Chapter 3, comparisons of entire product chains can only be made in a useful fashion when using very specific data. Also, the data used for the natural gas option have to be of the same quality, system boundaries, etc., as those used for the alternative option. That means that the current data base cannot directly be used for comparisons with other fuels, as those other fuels are not covered under the same conditions.

When satisfying that condition, however, the data can be used for such comparisons, provided, of course, that it is known what the life cycle of the natural gas for the given application looks like (e.g. LNG imported to Japan) and that the necessary data are covered in the current set. Again, this is not the case, as the database still contains many gaps, but is could form a good basis for future extensions to allow such comparison.

6 Final remarks

6.1 Conclusions

The objectives of this study were defined in Chapter 1 as:

- Initiation of LCA by constructing a database that provides:
    - Framework to collect industry data (instead of generic public data).
    - Flexibility with respect to later LCA applications.
- First overview of natural gas per region.
- Recommendations for way forward for IGU LCA project.

Those general goals have mostly been met, although some of the technical goals (as defined in Chapter 3) turned out to be unfeasible in the current study. For instance, upstream emissions of consumptions (notably electricity) as well as allocation between oil and gas could only partly be coherently integrated into the framework, as this study was limited in duration.

The assessment, along with available literature, shows that currently, natural gas is one of the fossil fuels of choice for many applications in terms of environmental impact over the life cycle. From the point of view of continuous improvement, there are several opportunities nonetheless, at several points in the life cycle.

Continuous improvement is an important part of environmental management, but also important to keep natural gas at its good environmental position, as several developments might change the environmental profile of other fuels favourably with respect to natural gas. These developments are partly market driven, such as a rising share of LNG and gas storage in the global natural gas demand because of higher flexibility. Other developments are of a more technical nature, such as CO_2 capture and sequestration.

Opportunities to stay ahead of such developments in the life cycles of fossil fuels are available in measures to limit fugitive emissions and venting at several stages in the life cycle. The emissions of methane over the life cycle of natural gas not only result in a loss (possibly about 1%) of valuable product, but also give rise to a significant greenhouse impact. The volume of these emissions is similar to what is reported for global paddy rice production, another known source of methane emission. Another opportunity would lie in focussing on application of best available technology in new capacity for LNG production.

The IGU feels that public life-cycle databases do not reflect the true situation of life-cycle effects of natural gas. This feeling may be valid, given some of the results shown in Chapter 4. A continued effort to collect industry data in a solid life-cycle inventory structure could show to what extent public databases are indeed deviating from the actual situation.

6.2 Recommendations and opportunities

As concluded above, there are several reasons for the natural gas industry to continue life-cycle data collection and to work on continuous improvement of the environmental performance of natural gas.

In projects to collect and structure data, IGU could assume the role of coordinator. Several international industrial organisations have actually started such initiatives and industrial life-cycle databases exist for e.g. plastics and metals. It should be noted that a truly global database may be a goal that is too far from the current level of data availability. An interesting option could be to assess a number of very specific life cycles by way of illustration. Another possibility would be to work at a regional level and initiate efforts like the Marcogaz project in various global regions. In all cases, uniformity and transparency are essential to make the results useful for a wide range of applications. This will require commitment from the gas industry, but it should be noted that detailed data are actually globally collected at plant and/or company level.

The data collection should also provide support for strategic decisions and continuous improvement. It will help the IGU to prepare itself strategically for changes in the global energy market in the coming decades. Apart from measures that can be taken directly in the life cycle of natural gas, as described before, it could also be feasible to focus on improving overall performance by using electricity produced with lower impacts (e.g. with CO_2 capture, wind).

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