*Rapport SGC 197*

# LNG As an Alternative Energy Supply in Sweden



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# Foreword

This final thesis work is the concluding piece of my Master's degree in Chemical Engineering at Lund Institute of Technology. The work was conducted by assignment of the Swedish Gas Centre (SGC) during the spring of 2008.

I would like to thank my examinator professor Hans T. Karlsson and my advisor Christian Hulteberg at the Department of Chemical Engineering, as well as Corfitz Nelsson at SGC for their much appreciated help. I also would like to display my great gratitude to the personnel at Gasnor in Bergen and Oslo, and to Gustav Tjernberg at Green Cargo for their generous contribution to this study. Other benefactors to whom I owe gratefulness are mentioned in the 'Reference' section.

Lund, September 2008

Jens Hansson

# Executive Summary

Liquefied Natural Gas (LNG) is Natural Gas cooled to -162 $^{o}C$. As a cryogenic liquid, it takes up about 1/600 of the volume of uncompressed gas, making it an easier product to store and to transport. As well as summarising the possible alternatives, environmental aspects and uses of LNG, this study aims to investigate the cost involved in the import of LNG to Sweden, from well to user.

Today, the world is dependent on oil as a source of energy. It contains many harmful components and replacing it would be good for the environment. Natural Gas is a fuel, which however fossil has cleaner burning characteristics, contains more energy per atom of carbon and is easier to extract from the ground and to handle than oil and coal. After almost 200 years of industrial usage, the Natural Gas resources which are located near the largest users are running out and hence, other sources will need to be used if the present Natural Gas use wishes to be maintained. Whereas European and North American Natural Gas is expected to last about a decade, the Russian and Middle Eastern available resources are each ten times as large. When Natural Gas from sources nearby has been utilised, pipelines as means of transport have been the obvious choice but when shipping distances greater than 1000 km (off-shore) and 3000 km (on-shore) are the case, the least expensive option is to transport the Natural Gas as LNG by ship.

In Sweden, Natural Gas is used to cover 2 % of the total energy input. The pipeline network stretches from Malmö to Stenungsund and Gnosjö, which means some of the most densely populated areas are covered, but there is still 1200 km of the country left, including larger cities such as Stockholm, Uppsala and Linköping as well as areas that host some of the most energy demanding industries, e.g. Sundsvall, Umeå, Luleå and Kiruna. The absence of Natural Gas typically causes these regions to rely on fuel oil, coke or coal. If these sources of energy could be replaced by Natural Gas, great environmental benefits could be achieved. Research shows that the use of Natural Gas adds 20 % less $CO_2$ to the atmosphere than oil and also mean lower emissions of $NO_x$, $SO_2$ and particles, making it the better alternative from both local and global perspectives. LNG is potentially a fire and an explosion hazard, but in the last 45 years of usage, no major accidents have occurred. Major exporters of LNG are Indonesia, Quatar, Australia and Algeria. Some of the largest importers are Japan, USA, France and Spain. Japan imports nearly 100 % of their Natural Gas as LNG. The available LNG liquefaction capacity increased by 60 % between 2002 and 2007.

The main field of use for Natural Gas and LNG is as energy supply. It is also used as feedstock for chemical processes. Since LNG is easy to store, it can with good results be used as fuel for ships and road vehicles, which commonly are large polluters. Being a cryogenic liquid, the cold in LNG can also potentially be utilised in power generation cycles, to produce liquid or solid $CO_2$, for air separation, in the food industry or as district cooling. A varied usage pattern of Natural Gas could cause expensive LNG import facilities to be used infrequently at some times of the year and thus mean a higher specific cost. By combining a number of uses such as the ones mentioned above, the feasibility is increased.

The total import cost for LNG includes the purchase cost from the producer, the transport cost, be it sea, railroad or road transport, and the cost for the terminal which receives and stores LNG. The study of different routes, volumes and means of transport creates a picture of how the total cost varies in proportion to these parameters. In the calculation of these costs, sources from the industry or estimations of purchase prices, transport costs and terminal costs are used. The uncertainties in this study are especially high when it comes to the purchase costs and the railroad and large-scale sea transport costs. It is also worth noticing that the cost estimation models used in this study sometimes contain large steps for the different cost situations. This is the case for small-scale/base-load ships, purchase cost for Norwegian/Algerian LNG and wagon transport/system trains. The results are hence sometimes less accurate.

The routes chosen are meant to be feasible and possible in the future. As consignors for the LNG, StatoilHydro (Melkøya, Norway), Gasnor (Kollsnes, Norway) and an Algerian producer are chosen. The trade routes then go to Lysekil (on the Swedish west coast, near Stenungsund which is connected to the Swedish Natural Gas network), Oxelösund (in mid-Sweden) and Luleå (in the far north-east). Studied volumes are 100, 200, 500, 1000, 5000 and 20 000 GWh/year.

LNG can also be produced locally in a Gas pressure regulating and measuring station (GPRM station), where the pressure of the pipeline Natural Gas is reduced from 60 to 4/10/12/28 bar. The expansion cycle requires heat and by taking this from a smaller fraction of the incoming gas, LNG is produced and the temperature of the expanded gas maintained. The cost of LNG production in a Gas pressure regulating and measuring station located in Göteborg (60-28 bar) is also studied.

As a side assignment, the costs for peak-shaving by the use of LNG is looked into. 20-30 MW for 24 hours per year need to be cut at Öresundskraft's combined power and heat plant in Helsingborg. Here, the possibility of utilising portable LNG containers (as used by the Norwegian company Liquiline) is studied.

In order to indicate the extent to which some key parameters affect the final cost, sensitivity analysis is carried out on the purchase price and the terminal costs.

The results show that the Norwegian LNG costs 560-608 SEK/MWh (road), 570-689 SEK/MWh (railroad) and 537-555 SEK/MWh (sea). Algerian LNG costs 315-324 SEK/MWh (sea). The large difference between Norwegian and Algerian LNG is caused primarily by the much lower purchase costs of Algerian LNG, and also due to the difference in sea shipping costs. The purchase cost is about 80 % of the total cost for all cases. The transport cost is between 3 and 6 % and the terminal costs the balance, making it a larger component in the cases of Algerian than Norwegian LNG. See diagram I for the average cost distribution and the actual costs for the different routes.

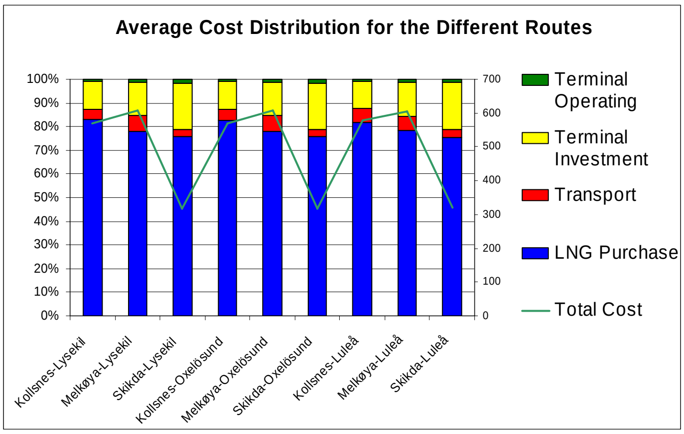


**Diagram I: Average Cost Distribution for the different routes on the left scale (per cent) and the total cost (SEK/MWh) on the right scale.**

Sea shipping is shown as the most versatile mean of transport, as there are different sizes of ships available and everything from short to very long range can be covered for competitive costs. For short ranges, road transport is the least expensive. Railway transport is the most expensive alternative. However, compared to the purchase and terminal costs, the transport cost does not affect the total cost that much. Consequently, the mean of transport can largely be chosen with respect to environmental and energy efficiency aspects as opposed to economic. Railway and LNG powered ships have an advantage here.

For the peak-shaving side case, it is shown that there are options to use LNG import, both "small-scale LNG" and portable LNG containers. If the demand is 25 MW for 24 hours and one day, it is roughly twice as expensive for the distribution system as it would be if the demand would be seven times greater (one week instead of one day). See diagram II and III. Portable LNG containers are suitable for the smallest scale of LNG distribution. They are especially beneficial when reloading between for example ship and train, as no reloading terminal is needed and because less LNG storage volume is "lost" due to temperature increase and density decrease caused by the reloading procedure that would take place if the LNG is transferred between different transport vessels.

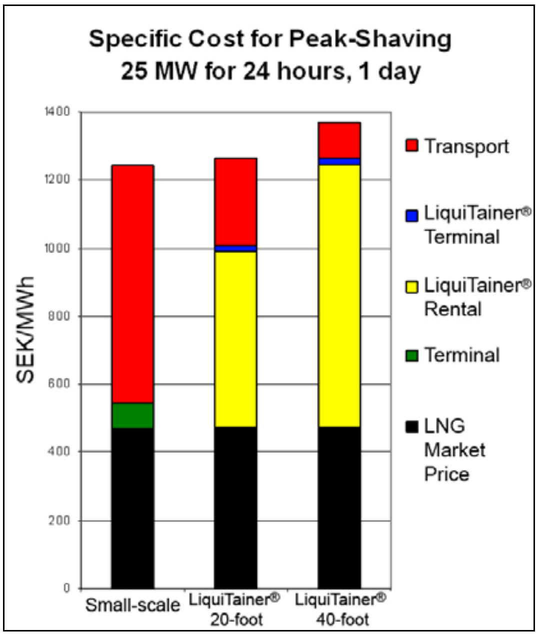


**Diagram II: Specific cost for LNG imported for peak-shaving purposes - 25 MW for 24 hours, 1 day per year**

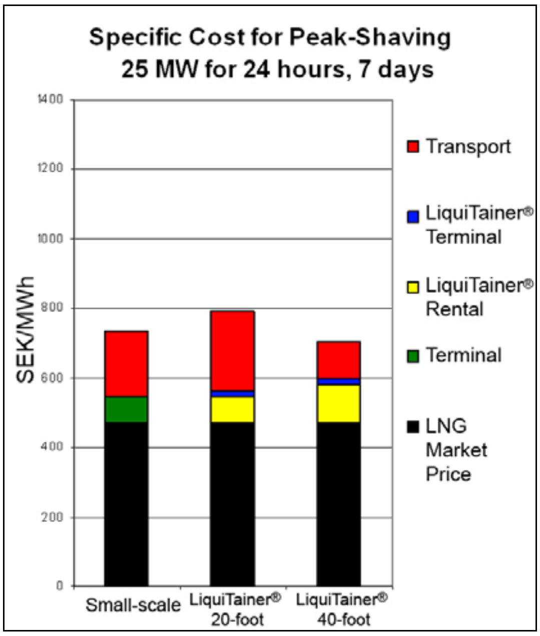


**Diagram III: Specific cost for LNG imported for peak-shaving purposes - 25 MW for 24 hours, 7 days per year**

The calculations indicate that it would be feasible to produce LNG in a Gas pressure regulating and measuring station, perhaps for peak-shaving purposes. The concern about this kind of system is the usage pattern; since the maximum amount of produced LNG is directly proportional to the flow of Natural Gas through the GPRM station, the demand of LNG would have to match that of Natural Gas.

It is shown that LNG could be an alternative to secure the Natural Gas supply after the Danish supply has run out. It has proven safe and the market is getting more and more mature. The fate of base-load LNG is largely determined by the other Natural Gas projects in the Nordic countries. If the *Skanled* connection is realised, Norwegian gas can be brought in; if the *Nord*

*Stream* pipeline project is carried out, Russian gas could cover the needs. The small-scale LNG market is however still a possibility if it continues to be competitively priced. The Natural Gas market price largely follows the oil price and as a consequence from this, LNG prices are also linked to the source of energy which it is primarily supposed to replace. The question is whether the market price is reduced - or at least less increased - due to the increasing available world-wide liquefaction capacity, and how much effect the increasing steel costs will have on LNG equipment. In either way, Liquefied Natural Gas is always going to be better for the environmental than oil and hence, it is worth to keep in mind when the world's sources of energy are changing.

## Index

# 1 Introduction

As of today, the world is dependent on oil as a source of energy. No matter if it will run out one day, it is a mixture of many components of which many are harmful to us and to the environment. It is rich in carbon which means high $CO_2$ emissions when combusted. The cousin of oil, Natural Gas, is also a fossilised fuel and extracted from beneath the earth crust. It is however a better source of energy in terms of $CO_2$ emissions, environmental effects and handling compared to oil. As long as the bio-based alternatives have not reached enough maturity and scale, Natural Gas plays an important role in the world's energy supply.

Sweden is supplied by Natural Gas through a pipeline which stretches from Malmö to Stenungsund, a distance of 340 km, while the country is 1500 km from North to South. This is one of the country's most populated areas, but there is still a huge part left without Natural Gas supply. Many of the most energy demanding industries are located in regions which are sparsely populated and where oil is presently the only option. The pipeline could be extended to more users, but it is also worth studying Liquefied Natural Gas (LNG) as an alternative supply.

LNG is Natural Gas cooled to about -162 $^oC$ and hence a liquid which only needs 1/600 of the volume for the same amount of energy rich Natural Gas. It needs cryogenic storage but in this state it is feasible to transport long distances without too high costs. The prices of LNG ships and LNG production facilities have decreased lately and around the world, many new LNG projects are underway. The deregulation of the gas markets and the fact that Natural Gas resources close-by to the consumers are running out, have moreover caused LNG expansion. From a Swedish point of view, there is the need to look for a new gas supplier since the present one, Denmark, will soon have depleted their sources. As the LNG shipping cost is fairly insensitive to the transport distance and since the natural interlocks in gas grids is removed, the LNG market is more flexible than that of pipeline Natural Gas.

When looking at the European gas grid, it is notable that it is well built-out in most countries on the central continent but what is strikingly is that there are hardly any distributional pipelines in the Nordic countries. The United Kingdom, France, Spain, Italy and Belgium have LNG import terminals connected to their networks as support to the all-pipeline imported gas. The exception in the Nordic countries is Norway - it has a large number of small receiving terminals scattered along the coast. A few years ago, they launched small-scale LNG distribution to support various areas with gas and replace oil and this system is still expanding. Sweden could possibly use this sort of system as their model, as well as a larger scale alternative.

From an environmental point of view, Natural Gas and LNG has an advantage over oil, but it is still a fossil fuel which has an impact on the climate. Because of this, Natural Gas should not be seen as a final solution to the energy problem but more as an intermediate to new energy sources. It is a belief by many that bio-based energy gases such as biogas and hydrogen will become of importance in the future - already using gas gives useful experience in this field.

This study aims at creating an approximate cost of LNG import to Sweden. Means of transport studied are sea, railway and road. Consignors are Norway and Algeria.

Exploiting the pressure reduction at local gas Gas pressure regulating and measuring stations for cooling Natural Gas is a close-at-hand way of producing LNG from an existing high pressure gas network - this alternative will also be investigated.

A further use of LNG is that of a peak-shaving plant; to be able to cover peak-loads of a gas network, you could use stored LNG which is regasified when needed. Some solutions to satisfy the need of 20-30 MW of Natural Gas during 24 hours in a day are presented. This, as well as a brief review of the environmental effects and an overview of some specific usage areas of LNG will be scrutinised in this piece of work.

# 2 Natural Gas and LNG

## 2.1 Natural Gas

Natural Gas is a fossil fuel found beneath the crust of the earth, mainly consisting of methane but also of ethane, propane, butane and pentane as well as carbon dioxide, helium, nitrogen and hydrogen sulphide. The gas composition varies greatly with the location that it is found.

“Burning springs” have been noticed early in the history, as people discovered gas seeping up from the ground. The first wells were drilled in Japan as early as 615 AD and in 900 AD bamboo tubes were used as transportation for Natural Gas to salt works in China. The first serious use of the gas occurred in Fredonia, NY in 1821 when residents drilled wells and piped Natural Gas through hollowed-out logs for use in lighting. The steel works in Pittsburgh, PA pioneered in industrial use in 1884. Initially, only small and shallow fields were located - and consequently quickly depleted via intense, temporary industrial rushes around them. But larger fields and better piping opportunities eventually came into use and these chaotic cycles of events could stop. As the gas treatment technology evolved, more areas of utilisation were added and currently Natural Gas is used throughout the industrialised world as a source of energy and feedstock in many fields of the chemical industry. [1] The available reserves and the use of Natural Gas continue to increase as of today, and it is expected to be the fastest growing component of world primary energy (+2.8 % per year until the year 2025) [2]. It is the third most important source of energy, after coal and oil. Its success is dependent on its clean burning characteristics, availability and competitive price [1].

Most of the world’s Natural Gas reserves (71 %) are located in the Middle East, Eastern Europe and Russia. Norway has roughly 1.4 % of the world reserves. The U.S. Geological Survey estimates that there is much more undiscovered gas than already found. A significant part of this is however too remote for a feasible use with conventional methods. [1]

Sweden is supplied by Natural Gas from Denmark by a pipeline which enters the country south of Malmö. The pipeline then goes north, as far as Stenungsund, with a branch to Gnosjö in Småland. The rest of the country is not a part of the Natural Gas network. Stockholm uses town gas, produced locally through naphtha gasification, but this procedure is currently undergoing a change (see below).

## 2.2 LNG in Brief

Natural Gas transport is normally performed in pipelines. Greater distances however make this an expensive alternative and since many of the using countries are located far away from the gas fields, a substitute is needed. This has been more of an issue lately, when nearer gas fields are being depleted. As shown in table 1, most of the world resources are located elsewhere than the large users are. The solution is to increase the density, i.e. compress or liquefy the gas. The volume ratio between Liquefied Natural Gas, LNG, and uncompressed gas is 1/600. LNG can be shipped by sea, train and road and has a clear economical advantage over piped gas at distances >3000 km (on-shore pipelines) and >1000 km (off-shore pipelines), see diagram 1. [1]

**Table 1: The distribution of the world Natural Gas reserves and consumption rates indicates that the gas needs to be transported inter-continentally. [3]**

| World-wide available reserves and consumption rates | | | |
|---|---|---|---|
| | Available reserves (Tcf) | Consumption rate (Tcf/Year) | Reserves/ Consumption (years) |
| North America (ex Arctic) | 263 | 27.3 | 10 |
| Europe | 201 | 18.5 | 11 |
| Asia Pacific | 524 | 14.4 | 36 |
| South & Central America | 248 | 4.4 | 56 |
| Former Soviet Union | 2059 | 21.1 | 98 |
| Africa | 508 | 2.5 | 203 |
| Middle East | 2546 | 8.9 | 286 |
| TOTAL | 6348 | 97.1 | 65 |

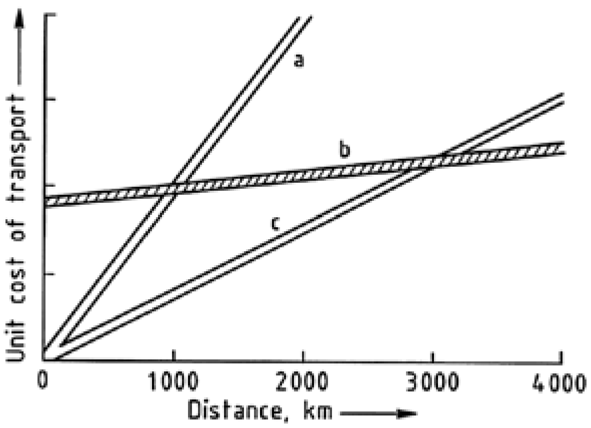


**Diagram 1: Cost situation of LNG (b) compared to off-shore (a) and on-shore (c) pipelines [1]**

Due to the fact that LNG can be shipped between a variety of destinations, the market is fairly flexible. Naturally, the economical feasibility depends on for example distance, toll, taxes and the required gas quality, and the case has often been that long-term contracts have been established, but importing Natural Gas by pipelines certainly limits the options more. Moreover, in the recent development spot trade has become more common.[4]

LNG is produced by cooling Natural Gas to under -160-163 $^{o}$C (depending on the composition and pressure). The low temperature requires gas to be purified at the production stage and hence means that the LNG product is somewhat free from impurities. Since heavier hydrocarbons (pentane and above) and water would freeze and possibly damage process equipment, these substances need to be removed from the gas mixture prior to liquefaction. [1]

## 2.3 LNG Safety

Liquefied Natural Gas is colourless, odourless, non-corrosive and non-toxic gas stored at atmospheric pressure or pressurised. It has a great safety record – for the past 40 years there have not been any major accidents. Although a high density fuel, LNG poses a small risk of explosion. It cannot be released rapidly enough to cause the overpressures needed and evaporated LNG mixed with air is only explosive in a confined environment, where the gas concentration is 5 - 15 % and a source of ignition is present [5].

Overpressures in storage vessels is however a possible explosion hazard. This can be caused by so-called rollover; if a tank contains LNG of various densities, the LNG of different-density could layer in unstable strata within the tank. After some time, these strata may spontaneously roll over to stabilise the tank contents. Normal heat-leakage into the lower layer LNG could decrease its density and potentially set off a rollover with the upper layer with rapid evaporation and pressure rise as a consequence. Distributed heat sensors and pump-around mixing systems are examples of effective rollover protection systems. The rollover behaviour can through calculation models even be used as a means of reducing boil-off costs. [6]

A large LNG release in water could physically explode due to rapid phase transition (RPT) [6].

Leakage of any kind is a fire hazard. Only the evaporated gas would ignite, but this would cause a more rapid evaporation and the result would most likely be a pool fire. In facilities handling LNG, regulations require safety zones where fluid is collected in the case of leakage, as well as large setback distances. There is only minor risk of vapours to accumulate near the ground since Natural Gas is lighter than air, though at certain temperatures this can occur. The ignition of an unconfined vapour cloud would typically deflagrate and burn back to the source of the release. [6]

## *2.4 LNG Worldwide*

### 2.4.1 Past

One of the pioneers within the field of condensing gases was Michael Faraday (1791-1867). He was able to condense heavier gases, such as carbon dioxide and hydrogen sulphide, but did not succeed with lighter gases including the town gas of that time. During the 1870's, Karl von Lindhe however built the first compressor driven cooling machines. The first system for condensing Natural Gas was taken into use in USA in 1917. Godfrey Cabot patented a barge-carried system in 1914 and his son Thomas Cabot wrote an article on the topic in 1920. The first actual use is believed to have been in tractors in Ukraine 1935 and was caused by the long trade route of Natural Gas. Concurrently, Natural Gas was condensed in Texas but only the helium was of interest at that time. [7]

The first commercial condensing plant was built in 1941 in Cleveland, Ohio. A severe accident was caused in 1944 due to the lack of material supply, knowledge of material behaviour and the absence of a collector of the LNG in the case of leakage. As a new tank burst, LNG poured into the adjacent sewer system before it ignited, killing 128 people. Because of this, the technology became less popular and the development slowed down for a decade. The technology was nevertheless exported to the USSR. [7]

In 1959, the next large LNG shipment was carried out. This was between Louisiana, USA and Canvey Island, the UK, and became the new start for the technology. Mainly in the US, but also in other countries, LNG storage was used for peak-shaving in gas networks. Customized LNG ships, new plants and receiving terminals were built and ever since then, the LNG industry has expanded. The actors at the early stages were USA, Algeria, the UK and Japan.

Sweden also played a part early on - four LNG ships with the membrane technology were built at Kockum's shipyard in Malmö 1969-1979. They were the largest carriers at the time and they are still in use today. [7]

### 2.4.2 Present and Future

The world's largest importer of LNG is Japan. Almost 100 % of their Natural Gas demand is covered through LNG import [8]. LNG produced in the Middle East and throughout the Pacific Rim supplies 10 % of Japan's primary energy consumption.[1] South Korea, the United States, France and Spain are also large importers. See figure 1.

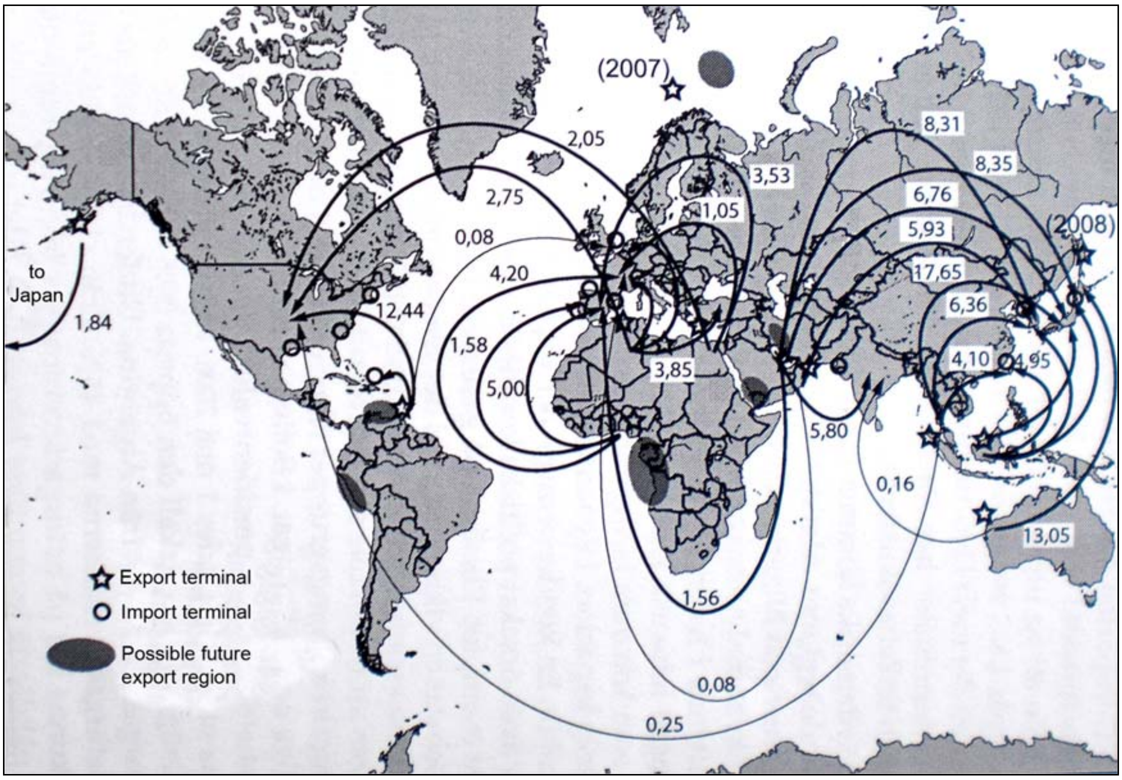


**Figure 1: An indication of the worldwide LNG trade represented by a map of the major LNG trade movements of 2007. [9]**

Indonesia, Qatar, Australia and Algeria are the world's largest exporters. Other important exporters include Trinidad and Tobago, Egypt, Malaysia and Nigeria [10]. New production facilities are being constructed in several of the above mentioned countries as well as in Russia, Iran and Norway. [1] In 2002, the LNG production capacity was 139 million metric tons of LNG and in 2007 this volume was 60 % higher at 220 million tons [10]. The increased LNG production capacity has decreased the LNG cost and the number of LNG ships is booming. In 2000, 120 ships existed but in the year 2010 it is expected that there will be 370-380. Most of the new LNG carriers are built in South Korea. Because of the large demand, there is a shortage of available construction material. This problem causes the prices to rise somewhat. [11]

## 2.5 Specific LNG Uses

Natural Gas, being a fuel of clean burning characteristics, is of course a fair choice as source of energy in power plants, remote heating and in industrial applications. It is also the raw material for several chemical processes, such as hydrogen production by reformation, ammonia production by the Haber-Bosch process and synthesis gas that can be used to make methanol, which in term is feedstock for a variety of chemical substances. But as a compact, cryogenic and energy rich liquid, Natural Gas has a wider potential of utilisation areas. Some of these are presented below.

### 2.5.1 Peak-Shaving

A possible area of usage is LNG in peak-shaving. Since the demand of gas in many cases varies, there is the need to be able to store the fuel in a compact, cost-effective manner. There is either the method to on-site produce and store Natural Gas which is acquired in from the pipeline network, or the possibility to buy LNG from an external source and use as backup. This is commonly used where biogas is produced locally and used as road vehicle fuel and where the supply source is not completely reliable [12].

### 2.5.2 Ship Fuel

Some of the heaviest air polluters across the globe of today are ships. Since they mainly use the heaviest fractions of oil and because the regulations of emissions from sea vessels are very soft, $SO_2$ and $NO_x$ emissions are significant. There is currently much research being made on ships propelled by LNG. For example, replacing a conventional passenger ferry in Norway to a LNG-powered vessel would be equivalent to taking 160 000 cars out of traffic as far as NOx-emissions are concerned. [13] 22 LNG ships are in use in Norway as of today, types ranging from coast guard boats to large car ferries [14]. The Norwegian car ferry *Bergensfjord* is an example of the new LNG powered ships (figure 2).

There is currently a partly EU financed project carried out called *MAGALOG*. This has the objectives to create a supply chain throughout the Baltic Region for LNG refuelling purposes for ships. It is believed that this could reduce air pollution heavily. [15]


**Figure 2: One of many new LNG powered ships, which partly are a result of the MAGALOG project. Photo courtesy of Gasnor AS.**

### 2.5.3 Road Vehicles

The most commonly used gas fuel in transportation is CNG - Compressed Natural Gas. There are also advanced plans about using LNG as fuel for road vehicles. The idea is to expand the current use of CNG driven vehicles by exploiting the distributional advantages the liquid gas possess and increase the number of refuelling stations. In LCMG (Liquefied to Compressed Methane) stations, LNG is stored and then on demand either gasified to CMG (Compressed

Methane Gas) or simply pumped over to an LNG driven vehicle or an LNG carrier. Utilisation of LNG as a refrigerant in cold-storage transports is also a possibility. [16]

An LNG tank in a road vehicle has about a third of the space requirements of CNG (at 200-250 bar) but as the highest possible pressure of CNG storage is increasing, the gap between the two is getting smaller. The question is whether it is more cost-effective with an increase of pressure instead of liquefaction. The LNG buses in El Paso, Texas, reach about as far as their diesel equivalents (650 km) whereas the CNG buses have a shorter range (490 km). There are today 1000 LNG powered buses in USA. Their fuel is not liquefied at the refuelling station and is instead transported there by road. [7]

LNG in road vehicles is stored in two layer tanks with vacuum in the intermediate space to reduce heat transfer. As more and more LNG is gasified into this layer however, the rate of heat transfer is increased. It is required to pump this gas somewhere and reliquify or flare it to avoid this. This can be performed by the refuelling system. [7]

An example of a developer of LCMG is Hardstaff Group, in the UK. This transport company has constructed their own LCMG system and has 70 converted lorries [16].

### 2.5.4 Utilising the Cold

The normal procedure to evaporate LNG into Natural Gas is to take heat from a heat source by heat exchanging, either directly or by the use of a cooling agent. Since the liquid is only evaporated and then heated to no more than about 10 $^{o}$C, there is usually no need to use a higher form of energy than ambient air or sea water. Additional heat is needed only if the rate of evaporation is too high or if it is too cold at the site location. When the heat source has lost its energy to the evaporation it is usually transferred back to where it came from, now being cooler than before. This however wastes the possibility of using the cold of the LNG. A cryogenic liquid of -163 $^{o}$C could potentially be utilised in a variety of areas.

**Air Separation**

In the cryogenic method for air separation, the difference in boiling points for the components is exploited. The first step is to remove impurities and particles from the air. Water and $CO_2$ are then separated by condensation. Thereafter, the air is cooled to -194 $^{o}$C, at which point it is condensed. It is led to a container, where it slowly evaporates. The different components are then subsequently evaporated and hence separated from one another. The ratio of the resulting products is the same as the incoming air, i.e. about 78 % nitrogen, 21 % oxygen and 1 % argon. Other noble gases can be separated this way, e.g. neon, krypton and xenon. [7]

LNG can be used to cool the air. The boiling points of oxygen and nitrogen are however lower than that of LNG (-185 $^{o}$C and -195 $^{o}$C, respectively, at atmospheric pressure compared to -162 $^{o}$C for LNG). By increasing the air pressure to 40-50 bar, this problem can be overcome. 2 kg of air can be condensed by 1 kg LNG. [7]

**Production of Liquid or Solid $CO_2$**

Some industrial processes as well as carbonated drink need carbon dioxide in liquid phase. By liquefying or solidifying $CO_2$ which is separated from power generation or Natural Gas reformation, it can be stored effectively for re-injection to beneath the earth crust. It can also be used to separate $CO_2$ from exhaust gases. [7] With the current climate debates and witch hunt for carbon dioxide, these methods could become useful.

**Cooling Medium in Thermodynamic Cycles**
In some types of power plants, LNG could work both as source of energy and as a cooling medium. This increases the effectiveness. It has only been studied where large quantities of LNG are present, i.e. in large import terminals. There is a number of Japanese plants which uses a Rankine cycle, with a combined effect of 85 MW. [7]

LNG can also be used as intercooler medium for the incoming air to a gas turbine and increase the effectiveness (figure 3). [7]

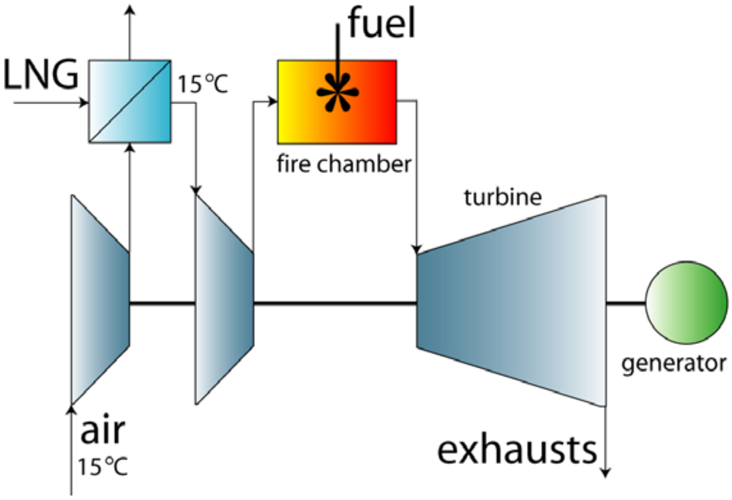


**Figure 3: LNG utilised as intercooler medium in gas turbine cycle [7]**

**Cooling in the Food Industry**
LNG can be used as a source of cold in the food processing industry as well as in frozen food transports. [7]

**District Cooling**
In the same way as district heating is used to heat buildings, district cooling could be used in refrigerant systems and air condition. [7]

## 2.6 Current Natural Gas Projects in the Nordic Countries

Originally, town gas was used for lighting purposes but later on also in heating and industrial processes. Town gas is produced by dry distillation of for example coal, shale or naphta in local gas works. As in the rest of the Western world, larger urban areas in Sweden were connected to a local gas work from the 19$^{th}$ century. In the 1910, there were 30 gas works in the country. Most of these were closed down during the late 20$^{th}$ century. Stockholm Gas in Stockholm still produces town gas from naphta. They are however planning to have converted to Natural Gas by 2010 in the project *Stadsgas 2010*. To supply the network among others, Stockholm Gas, AGA and Nynas are planning a 20 000 m$^3$ LNG import facility in Nynäshamn, 55 km south of Stockholm [7]. Road tankers would ship the LNG from the import terminal to a gasification plant in Sofielund, Huddinge, just south of the city centre. The Nynas oil refinery in Nynäshamn would also use some of the LNG as well as other, smaller industrial users. There is also the possibility of forwarding LNG to additional local gas networks. [17]

The Stadsgas 2010 project is one of several independent plans in progress for the utilisation of Natural Gas. "Naturgas Mellansverige" is the name of another developing project, conducted by E.ON Gas Sverige AB. In this, the current Natural Gas network would be expanded to Jönköping, Södermanland, Örebro and Östergötland Counties. [7]

E.ON previously had plans to open a base-load LNG import terminal somewhere along the coast between Norrköping and Gävle. Oxelösund seemed like the most suitable location for the planned terminal, which were to have a storage capacity of 200 000 $m^3$ of LNG. These plans have however been postponed due to political resistance as well as the fact that the Natural Gas demand would vary too much between the winter and summer seasons – the terminal would not run on full capacity during the summer and this would be too cost-ineffective. E.ON also had some doubts about the LNG market, which supposedly is too much of a "seller's market" at the moment. The company is however open for possibilities of combining LNG distribution to the Nordic countries with the planned import terminals in Wilhelmshafen (north Germany) and Krk (Croatia) and with other facilities. [18]

Yet another gas project is the so-called *Skanled* project. The general idea of this is to build off-shore pipelines from the Kårstø gas treatment plant outside the Norwegian south coast to eastern Norway and to the Swedish West coast all the way to north-eastern Denmark. If this project is realised it is scheduled to start operating in 2012. The decision for this will be taken on October 1st 2008. [19]

Other infrastructural improvements include the *Baltic Gas Interconnector* (Rostock in Germany - Trelleborg in Sweden), which was to be finalised in 2009 but has been postponed indefinitely [20] and *Nord Stream* (Vyborg in Russia to Greifswald in Germany), which is scheduled to be completed in 2011 [21] and possibly include a T-connection to Sweden as a later step.

## 2.7 LNG in Norway

From a Swedish point of view, LNG import from Norway is close at hand. Whereas other suppliers could only distribute LNG by ship, the road or railway alternative is a possibility because of the relatively short distances and land connection. During the last few years the production capacity in Norway has been increasing, and this is believed to continue [14]. Norway could also be a role model of the distribution system, with small-scale receiving terminals scattered along the coast. The reason why this system is so successful in Norway is because of the high cost of building pipelines across the Norwegian landscape, which may be beautiful but unfortunately very challenging for a pipeline constructor.

The small-scale LNG should be distinguished from the base-load LNG, where much larger quantities are handled. The ship currently operating in Norway carries 1100 $m^3$ of LNG (Gasnor operated *Pioneer Knudsen*), whereas base-load ships handles volumes of 80 000 – 300 000 $m^3$ of LNG. The consignees in Norway are small users such as local industries or towns. Base-load LNG users are typically complete Natural Gas networks with thousands or millions of users. An intermediate market position is presently developing in that new ships are under construction with loading capacities of 7500 – 10 000 $m^3$ of LNG. These are neither bound by the concepts of large scale base-load imports nor small-scale distribution, creating a new type of market.

The largest Norwegian production facility, which has recently sent their first LNG shipment [22], is situated on the island Melkøya, just off Hammerfest, the northernmost city in the world. StatoilHydro operates and co-owns this pure-LNG production plant which uses Natural Gas from the Snøhvit field, extracted completely by underwater equipment. This technology as well as the gas cooling advantages of the Arctic climate, is claimed to affect the sensitive environment minimally. The 60 BNOK plant will however increase Norway's $CO_2$ emissions by 4 % but they intend to pipe this back for storage in the field. The planned annual production capacity of Melkøya is 65 TWh and it can therefore be classified as base-load LNG. Four new LNG carriers of each 140 000 $m^3$ will cover the transport demand. [23] There are plans to distribute some of the LNG through a small-scale distribution network around the Nordic polar area as well. [14]

Currently, there are three plants operating and one plant under construction in the small-scale category. Gasnor operates the Karmøy and Kollsnes plants, just off Stavanger and Bergen, respectively. LNG is distributed by *Pioneer Knudsen* at present but in the first quarter of 2009 the new 7500 $m^3$ *Coral Methane* will start operate as well.

The small Tjeldbergodden LNG plant outside Trondheim is a part of a plant with combined methanol production, gas treatment and air separation. It is operated by StatoilHydro. [23]

Gas plant and district heating/cooling operator Lyse Gass, ship owner I.M. Skaugen and a few other companies have joined forces under the name Nordic LNG and are currently constructing Norway's second largest LNG plant in Risavika, near Stavanger. The planned capacity is 4.5 TWh/year with the possibility of expansion to double the capacity. Distribution will be carried out by 10 000 $m^3$ ships and by lorries. [14]

See figure 4 for an overview of the Norwegian LNG infrastructure.

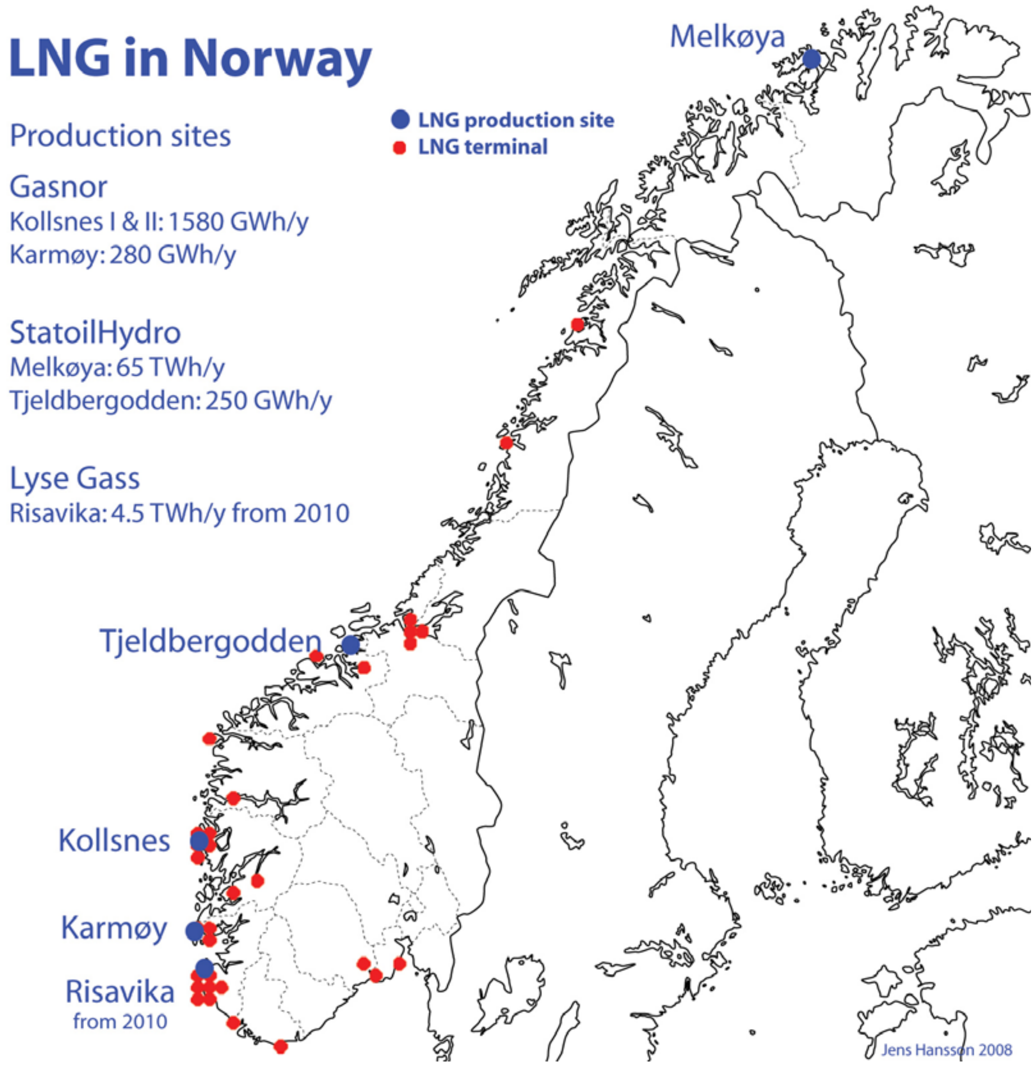


**Figure 4: The Norwegian LNG production sites and receiving terminals**

## 2.8 LNG in Sweden?

In Sweden, there was an early awareness of the potential of LNG but Natural Gas was not seen as a feasible alternative until the oil crisis of 1973-74 at which point the country had 70 % of its primary energy demand covered by oil. At first, the government was never positive to the LNG ideas. Kockums and a few other large companies suggested large scale base load import of LNG by sea from the Middle East or Algeria to two terminals, one on the west coast and one in Karlshamn but the government saw few advantages in association to the higher price. As larger resources than expected were discovered in Denmark, a contract was established in 1980 to import Natural Gas by pipelines. This severely reduced interest in larger scale LNG plans for the next two decades. [7] The Natural Gas network which was finished in 1985, started in Malmö reached as far as Gothenburg. In 2002, a branch to Gnosjö was built and in 2004, Stenungsund was also connected. But this still leaves huge parts of the country without a supply. [24]

For both Europe and Sweden, one advantage of LNG is that it causes the energy supply mix to be more varied which gives more flexibility. Buyers are less dependent on specific suppliers and transit countries than they are for a pipeline supply, and vice versa. Another advantage is the growing spot market, and the fact that the LNG systems have become cheaper. There are however great uncertainties of the future energy politics in Sweden, something which makes present actors hesitant to large investments in LNG import terminals. Moreover, an expansion of the pipeline network, e.g. from Germany or Russia could also be more cost-effective than LNG import if the maximum capacity could be met this way. [4]

There is a difference between Sweden and the rest of Europe in the potential LNG use. Europe imports LNG to a well-advanced gas network and either replaces pipeline Natural Gas or adding capacity to the network. In Sweden, LNG would replace other energy sources, by making Natural Gas available to more locations. Natural Gas currently covers 2 % of the energy demand in Sweden. In Europe, this figure is 20 %. [4]

As seen in figure 5, the European pipeline network is comprehensive but there is a large unexploited portion of densely populated areas left – Sweden.

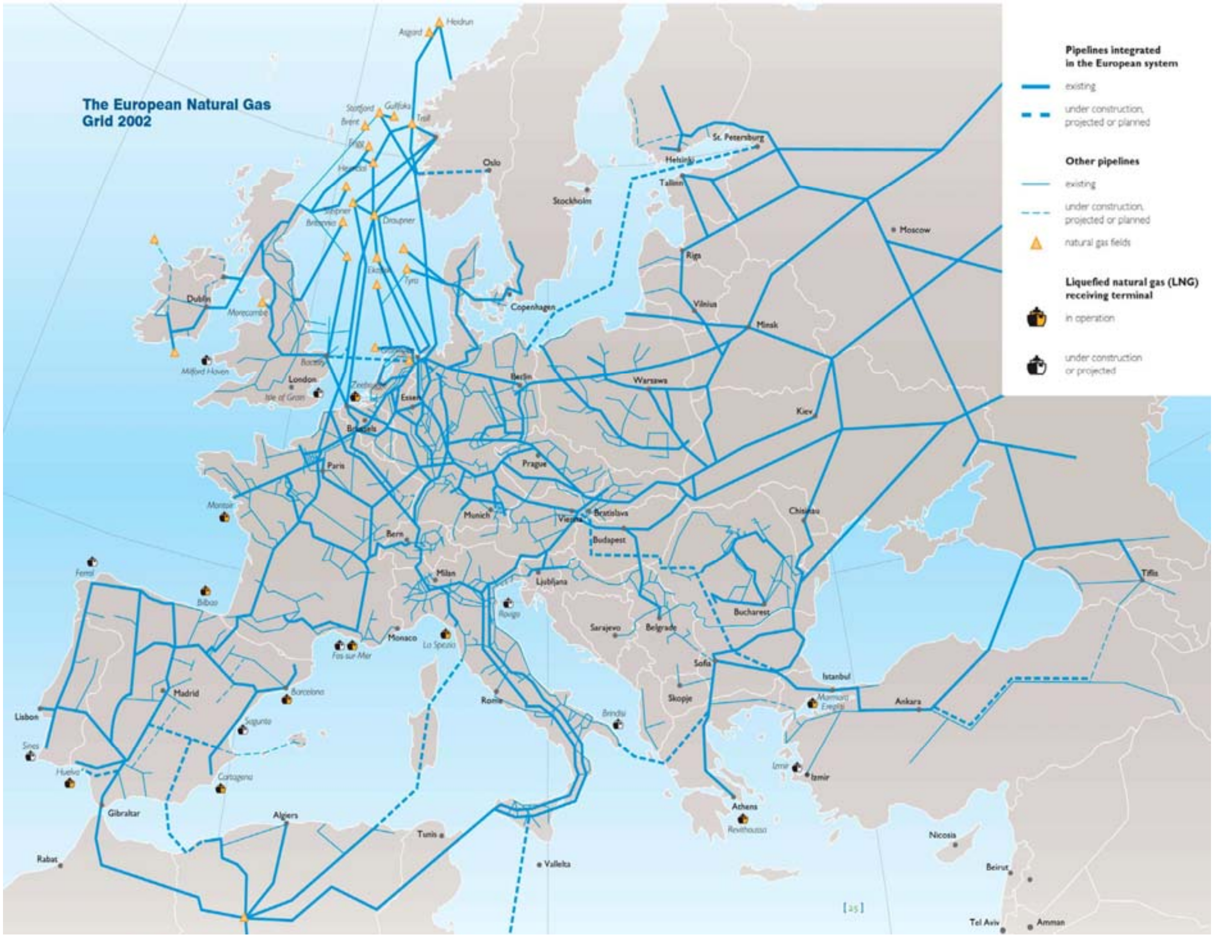


**Figure 5: The European Natural Gas pipeline network, with planned as well as operational LNG terminals indicated [25]**

Today there are three small LNG users in Sweden. They are used as back up for vehicle fuel biogas and are located in Linköping, Uppsala and Stockholm. [26]

The potential of LNG use has been estimated in Näslund's *LNG i Sverige* through the municipal energy balances put together by Statistiska Centralbyrån [7]. In this, the combined exchangeable amounts of oil, LPG, electricity and wood fuels in the studied area are included.

The final utilisation of these energy sources is used in the data. The fuels used for district heating and industrial counter-pressure are collected under their respective heading. See diagram 2.

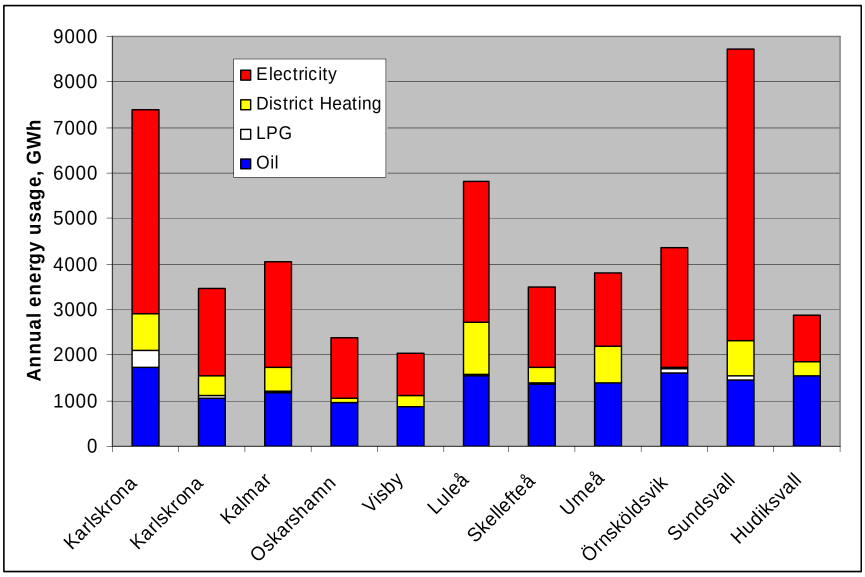


**Diagram 2: The annual energy usage around some potential LNG terminal placements along the Swedish coast. The figures derive from the municipal energy balances presented by Statistiska Centralbyrån and have been collected in Näslund's *LNG i Sverige* [7].**

With disregard to the actual plant conversion, the amounts of oil and LPG are mostly directly exchangeable with Natural Gas. The electricity used is in some cases produced by the above mentioned fuels and hence also replaceable by Natural Gas. Replacing only oil and LPG, Näslund et al figure there is a potential of 4.8-5.9 TWh for these 11 terminals, scaling them to at least 200-400 GWh each. The possibility of using LNG for vehicle fuel and replacing existing electricity production is not included in this. A possible scenario if this potential would be exploited is to construct a small pipe network around each terminal, which would have one or a few large industrial users and a community tied to it. [7]

**Figure 6: The present Swedish gas network and the stretches which are planned or under construction. [27]**

# 3 Processes in the LNG Chain

The general value chain of LNG is described as shown in figure 7. In this section, the most important process steps are described.

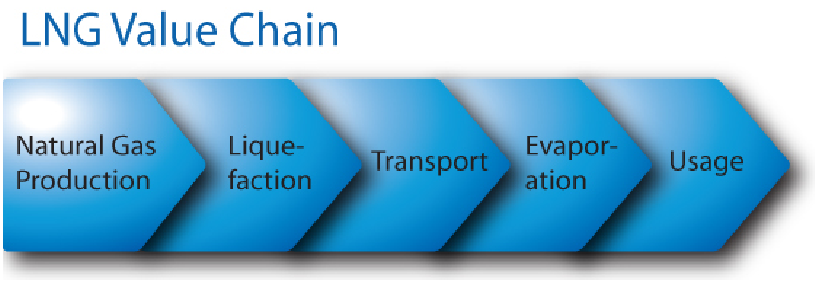


**Figure 7: The LNG value chain as well as the main process steps**

### 3.1.1 Pre-treatment

After the Natural Gas has been extracted from the gas fields, it needs to be pre-treated prior to liquefaction. Heavier hydrocarbons ($C_{5+}$) are commonly removed through absorption. The gas is also dehydrated and $CO_2$ is removed. [1]

### 3.1.2 Production

The liquefaction process takes place after the raw gas pre-treatment. Due to the high critical pressure of Natural Gas, the liquefaction is usually performed via temperature reduction as opposed to pressure increase. The large scale of the process means that production is economically favoured by lower operating costs, e.g. in terms of energy consumption. Process efficiency is more important than savings in investment. Various cooling agents are utilised in these elaborate cooling processes. [1]

### 3.1.3 Cascade Refrigeration Processes

In the earliest liquefaction processes, a number of single refrigerants are established in separate closed-loop refrigerators, which account for refrigeration at discrete temperature levels. Propane, ethylene and methane are typical cooling agents. By preset pressure letdowns, each refrigerant answers for a number of temperature levels. They are heat exchanged with the Natural Gas and other refrigerants at suitable pressures, creating an elaborate system of effective cooling. Methane which is utilised in the cooling process can be successfully used in an open loop, for mixing with the product stream. An example of the Cascade Refrigeration Processes is shown in figure 8. [1]

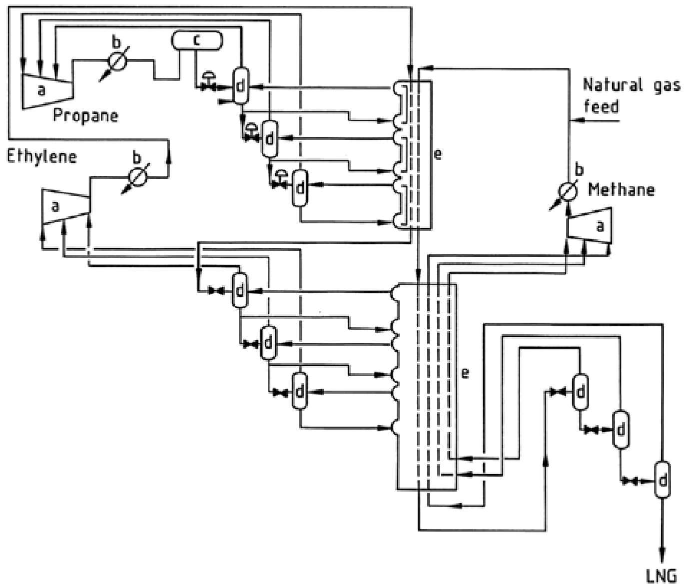


**Figure 8: Cascade Refrigeration Process. Three refrigerants in a nine-stage cascade.**
**a) Compressor; b) Condenser; c) Accumulator; d) Phase Separator; e) Heat Exchanger; [1]**

### 3.1.4 All-Mixed-Refrigerant Processes

Whereas the Cascade Refrigeration Processes are associated with high capital costs, complex layout and limited train capacities, the succeeding All-Mixed-Refrigerant Processes involve higher operating costs but higher capacities (figure 9). Equipment and analytical capabilities had advanced, making it possible to use a single refrigerant mixture of different cooling agents, typically pentane, butane, propane, ethane, methane and nitrogen. By this, the temperature-enthalpy warming curve of the refrigerant can closely track the cooling curve of Natural Gas. This process has performed well in plants and is simpler than the cascade process. It is however not thermodynamically efficient enough to be economically feasible as energy prices are rising. This is because such a wide range of temperatures need to be covered by the refrigerant mix and hence, compromises in the composition are necessary. Moreover, heavier components in the refrigerant are compressed to a higher pressure than required for their condensation to ensure the condensation of the lighter components, such as methane and nitrogen. To avoid this recompression penalty, the refrigeration components can be separated as in the Pre-cooled Mixed-Refrigerant Processes.

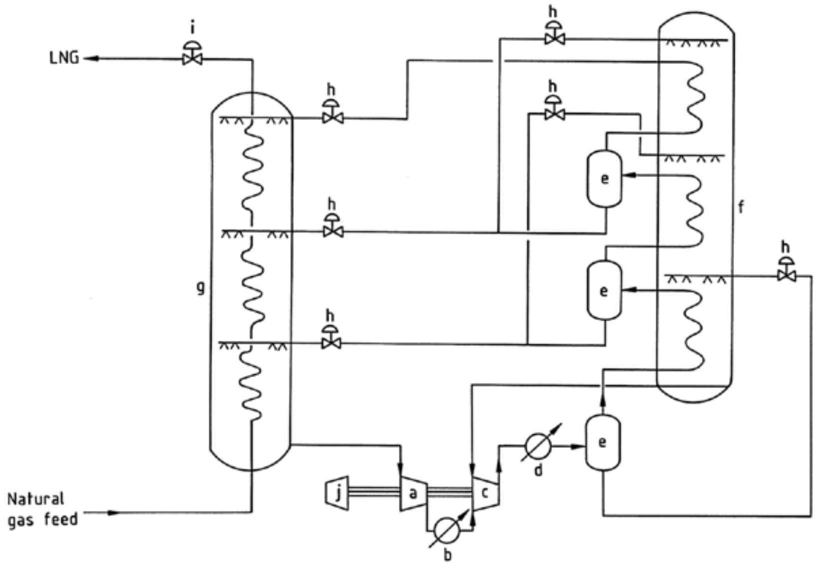


**Figure 9: All-Mixed-Refrigerant (MR) liquefaction process.**
**a) First stage MR compressor; b) Cooler; c) Second stage MR compressor; d) Cooler; e) Phase separator; f), g) Heat exchangers; h) Joule-Thompson valve; i) Product letdown valve; j) Driver [1]**

### 3.1.5 Pre-cooled Mixed-Refrigerant Processes

A third generation of processes was developed in the early 1970s. This combined the Cascade Refrigeration Process and the All-Mixed-Refrigerant Process. By using a propane cascade refrigerant process as the first step and then a mixed-refrigerant composed of propane, ethane, methane and nitrogen in series, the demands on the construction material and the boiling point range of the mixed-refrigerant decreased. The propane pre-cools the Natural Gas and serves as an intermediate refrigerant from the mixed-refrigerant section to water or air, whereas the second step cools the Natural Gas to LNG conditions. Less expensive carbon steel can be utilised as a construction material for the first step and the more costly aluminium or nickel steel which is needed for low temperatures can be used in the second step. Since the temperature range, which the mixed-refrigerant is needed for, is reduced, some recompression penalty can be avoided. These factors result in a more optimized and energy efficient process, which is widely used today.

Since the worldwide demand of LNG has increased recently, larger capacities of the liquefaction processes have been necessary. Later improvements include new compressors, gas turbines and cryogenic heat exchangers. The train capacity of liquefaction trains built today is typically 5 million tons per year.

Another recent development which increases train capacities without a substantial increase in equipment size is the AP-X$^{TM}$ or hybrid process cycle. In this, the mixed refrigerant only has to cool the LNG to -115 $^{o}$C – sub-cooled nitrogen is then utilised to take the temperature down to -160 $^{o}$C. The AP-X$^{TM}$ process is displayed in figure 10.

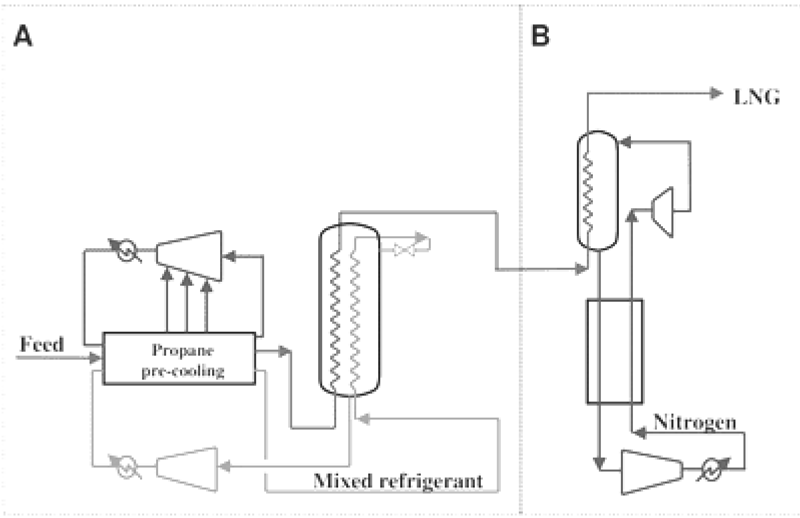


**Figure 10: AP-X$^{TM}$ process cycle. A) Propane pre-cooled mixed-refrigerant process; B) Nitrogen refrigeration closed-loop process**

The use of a dual mixed-refrigerant in the pre-cooling step (ethane is added to the propane) can make the process more flexible by distributing the refrigeration duty between the steps as desired, something which is useful in the face of changing feed gas conditions or power availability. It is however more complicated to operate since pressure control is more difficult.

## *3.2 Distribution*

Since the main purpose of liquefying the Natural Gas is to facilitate the forwarding, the choice of transport is of the essence.

### 3.2.1 Sea

The vast majority of LNG is today transported by sea and hence, at a large scale. Normally, the tankers load LNG at locations remote to the user, and forward it to the same, where it will be used in an existing Natural Gas network or on a larger industrial site (so-called base-load, as discussed in section 2.7). But in Norway for example, LNG is shipped at a much smaller scale (so-called small-scale, as discussed in section 2.7) along the country's coastline, simply because a pipeline network would be too expensive due to the mountainous fiord landscape.

Typically, the maximum load the tankers can take is 100 000 - 200 000 $m^3$ of LNG. But presently, the loading capacities are increasing - in September 2007, 137 new ships with an average capacity of 172 000 $m^3$ were under construction, where the largest one will load 267 000 $m^3$ of LNG. The ship used in Norway today can only load 1100 $m^3$ but during 2008, the new 7 500 $m^3$ *Coral Methane* (figure 11) will be delivered for the account of Gasnor/Anthony Veder. I.M. Skaugen/Norgas Carriers AS has two new 10 000 $m^3$ and six 12 000 $m^3$ ships being delivered in 2009 [28]. Japan is also using this kind of supply chain in addition to their base-load import, and China is launching domestic LNG shipping at this scale as well.[29]


**Figure 11: Artist impression of the new small-scale LNG ship *Coral Methane*, currently under construction in Poland. Picture courtesy of Anthony Veder.**

LNG is stored at atmospheric pressure. There are two main designs of LNG ships: spherical tanks/moss type and membrane tank. The spherical tanks are made of aluminium or nickel steel with a wall thickness of 40-70 mm with insulation made of for example polyurethane, making them ten times heavier than the membrane tanks (at a total loading volume of 125 000 $m^3$). The membrane tanks are made of several layers of metal which is not sensitive to temperature change, e.g. invar, and with insulation made of foam. [7]

Regardless of the tank design, every LNG tanker has a boil-off factor, i.e. the relative amount of cargo which evaporates, of 0.2 - 0.25 % per day. This gas is often used as fuel for the ship. [1]

### 3.2.2 Railroad

Railroad transport is often referred to as the most environment friendly alternative since it is mostly electrified in Europe. It is true that electricity is clean as long as it is generated in a clean way. The Swedish power mix mainly consists of hydropower and nuclear power and is therefore not a polluter of $CO_2$, $SO_x$ or $NO_x$. The case is different in most of the rest of Europe however – there are still much fossil fuels used for electricity production.

There is currently no LNG transport being performed by railroad in Europe, but some of the current railroad shipping actors think it will be reality within a few years. [30, 31]. Currently, large quantities of LPG are transported in the liquefied state, but because of the nature LNG, these wagons will be 7-8 times more expensive than the LPG wagons. There are already as good as finalised plans for the construction of these wagons, just waiting for the demand to arise. [31] For example, there are plans to use railroad shipping for Melkøya LNG, dispatched between Narvik and Luleå. [32]

Each wagon car has about 40 tonnes of loading capacity [7]. Depending on the volumes, *wagon transport* (a single or a few wagons per dispatch) or *system transports* (dedicated trains) would be used. Another advantage of railroad is speed - in most cases it only takes a day to cover the whole of Sweden per one-way trip. Well within the hold time, in other words. [30] As this is an unproven transport method, some issues need to be solved. For example, a wagon which would mistakably be left beyond the hold time at a goods yard somewhere would have serious consequences as LNG evaporates and the pressure increases. Another challenge is the reloading process – since the rail track in many cases do not reach all the way from producer to end user, reloading could be necessary, at which heat leaks into the LNG. This causes LNG to evaporate, increase the pressure and decrease the density, which means that less LNG can be transferred in the available volume of the vessel. [26]

### 3.2.3 Road

Regional LNG transport can be performed by road. The LNG lorries are equipped with a cryogenic tank; it is the same construction as for other cryogenic liquids, e.g. nitrogen, helium. Hardstaff Group has developed and constructed a system for LNG transportation, where the lorries are powered by their cargo. In Sweden, Cryo AB offers a 21 tonne capacity tanker, with a boil-off of 0.9 % per day, giving it a "hold time" of about 10 days. [33] Gasnor uses LNG lorries delivered by Ros Roca in Spain. These load 20-23 ton per trailer [7].

LNG lorries take 1-2 hours to load and to unload. The LNG is loaded at atmospheric pressure but because of the boil-off, the pressure has usually increased to about 2 bars at the point of unloading. The Ros Roca tanks are dimensioned to 10 bars but safety valves limits the pressure to 7 bars. The valves work independently from one another and thus they will work as planned even if the trailer would roll over. [7] The maximum range for LNG transport by road is traditionally said to be about 300 km [11] but recent developments indicate that the limit is a greater distance than that – it depends on what is most economically feasible in the current situation [34].

## *3.3 Receiving the LNG*

Whether the scale is base-load or small-scale, the terminal to receive the LNG is similar. Below, it is referred to as import terminal for base-load and as receiving terminal for small-scale.

Most of the world's LNG is handled in a base-load system. LNG is forwarded from a remote gas field to a gas network which is not connected to a supplier with enough capacity for the demand. The typical base load plant handles 4 million tons per year and the typical base load tanker has a capacity of 150 000 $m^3$. [13]

Many issues have to be looked into for a correct localisation of an import terminal, e.g. ecology, environment, weather, distance to end users, access to staff, infrastructure and construction material. [7]

An import terminal for ship distribution generally consists of:

- a docking facility, where the ship can be unloaded
- an unloading system for LNG
- storage tanks
- a regasification system and
- auxiliary systems and buildings, for operation and maintenance.

(See figure 12)

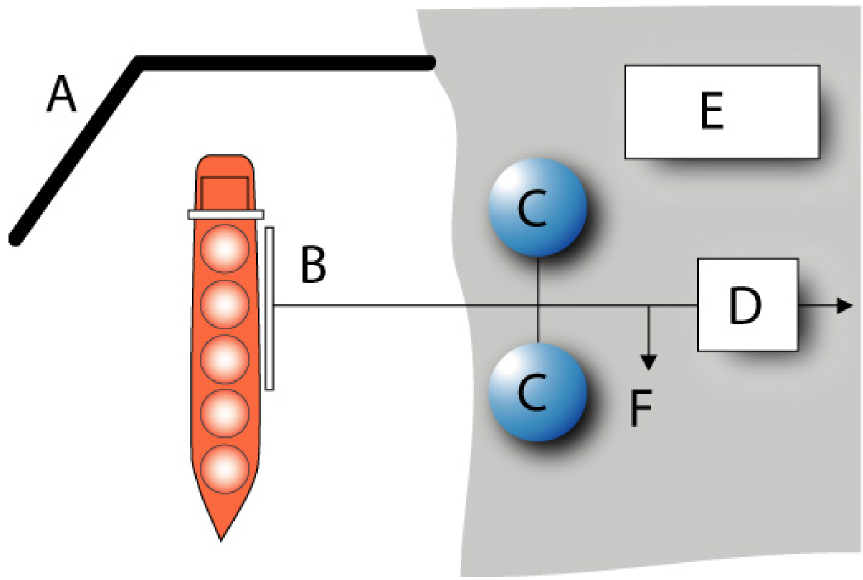


**Figure 12: Sketch of a typical import facility. A) Docking facility B) Unloading system C) Storage tanks D) Regasification system E) Auxiliary systems and buildings F) Direct loading of LNG, for road tankers etc.**

The harbour should allow a draught of 11 m and ship lengths of up to 300 m. The capacity of the unloading system usually allows an LNG carrier to be emptied in 12 hours [7], which typically means a flow of 12 000 $m^3/h$ [35].

There are import terminals which are partly or completely based offshore. 200 km south of the coast of Louisiana, USA, ships can unload their LNG, which is gasified and directly added to pipelines transmitting gas inbound from the Mexican Gulf. [7] In Livorno, Italy, a complete offshore import terminal is being built [36]. There are also projects where old LNG tankers are converted into import terminals [37].

Receiving/small-scale terminals are more or less a smaller scale of the import/base-load terminals. They are characteristically connected to a local gas network or to a smaller user and handle 20 000 – 200 000 tons per year. The ships have a capacity of 1 000 - 10 000 $m^3$ and naturally do not have the same spatial requirements as the base-load carriers. The 1100 $m^3$ *Pioneer Knudsen* in Norway is actually certified to use Göta Älv to reach as far as Vänern [38]. Norway implements small scale LNG distribution through a system of receiving terminals along the coast. The gas is either regasified onsite and piped to the users, or distributed in the liquefied state by lorry further, before the regasification.

Receiving terminals are very low maintenance – since the plant design is simple and the technology mature, most terminals are unmanned. Problems which occur during operation are reported remotely to operators on stand-by. The running costs are also low; except for the ordinary scheduled maintenance, there is only the electricity cost for the pump system. [26] A simplified process flow diagram is found in figure 13.

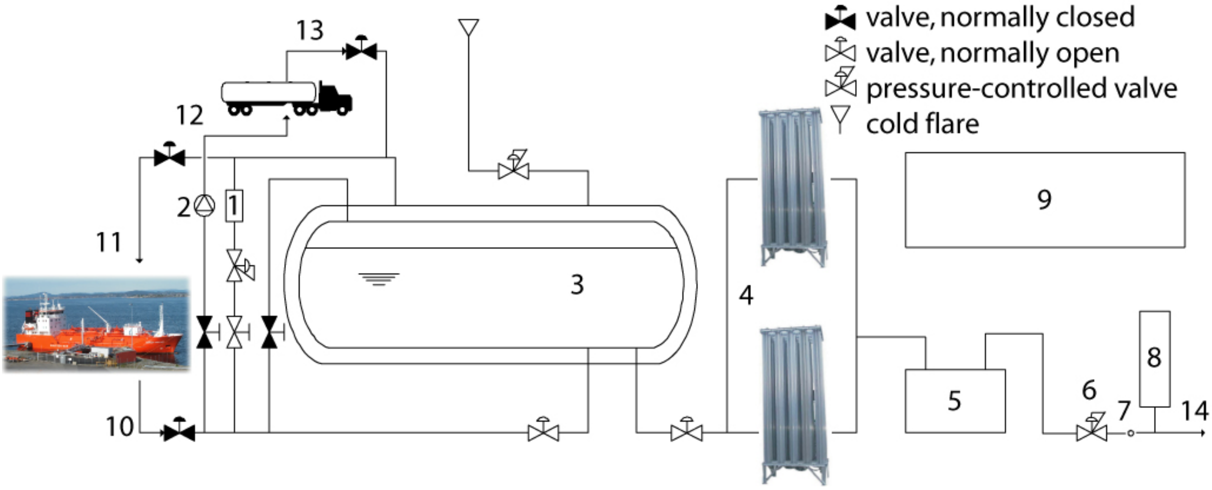


**Figure 13: Simplified process flow diagram of a typical LNG receiving terminal [7]**

**Photos: Jens Hansson**

1. **Pump for pressure increase**
2. **Pump**
3. **Storage tank**
4. **Evaporators**
5. **Trim heater**
6. **Pressure controlling valve**
7. **Flow meter**
8. **Odorising system**
9. **Control module**
10. **LNG from ship**
11. **Gas return to ship**
12. **LNG to lorry**
13. **Gas return to lorry**
14. **Gas to pipe network**

## *3.4 Regasification*

Restoring LNG into Natural Gas involves adding energy to the product by evaporation and increasing of the temperature of the gas. This is performed by heat exchange with a heating agent, usually sea water or air. There are also ways to use the cold stored in the LNG (see chapter 2.5.4).

The simplest and most common LNG regasification system is Open Rack Vaporisation (ORV). This uses ambient sea water to heat the liquefied gas. The efficiency is dependent on the ambient temperature but because of the low LNG temperature, the process is possible to use in many locations. In very cold conditions, there is the risk of ice formation if an additional heat source is not utilised. The operating costs are typically low and the process has a low environmental impact in terms of emissions but it could damage the local marine life. [39] The Broadwater Project will use ORV in their regasification terminal, which is to be located in the state of New York. [9].

In Submerged Combustion Vaporisation (SCV), combusted fuel gases are used to indirectly transfer heat to the LNG. This is done in a closed-loop system through a water bath. The environmental effects are mainly determined by the choice of combustion and flue gas treatment. Benefits include the availability for inland plants and the fact that less water is used. [39]

Intermediate Fluid Vaporisation (IFV) uses alongside ORV the heat in sea water but in this process an intermediate fluid is utilised. It is possible to recover some of the heat from the gasified LNG back to the sea water. [39]

Using the heat in ambient air, the Mustang LNG SMART$^{TM}$ Vaporisation is the most location sensitive system. An intermediate fluid is heated by the air and then heat exchanged with the liquid gas. The SMART system reduces fossil $CO_2$ and NOx emissions. Since the air needs to be warm enough, this vaporisation technique is often not that efficient in locations situated in cold climate (20 $^{o}$C means 93 % efficiency and 4 $^{o}$C only 42 %.). [40]

There is also the alternative of direct air evaporation. A large contact area between liquid and air makes sure that as much heat as possible can be transferred. This conventionally fin-shaped two-phase heat exchanger is one of the most common options for small-scale LNG because it is cheap and low maintenance. [26] See figure 14.

**Figure 14: A fin-shaped air evaporator is used at Gasnor's LNG receiving terminal at the CCB base, near Bergen, Norway. Photo: Jens Hansson**

LNG/air evaporators such as the Mustang LNG SMART™ Vaporisation are least effective in a humid climate at around 0 $^{o}$C, at which a maximum of ice build-up on the evaporator is achieved. Lower temperatures means that the air contains less heat but however, it contains less water and thus the level of ice fouling is lower. [26] Air evaporators are often built in pairs so that one of the two can be de-iced while the other is running. The maximum capacity of air evaporators are typically 3700-3900 Nm$^{3}$/hour while it can be as low 1700 Nm$^{3}$/hour when covered in ice.[7]

## 3.5 Storage

Storage tanks can be either pressure free or pressurised. The construction varies between these types, as well as the temperature at which LNG is stored. The pressure free tanks can store colder LNG (-162 $^{o}$C), which thus have a higher density, whereas pressurised tanks hold warmer LNG (~-140 to -150 $^{o}$C) of lower density. Pressurised tanks are usually constructed for a specific pressure and in order to maintain this, some forced evaporation through the own evaporating system or cold flaring could be necessary. As a consequence of these thermodynamic properties, it is an advantage to use pressure-free tanks as much a possible – the same amount of LNG in terms of weight uses more space when it is pressurised. These tanks are however more expensive. Some comparative figures of the thermodynamic properties are shown in diagram 3 below.

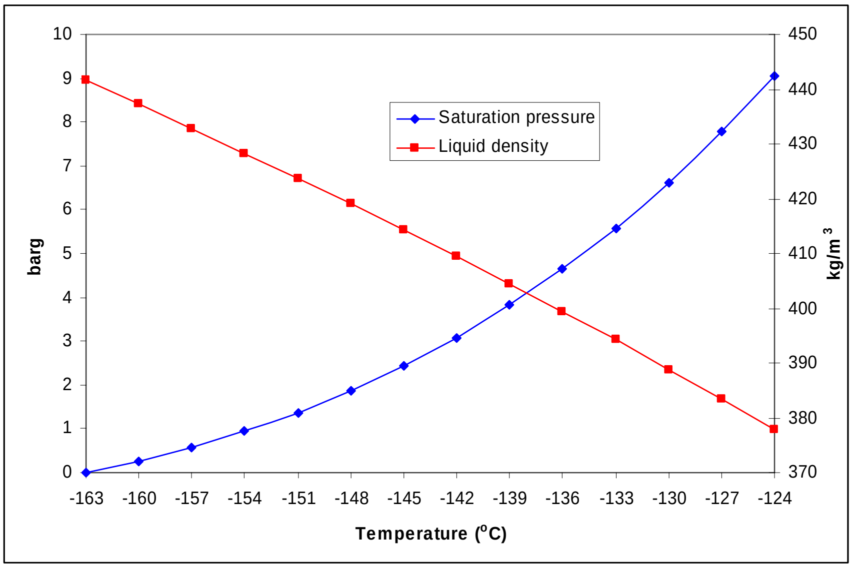


**Diagram 3: Some thermodynamic properties of LNG from Kollsnes Production Plant, Norway [41]**

Insulation is of the essence in the construction of LNG tanks. The storage tanks need an inner tank, an insulation layer and an outer wall to fulfil the demands on heat insulation and safety. 9 % nickel steel is the most common construction material of the inner tank, but aluminium has also been used. Aluminium has however twice the coefficient of thermal expansion than steel and this increases the risk of tank failure when cooled down. Reinforced concrete is commonly used in the outer tank for pressure-free tanks, in which the insulation often consists of perlite. In pressure tanks, vacuum is used to insulate.

To prevent roll-over (see chapter 2.3 above) agitation is obliged in larger tanks. Sometimes a regasification system is needed. Safety regulations also demand a dike around the tank so that LNG would be contained in the case of leakage.

Because of the high demand of insulation at the low temperatures required and the high safety regulations, LNG storage tanks are an important part of the cost of a LNG handling facility.

The size of the storage chiefly depends on the demand of Natural Gas but also on the size of ships which operate the facility. A large import terminal typically has a storage capacity of 1-2 shiploads, i.e. 150 000–300 000 $m^3$. For small-scale LNG, the optimal amount of storage volume has to be calculated with regards to the rate of usage, the ship frequency and the boil-off factor. [7]

In figure 15, a storage tank of the Melkøya LNG production plant is shown.

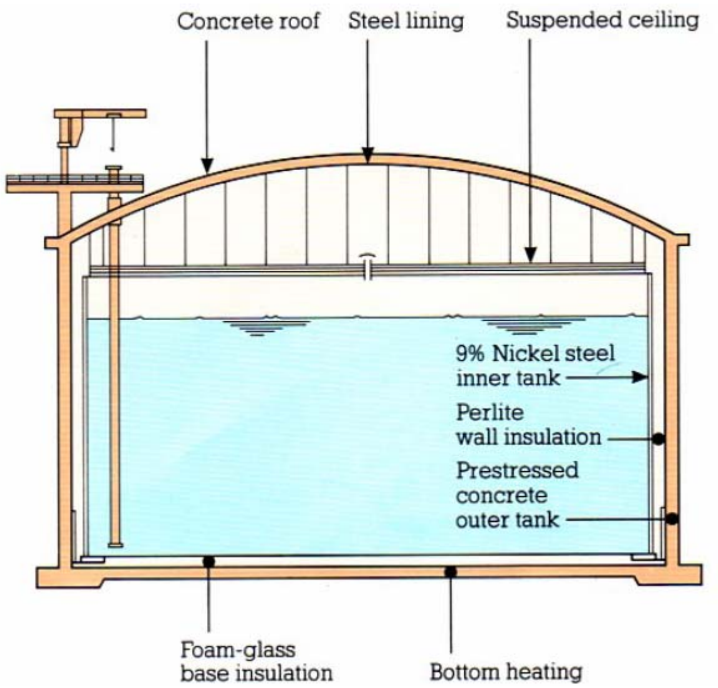


**Figure 15: An illustration of a low pressure storage tank at the Melkøya facility in Norway. [42]**

An acceptable level of boil-off is 0.2 %/day but in new tanks of net sizes above 100 $m^3$ of LNG, it can be as low as 0.1 %/day [43].

## 3.6 LNG Production in Gas Pressure Regulating and Measuring Stations

The pressure of the transmission lines of the Natural Gas grid in Sweden is about 60 bar. Before distributing the gas to the end user, the pressure has to be reduced. In Gas pressure regulating and measuring, the gas is expanded to typically 28.8 bar (Göteborg), 4 bar (Halmstad and Malmö), 10 or 12 bars (Malmö). The process needs heat which has to be taken from somewhere – by exploiting this cold to freeze some of the Natural Gas, LNG can be produced. An LNG production unit of this type is naturally located at a Natural Gas transmission line but the LNG could of course be dispatched to another location.

According to earlier SGC reports [33] this would be feasible with the commercial systems of today if the pressure reduction is large enough. The first pilot plant was built in 2003 in Sacramento, USA by INL (Idaho National Laboratory). Hanover Corporation was the first company to get a licence to use the technique and they are currently building two larger plants in the United States. To start with, only 10 % of the incoming Natural Gas could be liquefied but the figure of the new plants is 20-30 %. The purpose of these plants is to produce LNG as vehicle fuel. [16], [33]

The process used is an expander cycle. In this, as the fluid which performs the work in an expansion engine, Natural Gas is used (in other applications nitrogen is often used). Instead of reducing pressure of the "flowby" gas across valves, the gas is pre-cooled and work expanded to provide refrigeration to liquefy a small fraction of the Natural Gas. The flowby gas then needs to be re-heated before it enters the distribution grid. [1] A simplified process flow diagram is shown in figure 16.

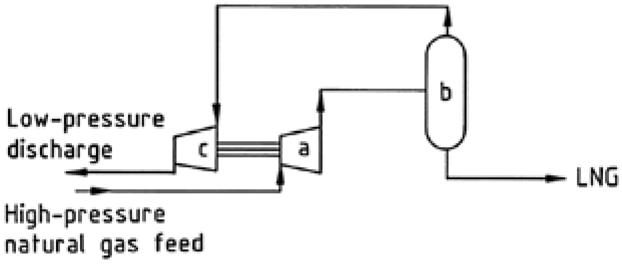


**Figure 16: LNG production in an expander cycle.**
**a) Turbine expander; b) Separator; c) Compressor [1]**

The big flaw with using a system like this is that the Natural Gas use would need to follow the LNG use closely. In Sweden, Natural Gas is largely used for heating, of which there is less demand in the warmer season. It is possible that the LNG which would be produced in the Gas pressure regulating and measuring station would be for road vehicle refuelling stations, which have a demand profile that is very different. This is a difficulty that needs to be looked into. [18]

## 3.7 Peak-Shaving

The purpose of a peak-shaving LNG plant differs from the base-load facility. Whereas LNG is liquefied, transported overseas and regasified at large scale in base-load handling, the purpose of peak-shaving operations is to either use Natural Gas that is distributed to the consumer end of a pipeline network or to purchase small quantities of LNG, and use this when the demand is high. In the first case, you little by little liquefy a part of excess incoming gas and store it as LNG until it is needed. This allows a higher annual utilisation without expanding the production and transmission facilities. A consumer does not have to agree to such a large delivery volume from the supplier when it can cover the peaks by regasifying stored LNG.

When LNG is produced on-site by the user, the objectives of the plant design are somewhat different from conventional LNG production. These plants are much smaller and only operated seasonally. Instead of utilising a highly thermodynamically effective design, the focus is on low capital cost. All-mixed-refrigerant liquefaction cycles have therefore largely been employed. If located at a local pipe network where the Natural Gas pressure is reduced enough from the transmission lines, the excess cold can be utilised in an expander liquefaction process. This process is described in the previous chapter. [1]

If the peak-shaving system only consists of a receiving terminal where the contents of the LNG tank can be used when needed, the main characteristics are small scale and low maintenance.

There are a few different solutions to satisfy the need of peak-shaving. A conventional small-scale LNG distribution system could be constructed. There is also the option to use portable LNG containers, which are especially suited for smaller uses. The Norwegian company Liquiline has developed and designed a distributional system, which consists of 40- and 20-foot containers constructed for LNG (so-called *LiquiTainer*®[1]) and an evaporisation station. The containers are shipped either by road, railroad or sea and work as the storage tank at the

[1] *LiquiTainer* is a registered trademark of Liquiline AS, patents pending

site location. When depleted, they are disconnected and swapped with a fresh container. [44] See figure 17.

**Figure 17: A Liquiline LiquiTainer® LNG storage and transport system in Norway. Photo courtesy of Liquiline AS. [44].**

An example of a site where there is a need of peak-shaving and its possible solutions is presented in the Calculations section below.

# 4 Environmental Issues Regarding Natural Gas and LNG

Since the utilisation of LNG as discussed in this study to a large extent would replace the use of oil and coal, the purpose of this environmental section is to compare and contrast these sources of energy feedstock. Alternative, renewable sources of energy are not examined below but this would be interesting to do in a future study.

The main area of significance when fuels are discussed is the actual combustion and its derivatives. The production and the transportation of these products are also important topics.

## 4.1 LNG Production

Natural Gas, oil and coal are all produced in a way which leaves an environmental footprint. Drilling operations and welling disturb the area of operation in a fairly similar way. Recent technologies of Natural Gas welling however reduce this. For example, at the gas field Snøhvit, a 100 % submerged extraction technique is used [23].

The LNG production process is energy demanding and less surprising, Natural Gas is utilised as the source of energy. This causes additional emissions.

## 4.2 Transport

LNG, as well as oil and coal are often shipped long distances to their end user. The environmental difference is therefore not very significant. One thing should be mentioned though – the ships used for LNG transport are in most cases powered by Natural Gas as opposed to oil and coal freighters. The combustion characteristics of these fuels are discussed below.

To illustrate the general environmental profile for a few different means of transport, the *EcoTransIT Environmental Load Calculation* model, whose construction was conducted by railway companies, is used for the Narvik-Lysekil route. In this model, oil is used as ship fuel is and thus, it is not a correct calculation for LNG transport by sea as this is normally performed by LNG powered ships. See the diagrams in figure 18. [45]

Piped Natural Gas does give some emissions when it is distributed. Apart from the environmental effects causes by the construction of the pipelines, pressure stations which are needed along a pipeline use Natural Gas to compress the distributed gas.

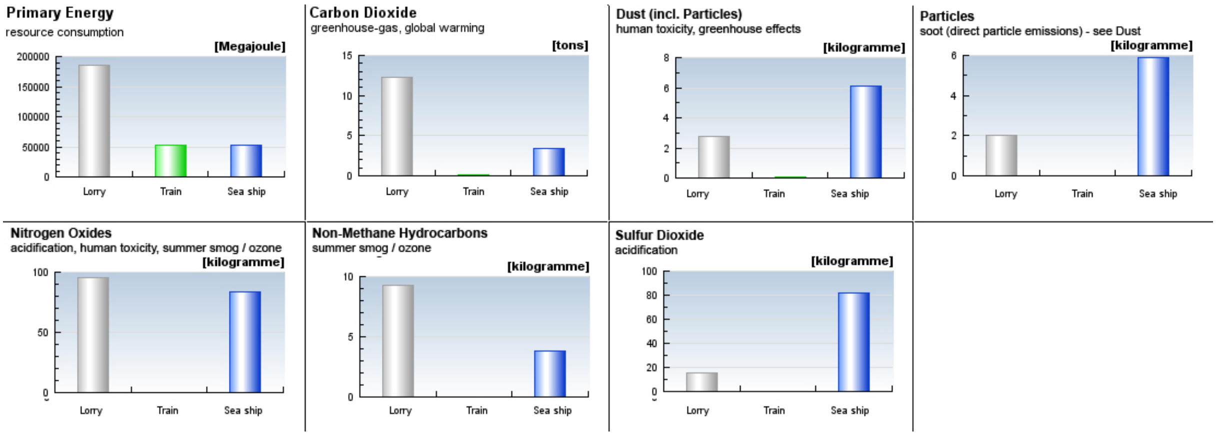


**Figure 18: Some key environmental figures for the transport of 100 tons between Narvik (Norway) and Lysekil (Sweden)**

## *4.3 Combustion*

### 4.3.1 Global Warming

Without its protective layer of "greenhouse gases", the Earth would be a lot colder and the possibilities of life greatly reduced. These gases include for example carbon dioxide, methane, nitrous oxide and ozone. Human activity has since the industrial revolution, particularly the combustion of fossil fuels such as coal and oil, is believed to have increased the amount of greenhouse gases in the atmosphere to such a large extent that the world is experiencing a worldwide increase of temperature – global warming. This will most likely affect the weather conditions, ocean levels, ecological systems and the amount of water bound as ice by the poles. In other words, it is one of our time's largest challenges to reduce to amount of greenhouse gases released to the atmosphere. [46]

Carbon dioxide is the substance which has the most significance, and there is much to gain if the net emissions of this can be reduced. Natural Gas, oil and coal are fossil fuels. By using them, additional carbon dioxide is released, unless this is captured and re-injected to underneath the earth crust where it came from.

The combustion of Natural Gas causes less carbon dioxide emissions than oil and coal for the same amount of energy released. [47] See diagram 4 below.

### 4.3.2 Acidification

One of the greatest environmental problems in Sweden these days is acidification. It depends on increased concentrations of hydrogen ions in the ground and waters. The hydrogen ions derive from acids released as an effect of combustion processes, agriculture and forestry. Fuels which contain sulphur and nitrogen cause their respective oxides to be emitted when combusted. These are typically oxidised into sulfuric acid and nitric acid, which reach the ground as acid rain. A reduced pH in the ground and waters has great impact on the biological ecosystems.

Natural Gas does hardly contain any sulphur and this is far from the case of oil and coal. [47] See diagram 4 below.

### 4.3.3 Nitrogen Oxides

In combustion processes, nitrogen oxides (NO and $NO_2$) are created both through oxidation of nitrogen which the fuel contains and by oxidation of the nitrogen in the air, if this air is used as an oxidising agent. The nitrogen oxide which derives from the air can be created through either thermal or prompt formation, of which the former is favoured by high temperature and the latter is temperature insensitive. The main part of the $NO_x$ produced in combustion of Natural Gas is thermal. [47]

The local environmental effects include oxidation of metal, acidification (as described above), over-fertilisation and damages on the vegetation. One of the global environmental effects is the formation of tropospheric ozone. Nitrogen dioxide is also believed to cause cancer. [47]

Because the creation of nitrogen oxides is temperature and pressure dependent, it is not possible to give altogether general information or to compare the different fuels in all cases, but in diagram 4 below some typical numbers are displayed. Since it is possible to burn Natural Gas at lower temperatures and as Natural Gas contains less nitrogen than other fuels, Natural Gas generally releases less nitrogen oxides. [24]

### 4.3.4 Dust and Particulates

Dust and particulates include for example soot, small drops of oil or sulphuric acid and metal fragments. Soot mainly consists of carbon and derives from incomplete combustion. At contact with sulphuric oxides, the particulates become acidic and contribute to acidification.

The amount of dust and particulates released largely depends on the composition of the fuel and the degree of purification of the smoke gases. Oil and coal combustion emit high concentrations of dust and particulates whereas the emissions for Natural Gas can be assumed to be close to zero. See diagram 4 below.

### 4.3.5 Miscellaneous

In addition to the above mentioned environmental aspects, Natural Gas is superior to coal and oil in terms the release of metals, carbon monoxide, dioxins and aromatic hydrocarbons. [24]

### 4.3.6 Summary

As discussed in the previous sections, the environmental effects of Natural Gas are lower than those of oil and coal. A comparison of some typical figures is displayed in diagram 4.

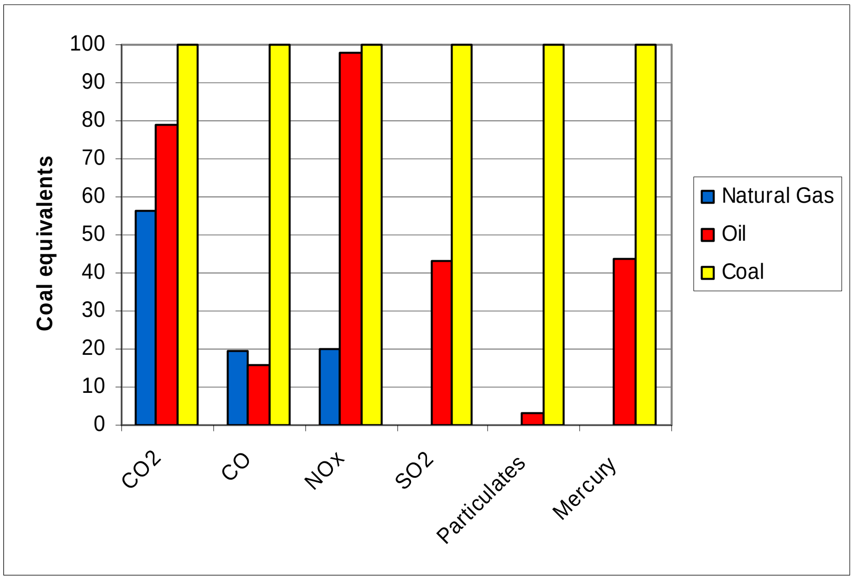


**Diagram 4: The emissions from the combustion of Natural Gas, oil and coal displayed as coal equivalents. [48]**

## 4.4 Different Sources of LNG

The environmental picture of LNG is not complete unless the profile from a number of different sources is studied. For example, a life cycle analysis from Norwegian LNG differs greatly from that of LNG from the Middle East or Southeast Asia, since the gas is processed, handled and transported differently.

In a study from NTNU about fuel cells, the environmental effects from LNG of different sources have been compared. [49]. LCA:s for oil, imported LNG and on-site produced LNG have been contrasted. A summary of the results is displayed in diagram 5.

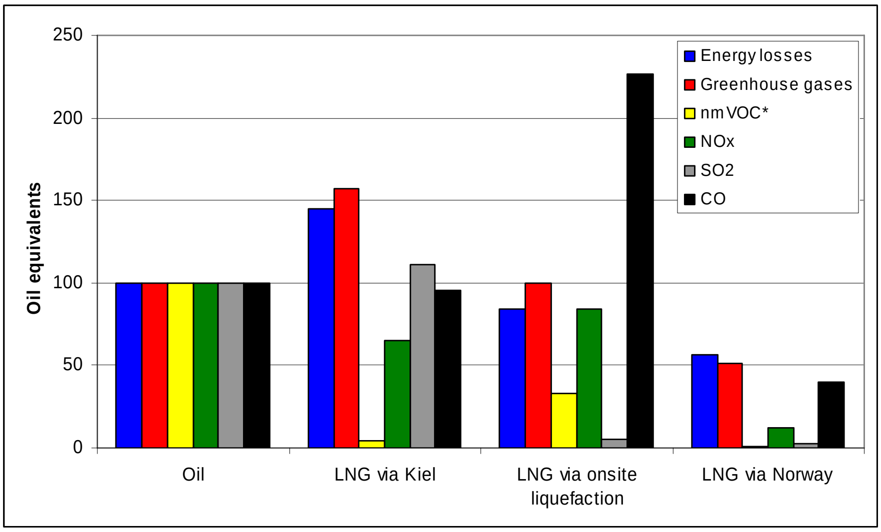


**Diagram 5: Life cycle analysis of oil and LNG from a variety of sources, expressed as oil equivalents. All source data is expressed as kWh/kWh and g/kWh for energy losses and emissions, respectively.**
*** non-methane Volatile Components**

The figures in diagram 5 cover all steps from the well to a ship refuelling station, i.e.:

- **Oil:** crude oil production, transport, refining and local transport to vessel
- **LNG via Kiel (produced at a remote location and imported through Zeebrügge, Belgium):** Natural Gas extraction and processing, liquefaction, export terminal, maritime transport 5000-6000 km, import terminal, transport to port and transport to vessel (in total 800 km of road transport)
- **LNG via onsite liquefaction:** Natural Gas extraction and processing, pipe transport (transmission pipe 1000 km, distribution pipe 500 km and local distribution 10 km), liquefaction at port and transport to vessel
- **LNG via Norway:** Natural Gas extraction and processing, liquefaction, transport to port and transport to vessel

The comparison shows that LNG can have large environmental disadvantages compared to oil. The levels of energy losses and greenhouse gases are much higher for LNG which has been produced overseas and shipped a long way to the end user. On-site produced LNG has high levels of CO-emissions. According to this study, Norwegian LNG is the “greenest” fuel.

For the case of LNG import via Kiel, it should be mentioned that the distances used in the calculation model are at their greatest. Firstly, 800 km of road transports is quite a long way (equivalent to Lysekil - Östersund; Zeebrügge - Kiel is approximately 730 km [50]). Secondly, 5000-6000 km of distance means that of the available producers, Indonesia, one which is located the furthest away from Belgium, is used in the example.

As a comparison, some figures from the European Council for Automotive R&D (EUCAR), the European Commission Joint Research Centre (JRC) and CONCAWE (European Oil Company Organisation for Environment, Health and Safety) joint Well-to-Wheel study [51] are presented in table 2. The numbers refer to LNG imported from a remote location and include extraction, processing, liquefaction, transport, receipt, vaporisation and distribution by pipeline.

**Table 2: Energy losses and emissions for diesel and LNG [51]**

| **Comparison of energy losses and emissions** | | | | |
|---|---|---|---|---|
| | Energy Losses (MJ/MJ) | Emissions from production $CO_{2eq}$ (g/MJ) | Emissions from usage $CO_{2eq}$ (g/MJ) | Total emissions $CO_{2eq}$ (g/MJ) |
| Diesel (light oil) | 0,16 | 13 | 76 | 89 |
| LNG | 0,25 | 17 | 57 | 74 |

According to table 2, there is a 16 % climate profit for LNG.

Both sources of information should be taken into account.

# 5 Calculations

## 5.1 *Base Cases of Cost Calculations*

### 5.1.1 General Approach

The purpose of this report is to calculate the final LNG price for the customer in Sweden, taxes and fees excluded. The final price depends on the following factors:

- LNG purchase price from the producer
- transport costs
- costs for the LNG receiving terminal

In order to give comprehensive picture of the cost situation of LNG import, a number of alternative sources, means of transport and import volumes are studied. These do of course examples not cover all of the possible options, but are meant to represent some of the believed feasible ones. The choice is also based on the level of available knowledge.

Since prices and costs vary greatly, the presented figures do not give the exact present price but will give the reader a rough idea of the situation. Some of the dominant factors will be varied in a sensitivity analysis at the end.

The following sections will give a more in depth presentation of the calculation methods used.

### 5.1.2 LNG Routes

Since there are hundreds of LNG producers worldwide and several potential destinations in Sweden, the number of possible trade routes is great. This report is limited to a few routes which are believed available today or in the near future. The chosen routes are described below and in figure 19.

Depending on the location of the Natural Gas resource and national standards, the composition and hence density and energy content varies. Some figures of LNG from a few different sources can be found in table 3. There should not be any larger problem associated with different composition - the heat value differs slightly but not significantly. If the gas were to be used as raw material in chemical processes it could have an effect on the purification methods.

**Table 3: Characteristics of few different gas mixtures. Sources: [52] except * which is [49]**

| Different gas mixtures | | | | | | |
|---|---|---|---|---|---|---|
| **Gas component** | **Danish Natural Gas** | **Russian Natural Gas** | **LNG (Algeria)** | **LNG (Qatar)** | **LNG (Nigeria)** | **LNG* (Norway)** |
| Methane | 88,97% | 98,40% | 87,60% | 89,30% | 90,50% | 92,0% |
| Ethane | 6,14% | 0,60% | 9,40% | 7,10% | 5,10% | 6,0% |
| Propane | 2,51% | 0,20% | 2,00% | 2,50% | 3,00% | 0,00% |
| Buthane | 0,95% | 0,05% | 0,20% | 1,16% | 1,50% | 0,00% |
| Penthane | 0,18% | 0,01% | 0,10% | 0,10% | 0,00% | 0,00% |
| Lower heat value kWh/Nm$^3$ | 11,05 | 9,99 | 11,04 | 11,26 | 11,22 | 10,67 |
| Upper heat value (kWh/Nm$^3$) | 12,21 | 11,08 | 12,21 | 12,45 | 12,41 | 12,72 |
| Density (kg/Nm$^3$) | 0,827 | 0,729 | 0,812 | 0,822 | 0,819 | 0,843 |

**Kollsnes, Norway** is Gasnor's largest LNG production site and it has been running since 2004. It is situated near Bergen and delivers Natural Gas as CNG as well as LNG by lorry or ship. Its location makes it the obvious hub for Gasnor's distributional network and a possible supplier for Sweden.

**Melkøya, Norway** started LNG production in the late 2007, 11 months too late and 48 % above budget. It is however a possible choice for Swedish LNG import as this StatoilHydro operated state-of-the-art facility has energy effectiveness and reduced carbon dioxide emissions in focus. It is also situated at a relatively short distance from some of the most energy demanding industries in Northern Sweden. Most of Melkøya's production capacity is tied to its investors but their might be some left to supply the Nordic countries. [3]

**Skikda, Algeria** was one of the first LNG exporting sites. Today Algeria supply Spain, Britain and other European countries. Their production capacities are enough to provide base-load LNG. Compared to other similar production sites, Skikda is situated closer to Sweden. It will be used as an example of a remotely-located base-load LNG supplier in this study.

**Lysekil** will be the representative import site of the Swedish West coast. Other examples would be Gothenburg and Stenungsund. There are a large number of potential users in the vicinity of Lysekil. The Swedish Natural Gas pipeline network reaches as far as Stenungsund (not more than 50 km from Lysekil), which means that LNG import into Lysekil would be seen as competitor to piped Danish gas or as a means of expansion of network capacity if this situation would occur. If Sweden would start with base-load LNG import, Lysekil is a good location of an import terminal since it is ice-free and as close to the consigner as it gets within the country's borders.

**Oxelösund** is located near Stockholm and Mid-Sweden, which contains some of the largest industrial areas of the country, which are not presently connected to the gas pipeline network. This area does not require any higher ice-class of the transport ships. [53] It is also one of the end points of the planned Natural Gas network [27] and has previously been subject to LNG terminal plans by E.ON.

**Luleå** is one of the northernmost cities in the country as well as home to some heavy industry (see section 2.8). It is one of the end points of *Malmbanan*, which is an important railway line stretching 500 km through Kiruna and its mining industry to Narvik in Norway [54]. There are presently plans to build a terminal for LNG distribution in Narvik, for supply of the nearby industries as well as Swedish industrial users [32]. LNG from Melkøya transported by railroad takes Malmbanan and in the cost calculation for this route, the cost for a reloading terminal and the extra sea transport is included. There is presently no railroad leading to Hammerfest/Melkøya.

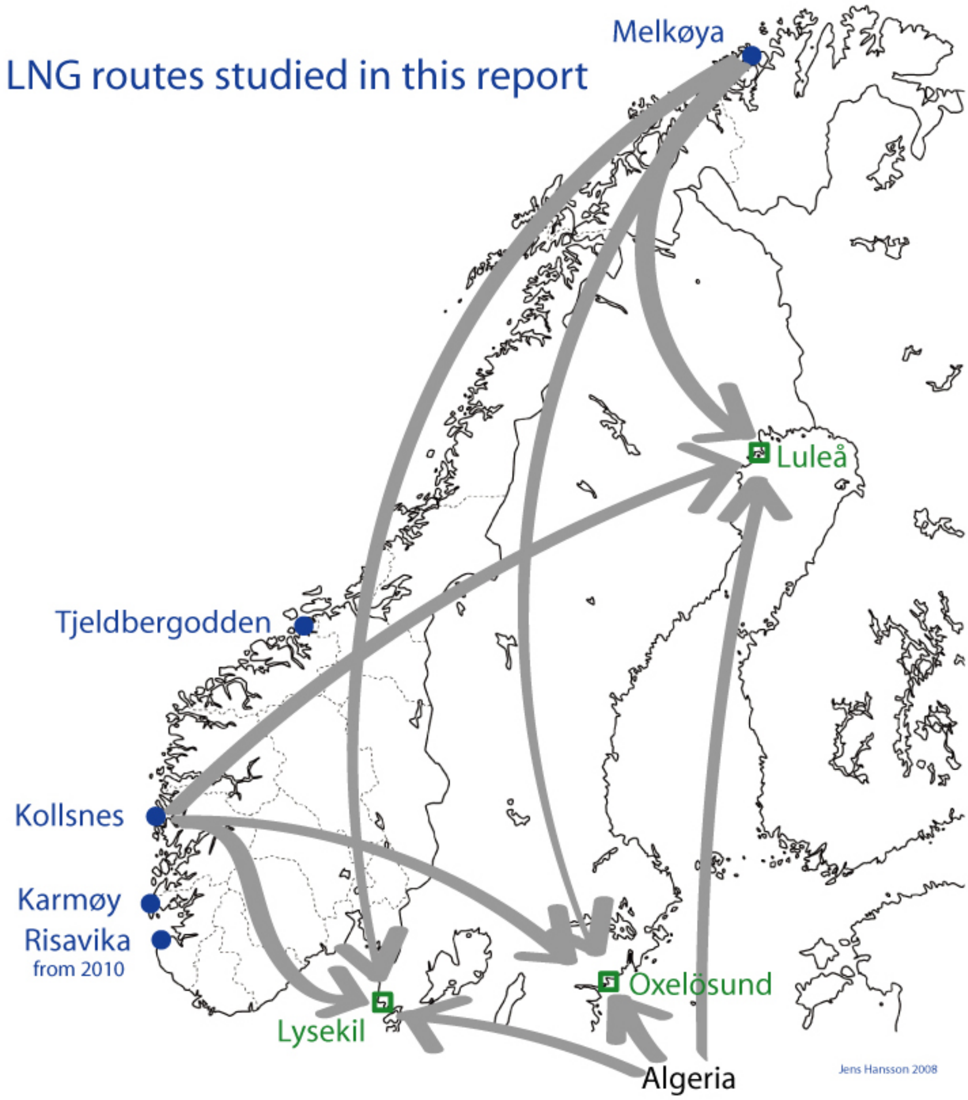


**Figure 19: Visualisation of the studied LNG routes**

### 5.1.3 Volumes

In order to register how the scale of operations affects the final cost of LNG, a variety of import volumes is studied. There is a large difference between the extremes; smaller volumes mean more flexible operations and a wider range of options but a smaller flow is often more expensive since the investments are higher per unit of product. Larger volumes typically mean a potential of lower specific cost because of the economics of scale but this limits the amount of available suppliers, import locations etc.

The volumes studied in this report and their respective characteristics are as seen in table 4.

**Table 4: The transfer volumes studied**

| Transfer volumes | | |
|---|---|---|
| **Volume (GWh/year)** | **Classification** | **Examples**<br>(Gross use in 2006 [55], unless otherwise indicated ) |
| 100 | Small-scale | The total use of coal in Skåne Country |
| 200 | Small-scale | The total use of heavy fuel oil in Gotland County |
| 500 | Small-scale | The amount of energy needed to produce 83 tons of steel at SSAB:s steel plants [56] |
| 1000 | Small-scale/Base-load | Total use of Natural Gas in Malmö Municipality |
| 5000 | Base-load | Total use of coal in Luleå Municipality |
| 20 000 | Base-load | Total use of fuels (coal, oil, petroleum) in municipalities Eskilstuna, Södertälje, Oxelösund, Trosa, Nyköpingand Norrköping |

### 5.1.4 Summary

Not all options are available or are obviously unfeasible and hence, the alternatives of choice are the ticked alternatives in table 5.

**Table 5: The annual transfer volumes, suppliers and means of transportation for LNG imports to Lysekil, Oxelösund and Luleå that are studied in this report**

| Base cases for this study | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual volume | Type of distribution | Kollsnes | | | Melkøya | | | Skikda | | | GPRM station |
| GWh | | Road | Rail | Sea | Road | Rail | Sea | Road | Rail | Sea | |
| 100 | Small-scale | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| 200 | Small-scale | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| 500 | Small-scale | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | |
| 1000 | Small-scale /Base-load | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | |
| 5000 | Base-load | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | |
| 20000 | Base-load | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | |

## 5.2 *Cost Factors*

### 5.2.1 LNG Purchase Prices

The Natural Gas price to a large extent follows the oil price. In addition, the LNG market is also dependent on the worldwide available liquefaction capacity, which is currently increasing, causing the LNG price to drop. The demand is however also increasing and this makes the markets prices go up. The LNG prices are furthermore linked with the building costs of the liquefaction facilities, which are in turn very much influenced by the price of steel at the time of construction. There is not really a market index to use as there is for commodities such as raw oil. A recognised world-wide market index is yet to come. [38, 57]

There are companies which specialise on collecting statistics and sell these on to their customers. For this study, there are no resources to acquire this kind of exact information and instead, rule of thumb, SGC report 167 [33] and the *LNG Journal European Spot Price* [58] are used. Since this is a dominant part of the price equation and figures between different sources vary so much, the purchase price is varied in the sensitivity analysis in section 6.2.

**Rule of Thumb**
The Norwegian LNG prices are slightly higher than for example Asia, Africa and the Middle East. It costs more to produce LNG here - the cost level for the country is higher, the scale is smaller and the design of the production process is often more elaborate to fulfil higher demands in safety, emissions and energy efficiency. The customers are also more willing to pay a higher price. [7] For Norwegian LNG, a rule of thumb is that the LNG price per energy unit is 75 % of that of Marine Gas Oil (The source of this information chooses to be unnamed.). Using the MGO price for Gothenburg, listed on Bunkerworld [59], and the conversion tools found in Engineering Toolbox [60], this price is converted to 479 SEK/MWh. This information is merely used to validate the price information given by SGC report 167 (see below).

**SGC Report 167**
In [33], the price for Norwegian LNG is approximated to 5,60 SEK/Nm$^3$. This calculates as 472 SEK/MWh. Sources [38] say that this estimation is too high.

**LNG Journal European Spot Price**
The LNG Journal is a technical magazine which provides analysis, industry and market news. On their website, they publish current market prices of oil, Natural Gas and LNG. The LNG Journal European Spot Price showed $12,70 per MMBTU on June 25$^{th}$ 2008. [58] This calculates as 261 SEK/MWh.

### 5.2.2 Transport

**Road**
In SGC report 167, the cost for road transport of LNG is calculated through a model, which includes the parameters:

- capital cost of the LNG carrier
- loading capacity of carrier
- loading/unloading time
- hourly rate for loading/unloading
- freight tariff per km
- pay-off time and loan interest

The model is then implemented on the requested annual transfer volume and distance. [33]

In this study, some other factors are added to the model, as follows:

- the number of trailers used
- the degree of usage of each trailer

These factors are used to make the model applicable on larger quantities – it is a question of optimisation to decide how many lorries are needed for the specified transfer volume.

See appendix B.

**Rail**
Since rail transports for LNG are not used today, the cost situation is uncertain and far-going estimations are necessary.

A rough idea of the price for forwarding of LNG rail cars is supplied by Green Cargo, the leading rail cargo forwarder in Sweden. The prices include a locomotive operated by a train driver from the loading point to the destination, i.e. everything except the cost for the actual wagon. The case is often that the customer buys or rents the wagon from a wagon supplier. In this study, price estimated by Vereinigte Tanklager und Transportmittel-Gesellschaft (VTG) is used. VTG is a large European rail logistics company which among other services offers wagon hire.

The time needed for a round-trip with railway transport depends on the volumes as well on the distance. In the base case (short distance, wagon transport) it takes 3 days for a round-trip. When system transport is utilised, about 1 day is saved on the round-trip. The border between wagon and system trains in this case is at an annual transport volume of 1000 GWh. Railroad transport is conventionally performed during Monday-Fridays. [30]

The result of these estimates is visualised in appendix C.

**Sea**
It is important to distinguish between the transfer volumes when it comes to sea shipping because it is a question of which type of ship to use. Here, ship sizes of 7 500 $m^3$ and 138 000 $m^3$ are studied. Surely, these ships are able to ship a lot less than full loads but the cost increases with unused capacity.

For the smaller ship class, a ship-owner company supplies full-load prices between specified ports [53]. The cost of the larger class ships is collected from IEA:s reports [8]. These figures give mean prices between some exporting ports and American ports. The distances between these examples are calculated and implemented on the actual distances. The Daft Logic *Google Maps Distance Calculator* [61] is used for the distance estimation.

From this, the specific prices (SEK/MWh) are calculated. See appendix D.

### 5.2.3 Receiving Terminal

The general idea of a receiving terminal is the same for smaller or larger facilities – the tank is the dominant cost factor and piping, instrumentation and auxiliary systems largely follow the scale of this.

In order to give a complete picture of the cost situation, data from the whole range of annual transfer volumes is needed, but unfortunately there are difficulties involved in this - suppliers and operators of plants are naturally reluctant to reveal these prices, since they are bound by agreements or would potentially be harmed by giving out this information to their competitors. It is believed however, that the cost varies fairly linear with the tank dimension and thus, approximations are made by estimated data from two sources. Stockholm Gas [62] gives the cost of a 200 GWh facility and the other is a calculated mean value from planned LNG import facilities in the USA [63].

For the reloading terminal needed in Narvik for the Melkøya/railroad base case, the cost of a terminal is approximated to 80 % of a receiving terminal. This is because of the synergy effects of building two terminals at once and because a reloading terminal does not need a large evaporation system (only one for pressure control purposes).

The operating costs for LNG terminals are estimated to 1 % of the total terminal investment cost. This figure is low because it is a simple, low-maintenance system.

See appendix E.

### 5.2.4 Peak-Shaving

In order to demonstrate some examples of peak-shaving solutions, a real case where there is a need to cut the effect peaks, is studied. At Öresundskraft's plant *Västhamnsverket* in Helsingborg, 20-30 MW (25 MW is used in the calculations) needs to be cut at peak usage, one day per year. Storage of LNG could solve this problem. In appendix G, three possible solutions are studied – normal small-scale LNG distribution and the use of two sizes of moveable LNG containers.

# 6 Results

## 6.1 Base Cases

### 6.1.1 Summary

The results of the calculations for the base cases are displayed in table 6 and in diagram 6.

**Table 6: Results of the calculations made on the base cases**

| Base cases results | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Specific cost (SEK/MWh) | | | | | | |
| Origin | **Kollsnes** | | | **Melkøya** | | | **Skikda** |
| Volume (GWh/y) | Road | Rail | Sea | Road | Sea + Rail | Sea | Sea |
| **To Lysekil** | | | | | | | |
| 100 | 595 | 589 | 566 | 607 | 689 | 585 | |
| 200 | 576 | 589 | 566 | 587 | 689 | 585 | |
| 500 | 558 | 586 | 560 | 568 | 671 | 579 | 321 |
| 1000 | | 580 | 544 | | 659 | 547 | 322 |
| 5000 | | 573 | 537 | | 646 | 540 | 315 |
| 20000 | | 573 | 537 | | 646 | 540 | 315 |
| **To Oxelösund** | | | | | | | |
| 100 | 595 | 586 | 579 | 608 | 687 | 597 | |
| 200 | 578 | 586 | 579 | 586 | 687 | 597 | |
| 500 | 561 | 583 | 572 | 566 | 669 | 591 | 322 |
| 1000 | | 577 | 545 | | 656 | 548 | 323 |
| 5000 | | 570 | 538 | | 644 | 541 | 315 |
| 20000 | | 570 | 538 | | 644 | 541 | 315 |
| **To Luleå** | | | | | | | |
| 100 | 602 | 604 | 589 | 596 | 666 | 607 | |
| 200 | 584 | 604 | 589 | 576 | 666 | 607 | |
| 500 | 565 | 600 | 582 | 558 | 649 | 601 | 324 |
| 1000 | | 587 | 546 | | 643 | 550 | 324 |
| 5000 | | 580 | 538 | | 630 | 543 | 317 |
| 20000 | | 580 | 538 | | 630 | 543 | 317 |
| **Gas pressure regulating and measuring station** | | | | | | | |
| 100 | 547 | | | | | | |
| 200 | 533 | | | | | | |

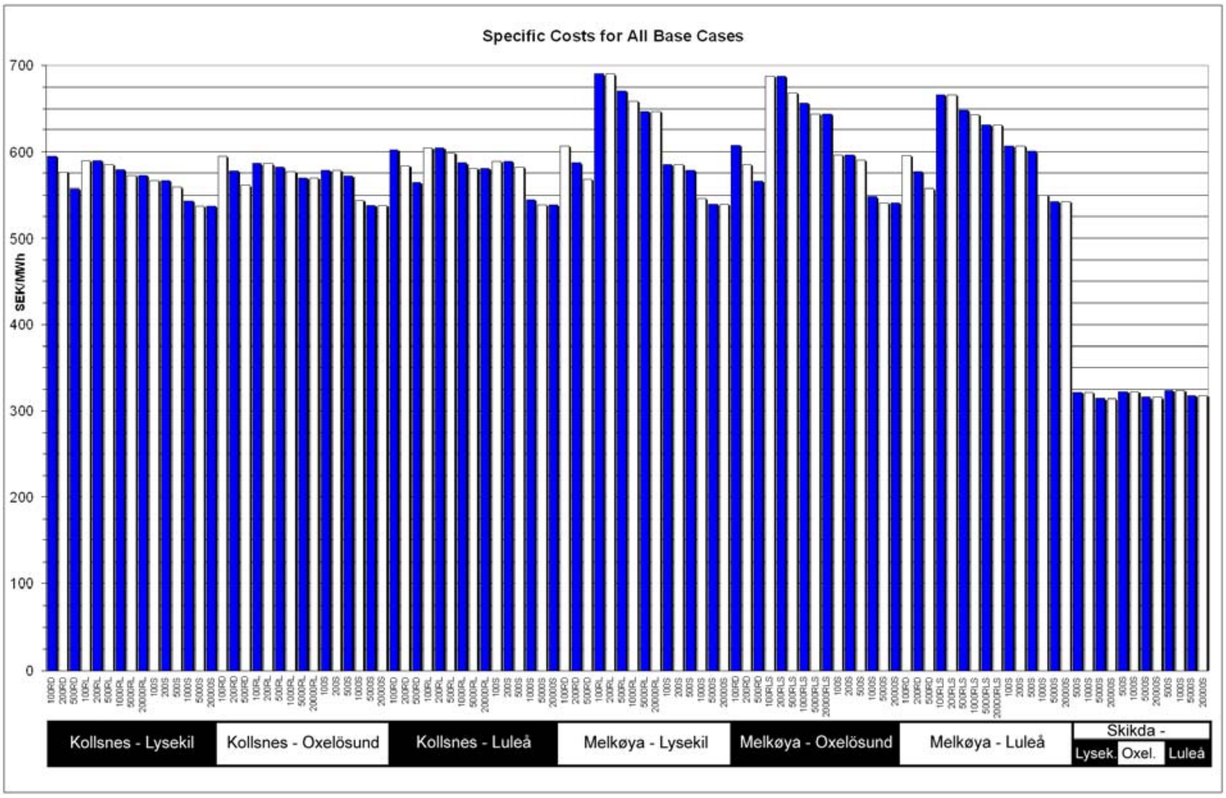


**Diagram 6: The total specific cost for all the base cases presented.**
**How to interpret the codes used:**
**The numbers below the bars indicate the transfer volume in GWh/year.**
**The letters subsequent to the number: RD=road, RL=rail, S=sea, RLS=rail and sea**

### 6.1.2 General Cost Distribution

The general cost distributions for the routes included in the base cases are presented in diagram 7.

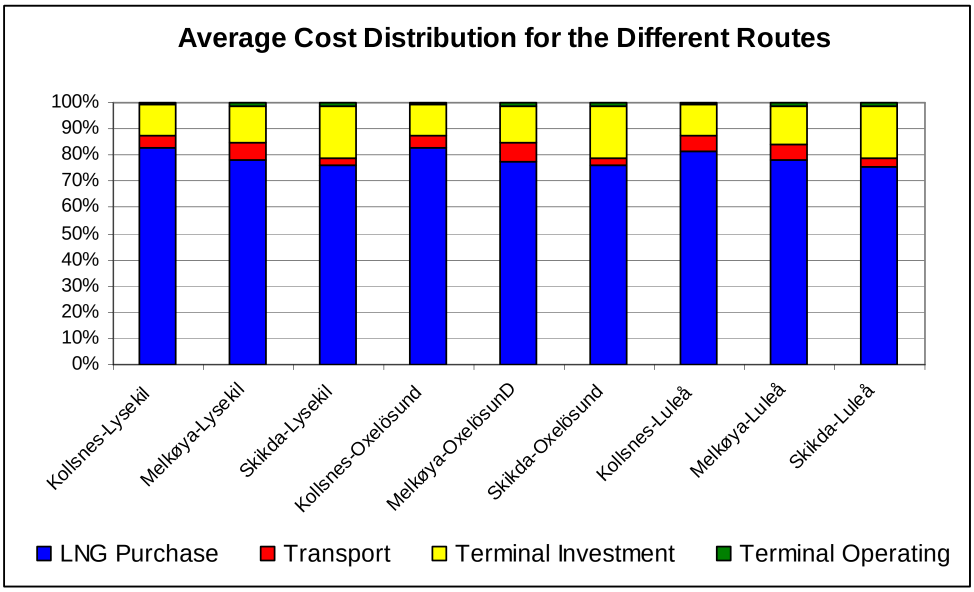


**Diagram 7: Average Cost Distributions for the Different Routes**

### 6.1.3 Volumes

A few cost distributions as a result of varied transfer volumes are shown in diagram 8 (Kollsnes-Oxelösund) and diagram 9 (Skikda - all destinations).

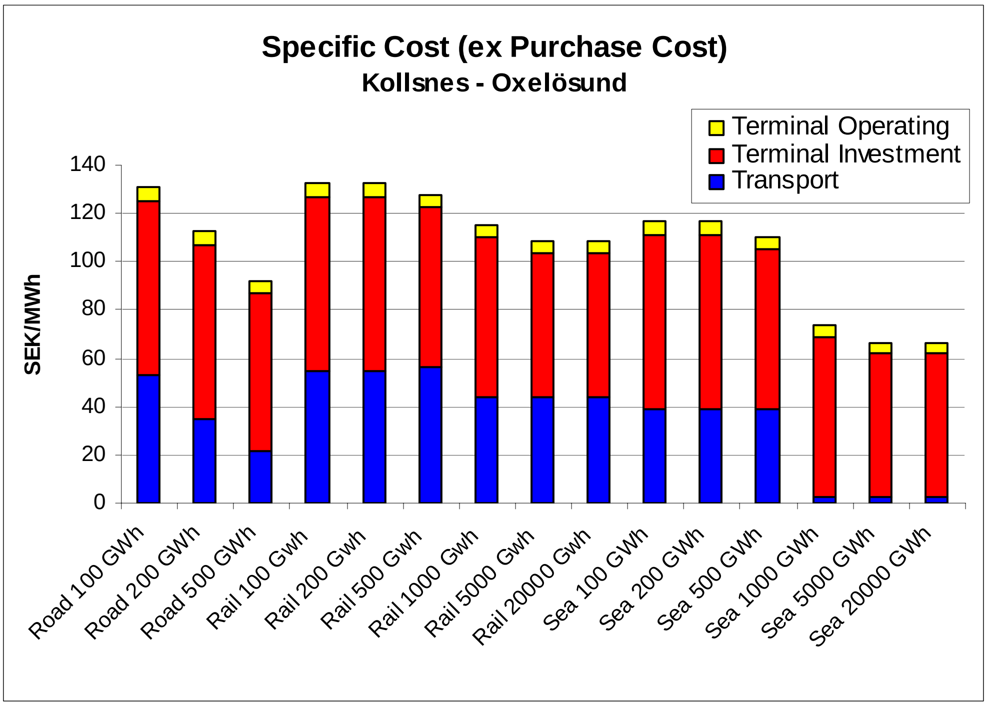


**Diagram 8: The specific cost (purchase cost excluded) for LNG shipped from Kollsnes-Oxelösund**

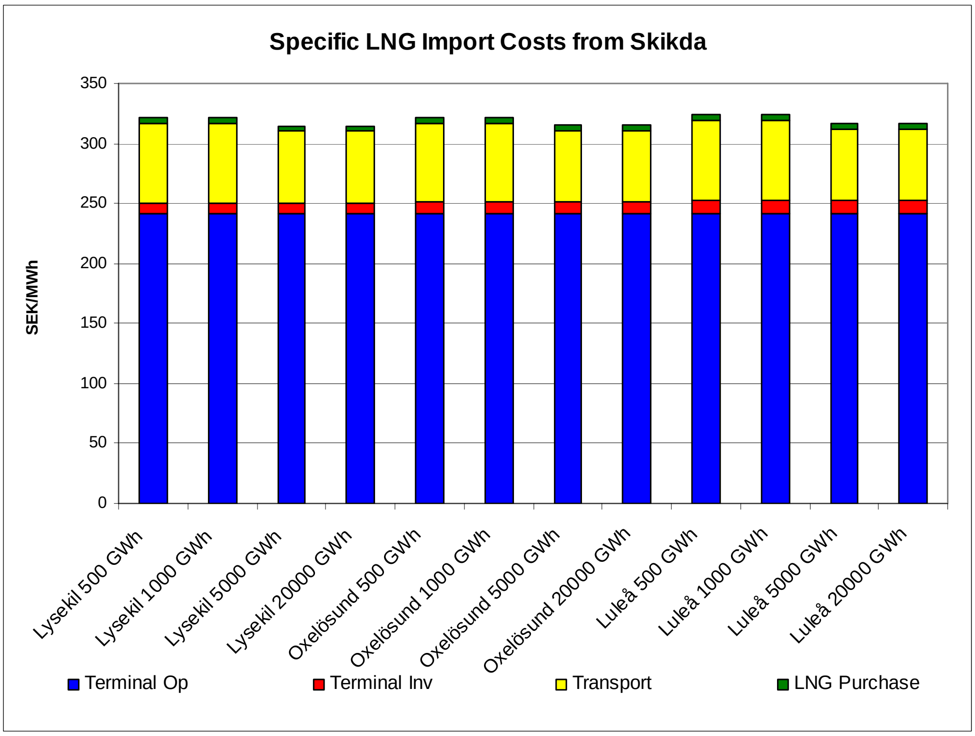


**Diagram 9: Specific LNG Import Costs from Skikda**

## 6.1.4 Means of Transport

To indicate the difference in transport costs, the average specific transport costs for the Norwegian routes are presented in diagram 10.

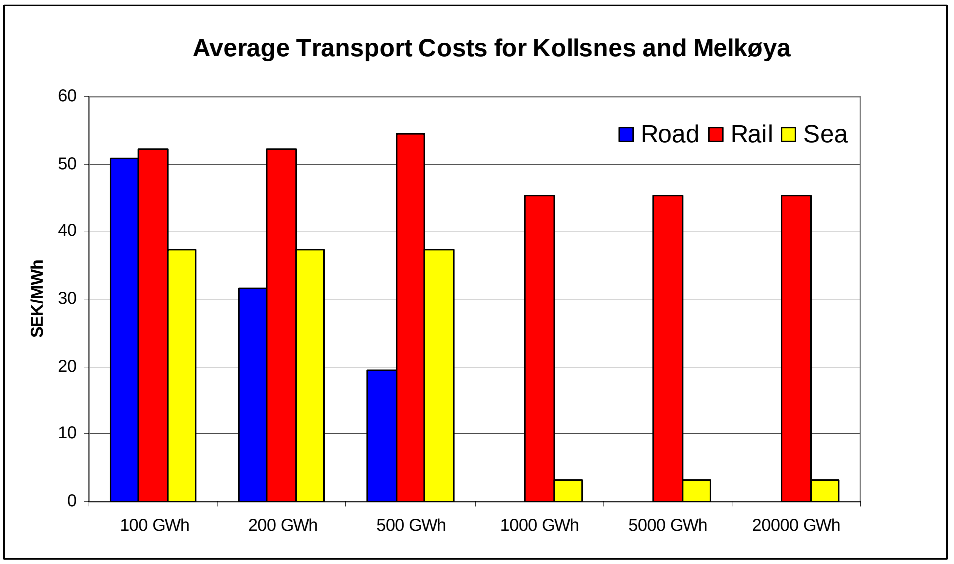


**Diagram 10: Average Specific Transport Costs for Kollsnes and Melkøya LNG to all destinations**

## 6.1.5 Routes

In order to give a picture of the cost situation for different routes, some figures of varied volumes and means of transport are presented in diagrams 11-13.

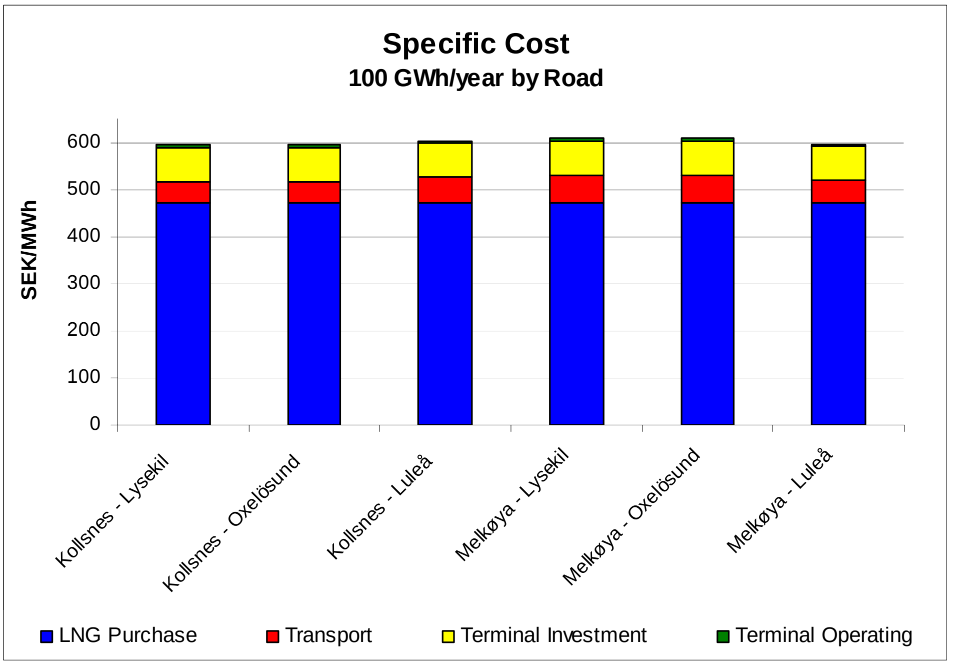


**Diagram 11: Specific cost distribution for road transport at 100 GWh/year from Norway**

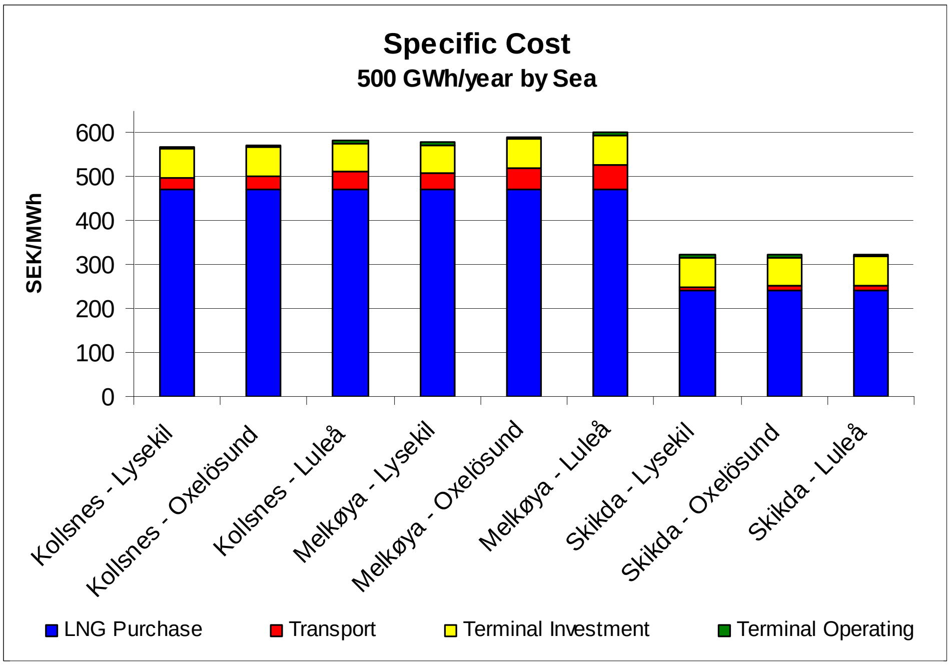


**Diagram 12: Specific cost distribution for sea transport at 500 GWh/year from all consignors**

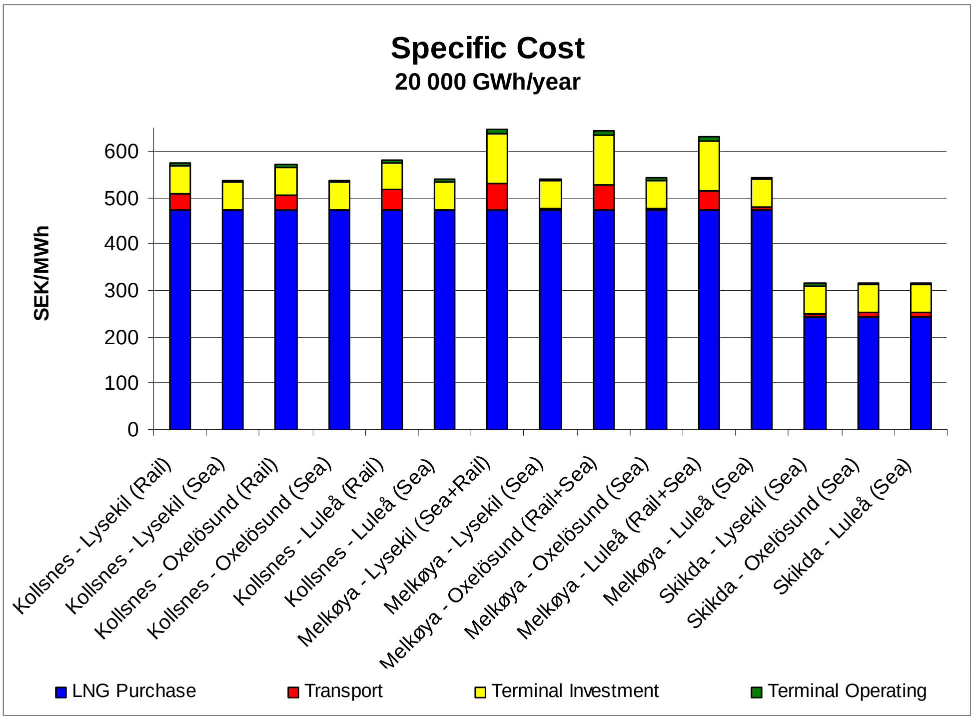


**Diagram 13: Specific cost distribution for rail, sea and rail+sea transport at 20 000 GWh/year (base-load) from all consignors**

### 6.1.6 Gas Pressure Regulating and Measuring Station

The results from the calculation of the costs for LNG production at a Gas pressure regulating and measuring station are compared to those of LNG received from small-scale distribution in diagram 14.

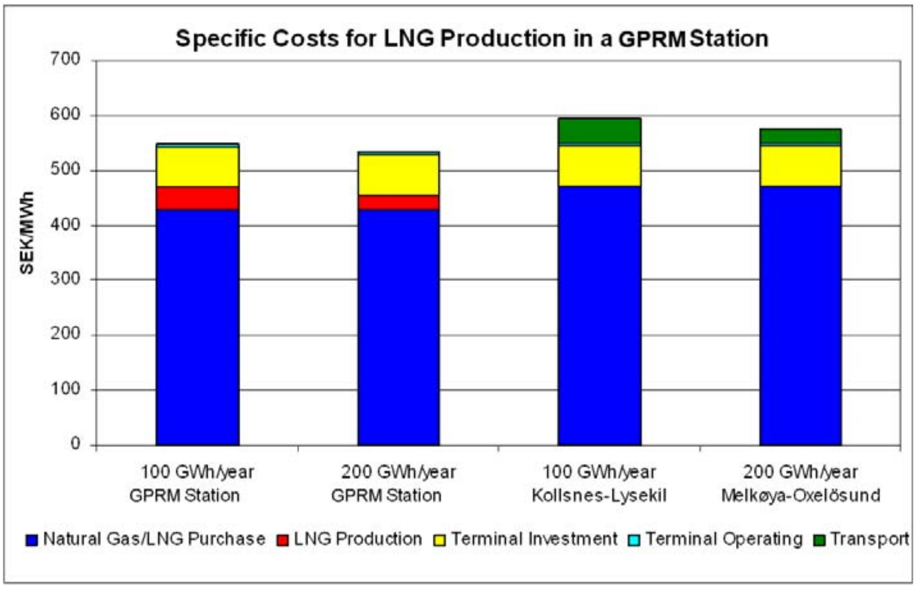


**Diagram 14: Specific costs for LNG production in a GPRM station**

### 6.1.7 Peak-Shaving Solutions

The results of the calculations performed on peak-shaving are displayed in diagrams 15-16.

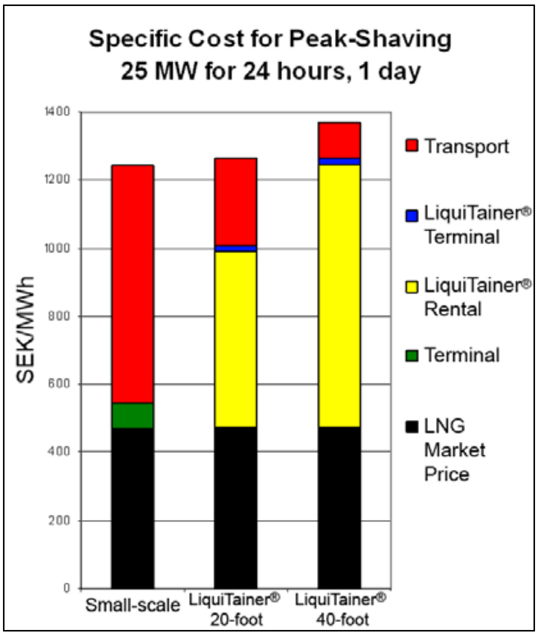


**Diagram 15: Specific cost for LNG imported for peak-shaving purposes - 25 MW for 24 hours, 1 day per year**

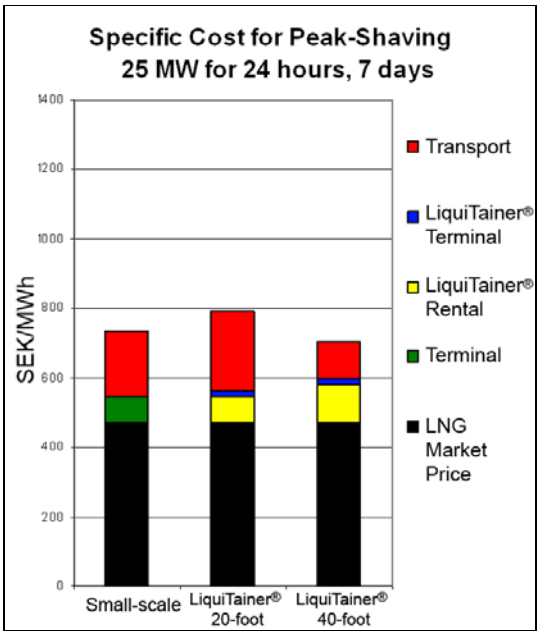


**Diagram 16: Specific cost for LNG imported for peak-shaving purposes - 25 MW for 24 hours, 7 days per year**

### 6.1.8 Discussion

**In General**

The results shown in diagram 6 indicate that there is no large distinction for the cost of LNG produced in Norway - since the dominant cost is the price for which the LNG is sold, different transport alternatives and transfer volumes are less important for the final cost. This causes a general cost profile where Norwegian LNG costs 550-600 SEK/MWh with the exception of the alternative of railway and sea distribution via Narvik which place themselves at 650-680 SEK/MWh. LNG imported from Algeria is much cheaper - low costs for large volume shipping and an LNG purchase price of 50 % of that of Norwegian LNG places the Algerian alternatives at 315-324 SEK/MWh, about half the cost.

**Cost Distributions**

As seen in diagram 7, the distribution of costs is similar for all studied alternatives: around 80 % for purchase, 3-6 % for transport, 12-14 % for terminal investment costs and 1 % for terminal operating costs. The fraction of terminal costs is somewhat higher for Algerian LNG, where the costs for transport and purchase are lower.

**Volumes**

For all studied means of transport and routes, there is a decrease of specific transport cost with increased transfer volumes. The Kollsnes-Oxelösund route is used as an example to show this in diagram 8. Transport rates are lower for larger volumes, as are the terminal costs. The difference in price is less significant for Algerian LNG and this due to the overall low transport cost (diagram 9).

**Means of transport**

Diagram 10 shows that the road transport cost is reduced significantly at higher volumes. It is also evident that it is the cheapest alternatives in all cases it has been studied.

Rail transport only shows a change in specific cost at the 500-1000 GWh/year interval - and this is due to the change from wagon transport to system trains. The model shows that it is even more expensive for 500 GWh/year than for 100 and 200 GWh/year.

Like rail, sea transport only shows a reduction in cost when the larger type of ship is utilised, and this reduction is significant.

**Routes**

Diagram 11 indicates that the total specific cost of LNG imported from Norway is quite insensitive to the distance it is transported. Purchase and terminal costs are the dominant costs though the cost difference is small.

When it comes to sea transport at 500 GWh/year, diagram 12 shows that the longer distances (Kollsnes-Luleå, Melkøya-all destinations) are slightly more expensive. What is strikingly in these results are that the by far longest transport routes (Skikda-all destinations) end up at much lower transport costs than the shorter distances. This is only due the fact that the larger ship type and hence a completely different source of costs is used.

Specific costs for the base cases with the largest transfer volumes, 20 000 GWh/year for all routes, are shown in diagram 13. The highest transport costs are seen for the rail alternatives and the lowest for base-load LNG from Skikda. The peaks at the rail and sea combinations are explained by almost double the terminal and as well as transport costs, because of the reloading in Narvik.

**Gas Pressure Regulating and Measuring Station**
The results from the cost estimation model used for GPRM stations show that the final specific cost for local LNG production and a terminal for storage and distribution purposes in both cases (100 GWh/year and 200 GWh/year) that this is the slightly cheaper option than LNG import (diagram 14).

**Peak-Shaving**
It is clear that the small transfer volume in the first calculation gives a high total specific cost for all of the alternatives (diagram 15). Both the LiquiTainer® rental and the LNG trailer investment (showed under Transport) would be high. However, if the peak-shaving need would occur during one week instead of one day in a year, the cost picture is completely different - the investments are distributed on seven times as much transferred LNG and this makes the 40-foot LiquiTainer® the cheapest option of the three (diagram 16).

## *6.2 Sensitivity Analysis*

In order to study the sensitivity of the calculated costs, variations of some of the key factors are analysed. This shows the effect on the total cost as a function of the variations. Uncertainties for the key factors are hence to some extent compensated.

By using Monte Carlo (MC) simulation software (RiskAMP) [64], the effects from the change of more than one variable can be studied. Using the resulting histograms from these simulations, indications of the likelihood of certain total costs is obtained. Below, the varied parameters are simulated using the PERT Distribution, where a minimum, a maximum and a approximated value are inserted.

### 6.2.1 LNG Purchase Price

Being the dominant cost factor in all base cases, the LNG purchase price is varied. The calculations are performed using average total specific costs for Norwegian and Algerian LNG, respectively. The prices in the base cases are 472 SEK/MWh for Norwegian and 242 SEK/MWh for Algerian LNG.

As seen in diagram 17, the effect on the total price is linear and Norwegian and Algerian LNG follow one another with a gap of about 40 SEK/MWh for all cases.

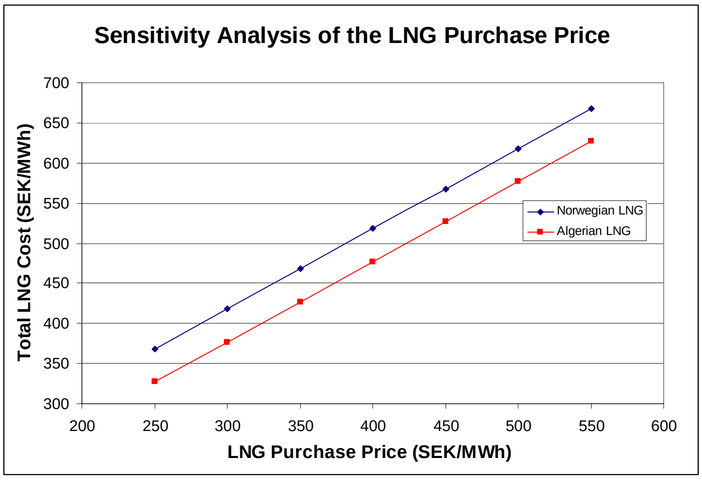


**Diagram 17: Sensitivity analysis of the LNG purchase price**

To show the probability of these prices, a MC simulation is performed for two of the base cases (diagram 18-20).

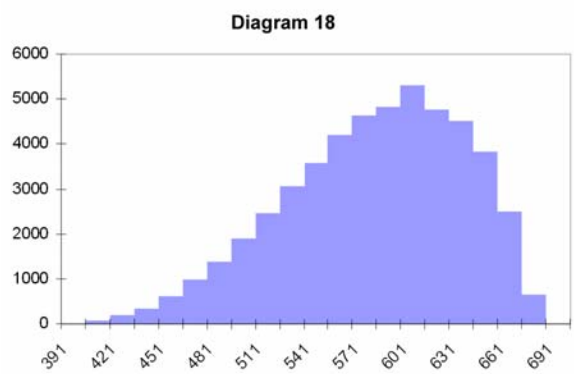


**Diagram 18: Histogram showing the total cost (x-axis) and the number of results within the cost interval (y-axis) as a result of a PERT-distributed LNG purchase price, with min=242, max=550, approx=472. 50000 iterations in RiskAMP. Base case: Kollsnes-Lysekil, 100 GWh/year, road**

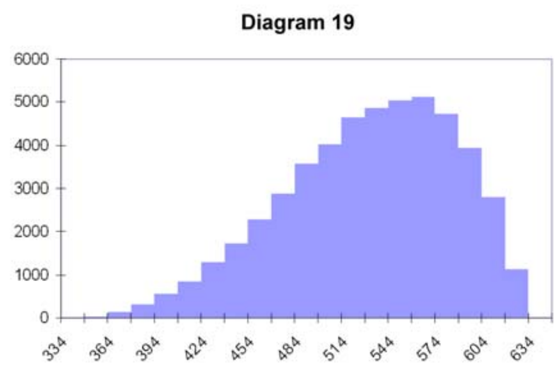


**Diagram 19: Histogram showing the total cost (x-axis) and the number of results within the cost interval (y-axis) as a result of a PERT-distributed LNG purchase price, with min=242, max=550, approx=472. 50000 iterations in RiskAMP. Base case: Melkøya-Oxelösund 20 000 GWh/year, sea**

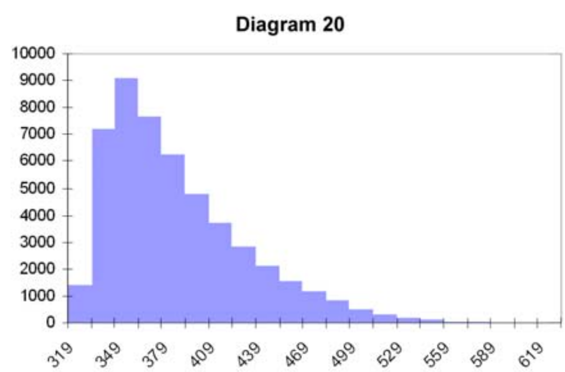


**Diagram 20: Histogram showing the total cost (x-axis) and the number of results within the cost interval (y-axis) as a result of a PERT-distributed LNG purchase price, with min=242, max=550, approx=472. 50000 iterations in RiskAMP. Base case: Skikda-Oxelösund 500 GWh/year, sea**

### 6.2.2 Terminal Cost

The terminal cost is one of the important costs for LNG distribution and hence, a sensitivity analysis is performed on this as well. Real causes for variations of terminal costs include changes of the interest rates and the cost of construction material, most important steel. Diagram 21 shows the average total cost of Norwegian and Algerian LNG when the terminal costs are varied from 80-200 % of the base cases.

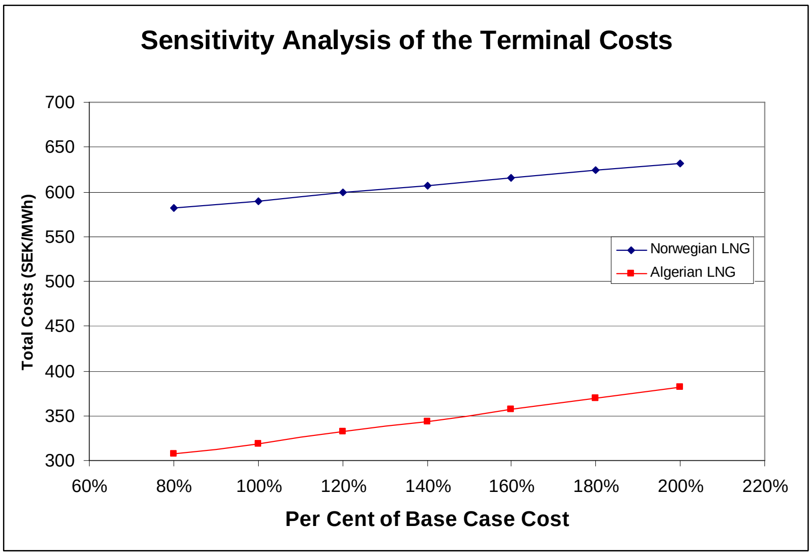


**Diagram 21: Sensitivity analysis of the Terminal Costs**

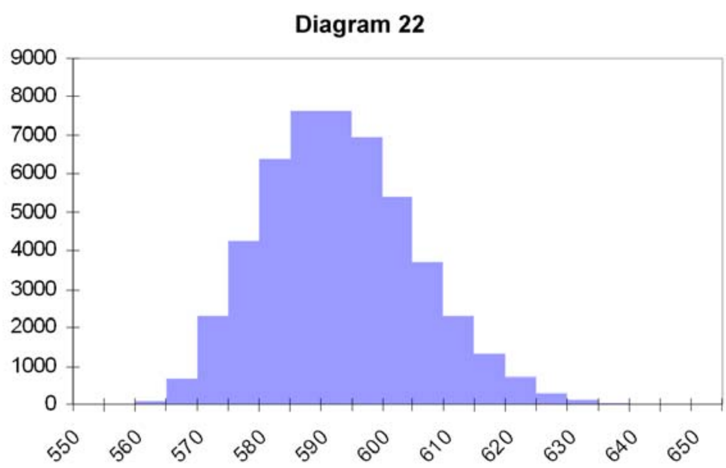


**Diagram 22: Histogram showing the total cost (x-axis) and the number of results within the cost interval (y-axis) as a result of a PERT-distributed terminal cost, with min=80%, max=200%, approx=100%. 50000 iterations in RiskAMP. The simulation is done on the average total price of Norwegian LNG.**

### 6.2.3 Discussion

**LNG Purchase Price**

As expected, the total specific cost of imported LNG is very much influenced by the LNG purchase price. It is a large part of the total cost and it varies linearly. If the purchase price would reach 550 SEK/MWh, both Norwegian and Algerian LNG would cost more than 625 SEK/MWh.

**Terminal cost**

The sensitivity analysis shows that the total cost is less affected by fluctuations in the terminal costs. Even redoubled terminal costs increase the total price by around 20 %.

# 7 Conclusions

In this study, Liquefied Natural Gas as an alternative energy supply for Sweden has been scrutinised from a few relevant aspects. Its purpose is to give a clearer picture of the:

- advantages and disadvantages
- uses
- possible trading routes
- costs involved
- environmental aspects of LNG.

The source of the LNG is important for two reasons: the means of transport and the cost involved in this, and for the environmental effects associated with each origin. Norwegian LNG is more expensive than the alternatives from less developed and more remote countries such as Algeria, but it has lower environmental effects and is more energy efficient for Sweden to use. One of the large disadvantages of LNG is the energy losses involved in liquefaction, large shipping distances and regasification. When a nearer source is used, at least the resources spent on shipping are reduced. The calculations made in this study however, contradict the economic side of this statement - LNG from a more remote consignor, Skikda in Algeria, has lower transport costs than Norwegian. But this is largely due to a weakness in the cost calculation model - only older prices are used for base-load sea shipping and these are believed to be higher. The Algerian costs are also to some extent lower because only larger volumes are studied; surely the purchase prices would be much higher if smaller volumes were imported. The Algerian production plants are also typically larger than Norwegian. The Norwegian purchase cost is however fixed on the small-scale level even for base-load volume in this model but at least for Melkøya LNG, it is believed to be somewhat lower, making the cost gap between Skikda and Melkøya gas smaller. The sensitivity analysis also shows this.

The specific import cost of LNG from Norway is quite independent of the means of transport. Road transport shows up as slightly cheaper than railway and sea. Railway is a bit more expensive but then again, the environmental aspects should be considered here - the environmental study indicates that railway is much more energy efficient than the other alternatives and proves to be a low emitter of $NO_x$, $SO_x$ and particles compared to road and sea. Transport by sea is not that representative though, since the model used assumes that an oil powered ship is utilised. Overall, the study shows that the use of road transports for LNG is suitable for smaller volumes and shorter distances whereas sea and rail should be considered for longer distances.

The combined route with sea shipping from Melkøya to Narvik and then railway transport to Luleå is the least energy demanding solution for LNG shipped with these end points, but it is by far the most expensive one. This is because of the reloading facilities needed in Narvik. Just in-time delivery, where the LNG is pumped directly from the ship to the train could be more cost-effective, but this increases the transport costs since either the ship or the train would be able to deliver less per year. Another way to solve it is to use portable LNG containers, such as the type studied in the peak-shaving section. This solution would neutralise the need of at least one of the storage tanks along the route. Moreover, the less reloading that takes place, the less LNG storage volume is “lost” - heat leakage to the LNG causes the density to be reduced.

Portable LNG containers also seem to be a cost-effective option to cover the need of peak-shaving. For smaller transfer volumes, every way to save on investments instead of operating costs is welcome for the economical feasibility of the supply chain solution. It is however worth mentioning that the cost calculations for LiquiTainers® in this study are based on an estimated of a rental cost, which is linked to an estimate of the cost of LNG rail wagons that have not yet been built. The result of the calculations also show that if the demand is 25 MW for 24 hours and one day, it is roughly twice as expensive for the distribution system as it would be if the demand would be seven times greater (one week instead of one day). The economic feasibility of the systems is determined by the cost of the subscribed Natural Gas at for the customer.

The question is whether LNG production in a Gas pressure regulating and measuring station would make a good solution to the peak-shaving problem. The more Natural Gas that flows through the station, the more LNG can be produced. It is possible that the flow can be controlled so that LNG can be produced and stored in the GPRM station right before a demand peak. If the gas user is the same person as the distributor is another question of course. In any case, the calculations on LNG production in GPRM stations indicate it is a cost-effective alternative compared to import options. It depends on the purpose of the LNG if this would be successful however - the demand of the produced LNG would have to closely track that of Natural Gas and this is hardly the case for LNG used as fuel for road vehicles - much more Natural Gas is needed in winter time than summer time and the vehicles would need fuel all year.

The varied demand profile for Sweden is also a problem which affects LNG feasibility. E.ON were reluctant to build a 200 000 $m^3$ facility in Oxelösund because it would basically be used half of the time and this is not a good way to get return on investment, especially not since an LNG import terminal is expensive. In the *Stadsgas 2010* project, the use is different - the town gas which is to be replaced by LNG is also used for cooking applications and large part of the import volumes will be used at the Nynas refinery and as fuel for road vehicles. The more combined uses and processes on-site, the more cost and energy effective the facility gets.

Another reason for not going through with the Oxelösund facility was the political and public opinion. The landscape would be affected by this large terminal and there is a general political resistance to fossil fuels in Sweden. Smaller terminals, such as the one in Nynäshamn, make less of an environmental footprint. Despite its fossilised origin, LNG can also be argued as ”good” when compared to what it would replace - oil. By replacing oil as energy source, a cleaner alternative is brought into the picture. Of course, being a fossil fuel, Natural Gas should definitely not been seen as the final conclusion to the energy problem, but an infrastructure for Natural Gas and LNG could be beneficial for the future use of other energy gases, such as non-fossil biogas or hydrogen gas. Natural Gas contains less $NO_x$, $SO_x$ and particles and this is a great advantage to the local environment.

It is especially beneficial to use LNG as ship fuel - ships are one of most significant polluters today so a network of LNG refuelling stations such as proposed in the *MAGALOG* project would be good for the environment. Another area where LNG has a clear advantage is when it is used as fuel for road vehicles - a smaller volume to transport to the refuelling station makes the fuel gas cheaper and more people would use gas powered vehicles, which are cleaner and emit less $CO_2$ than petrol or diesel vehicles.

This study has shown examples of where the cold in the LNG can be utilised - if regasification facilities could be combined with for example air separation, $CO_2$ solidification, power plants, food industry or be used as district cooling, the feasibility is increased.

The cost calculation model used in this study has given a rough picture of the cost situation of different alternatives of acquiring LNG in Sweden. Uncertainties are caused by the large extent of estimations made. Since cost data has been difficult to find - prices are often the last piece of information a company is willing to give out - there are some approximative estimations and steep steps between levels of volumes and sizes.

It is shown that LNG could be an alternative to secure the Natural Gas supply after the Danish supply has run out. It has proven safe and the market is getting more and more mature. The fate of base-load LNG is largely determined by the other Natural Gas projects in the Nordic countries. If the *Skanled* connection is realised, Norwegian gas can be brought in; if the *Nord Stream* pipeline project is carried out, Russian gas could cover the needs. The small-scale LNG market is however still a possibility if it continues to be competitively priced. The Natural Gas market price largely follows the oil price and as a consequence from this, LNG prices are also linked to the source of energy which it is primarily supposed to replace. The question is whether the market price is reduced - or at least less increased - due to the increasing available world-wide liquefaction capacity, and how much effect the increasing steel costs will have on LNG equipment. In either way, Liquefied Natural Gas is always going to be better for the environmental than oil and hence, it is worth to keep in mind when the world’s source of energy is changing.

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# Appendices

# Appendix A: Conversion Factors and Parameters used

Throughout the calculative section of this study, the conversion relations and parameters as seen in tables A1-A3 are utilised.

**Table A1: Properties and conversions**

| LNG and Natural Gas properties and some other conversions used | | | |
|---|---|---|---|
| **Property** | **Value** | **Unit** | **Source** |
| Density<br>LNG @ 1 atm and -162 °C<br>Gasified LNG | <br>450<br>0,80 | <br>kg/m$^3$<br>kg/Nm$^3$ | <br>[7]<br>[7] |
| Upper heating value<br>Norwegian LNG<br>Norwegian LNG<br>Norwegian LNG @ 1 atm and -162 °C<br>Algerian LNG<br>Danish Natural Gas | <br>11,87<br>15,27<br>0,147<br>12,21<br>12,18 | <br>kWh/Nm$^3$<br>MWh/metric ton<br>m$^3$/MWh<br>kWh/Nm$^3$<br>kWh/Nm$^3$ | <br>[7]<br><br>[7]<br>[52]<br>[7] |
| 1 Nm$^3$ (1 atm, 0 °C) | 1,037 | Sm$^3$ (1 atm, 15 °C) | |
| 1 Billion British Thermal Units (MMBTu) | 0,2931 | MWh | [65] |
| 1 US fluid gallon (gal) | 3,7854 | litres | [65] |
| 1 Cubic Feet (cf) | 7,61 | kg LNG | [66] |

**Table A2: Currency conversion rates used**

| Currency conversion | | | |
|---|---|---|---|
| USD | 6,03 | SEK | [67] June 25th 2008 |
| EUR | 9,40 | SEK | [67] June 25th 2008 |
| NOK | 1,19 | SEK | [67] June 25th 2008 |

**Table A3: Net Price Index for 2003-2008, data from [68]**

| Price updates using Net Price Index (NPI) | | | | | | |
|---|---|---|---|---|---|---|
| **Year (i)** | **May 2008** | **2007** | **2006** | **2005** | **2004** | **2003** |
| NPI (1980 = 100) [68] | 254,35 | 247,36 | 240,90 | 238,28 | 238,09 | 237,91 |
| | | | | | | |
| **Calculated price update factor** $P_n/P_i$ according to [69] with n=2008 | | | | | | |
| $P_{2008}/P_i = NPI_{2008}/NPI_i$ | | 1,0282584 | 1,0558323 | 1,0674417 | 1,0682935 | 1,0691018 |

In the investment calculations the annuity method is used. In this, the interest and the pay-off time are defined as seen in table A4. The annuity factor is calculated through:

$$Annuity\ \ factor = \frac{r}{1-(1+r)^{-t}}$$

where $r$ is the interest rate and $t$ is the pay-off time in years. [70]

**Table A4: Interest and pay-off time used for the base cases in the calculations**

| Investments | |
|---|---|
| Interest | 10 % |
| Pay-off time | 15 years |

# Appendix B: Road Transport Cost Calculation

The cost model used in the report SGC 167 is also utilised here to calculate the costs for road transport [33].

According to SGC 167, an LNG trailer costs 2.7 MSEK and a forwarder's transport rate is 15 SEK/km and this covers driver, fuel and tractor. The rate for unloading and loading is set to 550 SEK/hour.

To be able to calculate the number of trailers needed, a use of each trailer between 40 and 50 % (of all available hours of the year) is assumed. By changing the number of trailers, the level of usage varies and hence the specific cost (SEK/MWh) for delivered LNG.

The distances between the consignor and consignee have been calculated using Google Maps, see table B1. [50]

**Table B1: Road distances for the Norwegian base case routes**

| Calculated road distances | | |
|---|---|---|
| **Distance (km) [50]** | | |
| **Relations** | Kollsnes | Melkøya |
| Lysekil | 713 | 2005 |
| Oxelösund | 1015 | 1752 |
| Luleå | 1534 | 745 |

Calculations are displayed in the following two pages.

| Road transport cost model as in SGC report 167 [32] – From Kollsnes | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Kollsnes - Lysekil** | | | **Kollsnes - Oxelösund** | | | **Kollsnes - Luleå** | | |
| Annual transfer | GWh/year | 100 | 200 | 500 | 100 | 200 | 500 | 100 | 200 | 500 |
| Number of trailers | # | 2 | 4 | 9 | 3 | 6 | 15 | 4 | 7 | 18 |
| Distance one way | km | 713 | 713 | 713 | 1015 | 1015 | 1015 | 1534 | 1534 | 1534 |
| Number of round trips per trailer | #/year | 161 | 161 | 179 | 107 | 107 | 107 | 81 | 92 | 90 |
| Transport time, round-trip | hrs/shipment | 24,37 | 24,37 | 24,37 | 33,00 | 33,00 | 33,00 | 47,83 | 47,83 | 47,83 |
| Working hours per trailer | hrs/year | 3924 | 3924 | 4362 | 3531 | 3531 | 3531 | 3874 | 4400 | 4305 |
| Hours/year | hrs/year | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 |
| Usage of each trailer | % | 45% | 45% | 50% | 40% | 40% | 40% | 44% | 50% | 49% |
| Trailers/week | # | 6 | 12 | 31 | 6 | 12 | 31 | 6 | 12 | 31 |
| | | | | | | | | | | |
| Cargo load | kg | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 |
| Cargo load | Nm3 LNG | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 |
| Cargo load | MWh | 312 | 312 | 312 | 312 | 312 | 312 | 312 | 312 | 312 |
| Investment cost per trailer | MSEK | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 |
| Pay-back time | years | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Interest | % | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| Annuity | | 0,1314738 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 |
| **Investment cost** | Mkr/year | 0,710 | 1,420 | 3,195 | 1,065 | 2,130 | 5,325 | 1,420 | 2,485 | 6,390 |
| | | | | | | | | | | |
| Loading + unloading time | h | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Hourly rate, loading/unloading | SEK/h | 550 | 550 | 550 | 550 | 550 | 550 | 550 | 550 | 550 |
| | | | | | | | | | | |
| Transport rate (forwarder) | SEK/km | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| **Operating cost** | SEK/year | 3797990 | 3797990 | 4222610 | 3493550 | 3493550 | 3493550 | 3905820 | 4436240 | 4339800 |
| | | | | | | | | | | |
| Total transportation cost | SEK/year | 4507948 | 5217907 | 7417423 | 4558488 | 5623425 | 8818238 | 5325737 | 6921094 | 10729426 |
| Specific transport cost | SEK/$Nm^3$ LNG | 0,53 | 0,31 | 0,18 | 0,54 | 0,33 | 0,21 | 0,63 | 0,41 | 0,25 |
| Specific transport cost | SEK/MWh | 44,93 | 26,00 | 14,78 | 45,58 | 28,11 | 17,63 | 52,75 | 34,49 | 21,26 |

**Table B2: The specific road transport costs calculation sheet - Kollsnes LNG**

| Road transport cost model as in SGC report 167 [32] – From Melkøya | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Melkøya - Lysekil** | | | **Melkøya - Oxelösund** | | | **Melkøya - Luleå** | | |
| Annual transfer | GWh/year | 100 | 200 | 500 | 100 | 200 | 500 | 100 | 200 | 500 |
| Number of trailers | # | 5 | 10 | 23 | 4 | 8 | 20 | 2 | 4 | 10 |
| Distance one way | km | 2005 | 2005 | 2005 | 1752 | 1752 | 1752 | 745 | 745 | 745 |
| Number of round trips per trailer | #/year | 65 | 65 | 70 | 81 | 81 | 81 | 161 | 161 | 161 |
| Transport time, round-trip | hrs/shipment | 61,29 | 61,29 | 61,29 | 54,06 | 54,06 | 54,06 | 25,29 | 25,29 | 25,29 |
| Working hours per trailer | hrs/year | 3984 | 3984 | 4290 | 4379 | 4379 | 4379 | 4071 | 4071 | 4071 |
| Hours/year | hrs/year | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 | 8766 |
| Usage of each trailer | % | 45% | 45% | 49% | 50% | 50% | 50% | 46% | 46% | 46% |
| Trailers/week | # | 6 | 13 | 31 | 6 | 12 | 31 | 6 | 12 | 31 |
| | | | | | | | | | | |
| Cargo load | kg | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 | 21000 |
| Cargo load | Nm3 LNG | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 | 26250 |
| Cargo load | MWh | 312 | 312 | 312 | 312 | 312 | 312 | 312 | 312 | 312 |
| Investment cost per trailer | MSEK | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 | 2,7 |
| Pay-back time | years | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Interest | % | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |
| Annuity | | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 | 0,131474 |
| **Investment cost** | Mkr/year | 1,775 | 3,550 | 8,165 | 1,420 | 2,840 | 7,100 | 0,710 | 1,420 | 3,550 |
| | | | | | | | | | | |
| Loading + unloading time | h | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Hourly rate, loading/unloading | SEK/h | 550 | 550 | 550 | 550 | 550 | 550 | 550 | 550 | 550 |
| | | | | | | | | | | |
| Transport rate (forwarder) | SEK/km | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| **Operating cost** | SEK/year | 4052750 | 4052750 | 4364500 | 4435560 | 4435560 | 4435560 | 3952550 | 3952550 | 3952550 |
| | | | | | | | | | | |
| Total transportation cost | SEK/year | 5827646 | 7602542 | 12529022 | 5855477 | 7275394 | 11535144 | 4662508 | 5372467 | 7502342 |
| Specific transport cost | SEK/Nm$^3$ LNG | 0,68 | 0,45 | 0,30 | 0,69 | 0,43 | 0,27 | 0,55 | 0,32 | 0,18 |
| Specific transport cost | SEK/MWh | 57,55 | 37,54 | 24,98 | 58,00 | 36,03 | 22,85 | 46,47 | 26,77 | 14,96 |

**Table B3: The specific road transport costs calculation sheet - Melkøya LNG**

# Appendix C: Railroad Transport

There are two parameters to include for railroad cargo:

- all costs associated with the forwarding of the cargo, i.e. driver, fuel, railroad tariffs, and overhead costs for example
- the rail wagon rental or investment cost

To this study, Green Cargo provides data for the forwarding and VTG for the wagon costs. From this data, the total costs for railroad transport is calculated.

Data received from Green Cargo is shown in table C1 and C2 [30].

**Table C1: Presumptions used for rail calculations**

| **Presumptions** | | | |
|---|---|---|---|
| **Wagon data** | | | |
| Gross tons/wagon | 90 | | |
| Net tons/wagon | 40 | | |
| Transport weeks/year | 52 | | |
| | | | |
| **Annual tons** | **Annual GWh** | **Wagons per year** | **Wagons per week** |
| 6 600 | 100 | 165 | 3 |
| 66 000 | 1000 | 1 650 | 32 |
| 330 000 | 5000 | 8 250 | 159 |

**Table C2: The forwarding costs for the base cases, given by Green Cargo [30]**

| **Price examples 2008-05-28** | | |
|---|---|---|
| **Relations** | | **Prices ex wagon costs** |
| **From** | **To** | **Prices per wagon, round trip (SEK)** |
| Narvik | Luleå | **6 475** |
| Narvik | Oxelösund | **14 578** |
| Narvik | Lysekil | **16 066** |
| Kollsnes (Bergen) | Luleå | **19 158** |
| Kollsnes (Bergen) | Oxelösund | **12 822** |
| Kollsnes (Bergen) | Lysekil | **14 640** |

The specific costs for the forwarding are shown in table C3.

**Table C3: The specific forwarding cost, calculated from the information in table C3**

| Specific forwarding cost | | |
|---|---|---|
| Prices ex wagon costs | | |
| SEK/wagon | SEK/ton | SEK/MWh |
| 6 475 | 162 | 11 |
| 14 578 | 364 | 24 |
| 16 066 | 402 | 27 |
| 19 158 | 479 | 32 |
| 12 822 | 321 | 21 |
| 14 640 | 366 | 24 |

As there are presently no known existing LNG wagons in Western Europe, VTG uses the approximation that LNG wagons would cost 7-8 times more than LPG wagons. This is much due to new safety rules and regulations by the EU and Swedish authorities. The rental price for an LPG wagon is about 30 EUR/day and the rental time is always 365 days/year [31]. See table C4.

**Table C4: Calculation of the specific rental cost for rail wagons**

| Wagon rental | | |
|---|---|---|
| Rental LPG wagon | 30 | EUR/day |
| Times more expensive LNG/LPG | 7,5 | |
| Rental LNG wagon | 225 | EUR/day |
| Rental LNG wagon | 2 116 | SEK/day |
| Rental days per year | 365 | days |
| Annual rental | 772 210 | SEK/wagon |
| Loading capacity | 605 | MWh/wagon |

It should be pointed out that since no LNG wagons have been built by VTG, the starting price is high and in order to give it any economical feasibility, a long-term contract (15-20 years) with a great enough number of wagons (25-30) needs to be established [31].

In table C5, the number of needed wagons per time unit is calculated for each base case volume. Note that this also varies with the type of railroad transport (wagon transport/system trains).

**Table C5: The number of rail wagons needed for the base cases given by Green Cargo [30]**

| The number of needed wagons | | | | |
|---|---|---|---|---|
| GWh/year | Tons/year | Wagons/year | Wagons/week | Type |
| 100 | 6 740 | 168 | 3 | wagon |
| 200 | 13 479 | 337 | 6 | wagon |
| 500 | 33 698 | 842 | 16 | wagon |
| 1000 | 67 397 | 1 685 | 32 | system* |
| 5000 | 336 984 | 8 425 | 162 | system |
| 20000 | 1 347 936 | 33 698 | 648 | system |

*** Wagon transport could also work at this volume but to reduce the number of variables in the calculations, one of the two - system trains - is chosen.**

Since the distances between the base case routes differ, the number of times they can be used per week has to be calculated. In this approximation, it is assumed that it takes 3 days for each round trip for shorter distances (=1.6 round trips/week) and for longer distances 1 round trip per week. System trains take 1 day less than wagon transport. [30] The loading time is assumed to be included in the round trip time. See table C6.

**Table C6: The number of rail wagons needed for the different routes and volumes**

| Number of rail wagons needed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Relations** | | | **(GWh/year)** | | | | | |
| **From** | **To** | **Distance** | **100** | **200** | **500** | **1000** | **5000** | **20000** |
| Narvik | Luleå | short | 2 | 4 | 12 | 16 | 81 | 324 |
| Narvik | Oxelösund | long | 3 | 6 | 16 | 16 | 81 | 324 |
| Narvik | Lysekil | long | 3 | 6 | 16 | 16 | 81 | 324 |
| Kollsnes | Luleå | long | 3 | 6 | 16 | 16 | 81 | 324 |
| Kollsnes | Oxelösund | short | 2 | 4 | 12 | 16 | 81 | 324 |
| Kollsnes | Lysekil | short | 2 | 4 | 12 | 16 | 81 | 324 |

The wagon cost can then be calculated as in table C7.

**Table C7: The specific rental costs for rail wagons**

| Rail wagons rental, specific cost | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Relations** | | **(SEK/MWh)** | | | | | |
| **From** | **To** | **100** | **200** | **500** | **1000** | **5000** | **20000** |
| Narvik | Luleå | 15 | 15 | 19 | 12 | 13 | 13 |
| Narvik | Oxelösund | 23 | 23 | 25 | 12 | 13 | 13 |
| Narvik | Lysekil | 23 | 23 | 25 | 12 | 13 | 13 |
| Kollsnes | Luleå | 23 | 23 | 25 | 12 | 13 | 13 |
| Kollsnes | Oxelösund | 15 | 15 | 19 | 12 | 13 | 13 |
| Kollsnes | Lysekil | 15 | 15 | 19 | 12 | 13 | 13 |

Combined with the forwarding costs in table C3, the total cost of railroad transport for the base cases can be calculated, see table C8.

**Table C8: The total specific railroad costs**

| Total railroad costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Relations** | | **(SEK/MWh)** | | | | | |
| **From** | **To** | **100** | **200** | **500** | **1000** | **5000** | **20000** |
| Narvik | Luleå | 26 | 26 | 29 | 23 | 23 | 23 |
| Narvik | Oxelösund | 47 | 47 | 49 | 36 | 37 | 37 |
| Narvik | Lysekil | 50 | 50 | 51 | 39 | 39 | 39 |
| Kollsnes | Luleå | 55 | 55 | 56 | 44 | 44 | 44 |
| Kollsnes | Oxelösund | 37 | 37 | 40 | 34 | 34 | 34 |
| Kollsnes | Lysekil | 40 | 40 | 43 | 37 | 37 | 37 |

# Appendix D: Sea Transport

Calculations for two sizes of ships are performed: the 138 000 $m^3$-tanker, which is suitable for large scale base-load and the 7 500 $m^3$-tanker which is the an appropriate choice for small-scale or just above. Since the available data for these differs, two completely different approaches for the calculations are necessary.

**Base-load**

The US Energy Information Agency provides official energy statistics, among which some representative LNG shipping rates are presented, see figure D1 [8].

**Representative LNG Shipping Rates**
*(Dollars per million Btu)*

| Exporter | Everett | Cove Point | Elba Island | Lake Charles |
|---|---|---|---|---|
| Algeria | 0.52 | 0.57 | 0.60 | 0.72 |
| Nigeria | 0.80 | 0.83 | 0.84 | 0.93 |
| Norway | 0.56 | 0.61 | 0.64 | 0.77 |
| Venezuela | 0.34 | 0.33 | 0.30 | 0.35 |
| Trinidad and Tobago | 0.35 | 0.35 | 0.32 | 0.38 |
| Qatar | 1.37 | 1.43 | 1.46 | 1.58 |
| Australia | 1.76 | 1.82 | 1.84 | 1.84 |

Note: Prices based on a 138,000-cubic-meter tanker at a charter rate of $65,000 per day.
Source: LNG Shipping Solutions

**Figure D1: LNG base-load shipping rates from 2003 [8]**

From this, it is possible to calculate the rate per MWh and kilometre. The distances between Algeria and Norway to the four different ports are measured using Daft Logic's *Google Maps Distance Calculator* [61] (see table D2) and finally the average shipping cost is calculated. See table D1 for these calculations. Conversion factors used as in appendix A.

**Table D1: Calculation of the specific cost (SEK/MWh/km) for base-load sea transport**

| Base-load sea shipping cost | | | | | |
|---|---|---|---|---|---|
| **Loading capacity** | 138 000 $m^3$ LNG @ 162 °C, 1 atm = 938 776 MWh | | | | |
| | | | | | |
| **LNG Shipping Rate (USD/MMBTU) [8]** | | | | | |
| **Relations** | **Everett, MA** | **Cove Point, DE** | **Elba Island, GE** | **Lake Charles, LA** | **Average** |
| Algeria | 0,52 | 0,57 | 0,6 | 0,72 | |
| Norway | 0,56 | 0,61 | 0,64 | 0,77 | |
| | | | | | |
| **Distance (km)** | | | | | |
| Algeria | 6675 | 7420 | 7910 | 9738 | |
| Norway | 6753 | 7524 | 8071 | 10170 | |
| | | | | | |
| **Specific cost (SEK/MWh/km)** | | | | | |
| Algeria | 0,00161 | 0,00158 | 0,00157 | 0,00153 | 0,00157 |
| Norway | 0,00171 | 0,00167 | 0,00164 | 0,00156 | 0,00164 |
| | | | | | |
| **Average** | | | | | **0,00161** |
| **Price update using Net Price Index (see appendix A)** | | | | | |
| **Average 2008 price** | | | | | **0,00172** |

**Table D3: Calculated distances for sea transport**

| Calculated sea transport distances | | | |
|---|---|---|---|
| **Distance (km) [61]** | | | |
| **Relations** | Kollsnes | Melkøya | Skikda |
| Lysekil | 384 | 2114 | 5445 |
| Oxelösund | 900 | 2976 | 6345 |
| Luleå | 1406 | 3780 | 4951 |
| Narvik | | 610 | |

The average specific cost in table D1 is multiplied with the distances of the base case routes in table D2. The result is seen in table D3.

**Table D3: Calculation of the specific cost for base-load sea transport**

| Specific base-load sea shipping cost | | | |
|---|---|---|---|
| **Specific cost (SEK/MWh)** | | | |
| **Relations** | Kollsnes | Melkøya | Skikda |
| Lysekil | 0,66 | 3,62 | 8,49 |
| Oxelösund | 1,54 | 5,10 | 9,33 |
| Luleå | 2,41 | 6,48 | 10,88 |

A ship-owner company kindly provided the approximate cost for full loads between the base case routes and from these figures the specific costs have been calculated. See table D4. Note that Skikda is not a base case for small-scale LNG and hence omitted below.

**Table D4: Calculation of the specific cost for small-scale sea transport**

| Specific small-scale sea shipping cost | | |
|---|---|---|
| **Loading capacity** | 51 020 MWh | |
| | | |
| **Specific cost (SEK/MWh)** | | |
| **Relations** | Kollsnes | Melkøya |
| Lysekil | 17 | 35 |
| Oxelösund | 29 | 47 |
| Luleå | 39 | 57 |
| Narvik | | 20* |

***calculated value using given information for the other routes**

# Appendix E: Receiving Terminal

In the calculations for the cost of receiving terminals, the size of terminal is classified as lower range for 100-200 GWh/year, mid-range for 500-1000 GWh/year and upper range for 5000-20000 GWh/year.

An approximate cost for a receiving terminal wit an annual transfer volume of 200 GWh is given and the specific cost is calculated as in table E1. This is then applied to the base case sizes 100 and 200 GWh/year.

**Table E1: Calculation of the specific cost for lower range receiving terminals [62]**

| Lower range | | |
|---|---|---|
| Annual transfer volume | 200 | GWh |
| Total investment cost | 110 | MSEK |
| Pay-back time | 15 | years |
| Interest | 10% | % |
| Annuity factor | 0,131473777 | |
| Total capital cost | 14,5 | MSEK/year |
| Specific cost | 72,30 | SEK/MWh |

The cost for a "large" receiving terminal is calculated through a listing of planned import terminals in North America, where the planned send-out volumes and cost is stated. The average investment cost per unit of volume is calculated. The specific cost (M$/(bcf*day)) is listed as a comparison. See table E2.

**Table E2: Calculation of the specific cost for upper range receiving terminals, first step**

| Upper range – average terminal costs | | | |
|---|---|---|---|
| **Average costs of North American Regasification Terminals** | | | |
| from [63] | | | |
| **Terminal** | **Send-out** | **Cost** | **Spec cost** |
| | bcf/day | M$ | M$/(bcf/day) |
| Cacuana Energy, Quebec | 0,5 | 660 | 1320 |
| Canaport, New Brunswick | 1 | 500 | 500 |
| Quoddy Bay, MA | 0,5 | 400 | 800 |
| Altamira, Mexico | 0,5 | 370 | 740 |
| Cameron LNG, Louisiana | 1,5 | 700 | 467 |
| Calhoun, Texas | 1 | 400 | 400 |
| Freeport, Texas | 1,5 | 500 | 333 |
| Golden Pass, Texas | 1 | 600 | 600 |
| Vista del Sol, Texas | 1 | 600 | 600 |
| Energy Costa Azul, Mexico | 1 | 600 | 600 |
| Skipanon, OR | 1 | 500 | 500 |
| Terminal Mar Adentro, Mexico | 1,4 | 650 | 464 |
| | | | |
| Average send-out/day | 0,992 | | |
| Average cost (2004 prices) | | 540 | |
| Average cost (2008 update) | | 577 | |

The calculated average send-out and cost (2008 update) are used to estimate the specific cost of large receiving terminals. Conversions between units are performed according to the relations in appendix A. The average send-out capacity per year is calculated for means of comparison. The calculated specific capital cost is then applied to the base case sizes 5000 and 20 000 GWh/year. See table E3.

**Table E3: Calculation of the specific cost for upper range receiving terminals, second step**

| Upper range – specific cost | | |
|---|---|---|
| Average send-out/day | 0,992 | bcf |
| | 9,51E+09 | $Nm^3$ |
| | 21,1 | GWh |
| Average send-out/year | 7 700 | GWh |
| Average cost (2008 update) | 577<br>3 480 | MUSD<br>MSEK |
| | | |
| Pay-back time | 15 | years |
| Interest | 10% | % |
| Annuity factor | 0,131473777 | |
| Total capital cost | 457 | MSEK |
| Specific cost | 59,80 | SEK/MWh |

Since there is no data available for the range between 200 GWh and 7700 GWh, a value for the mid-range is estimated by simply working out an average of the two extremes in tables E1 and E3, as seen in table E4. The mid-range specific cost is applied to base case sizes 500 and 1000 GWh/year.

**Table E4: Calculation of the specific cost for mid-range receiving terminals**

| Mid-range – specific cost | | |
|---|---|---|
| Lower range specific cost | 72,30 | SEK/MWh |
| Upper range specific cost | 59,80 | SEK/MWh |
| Arithmetic mean between the above values<br>= Mid-range specific cost | 66,00 | SEK/MWh |

# Appendix F: LNG Production in Gas pressure regulating and measuring station

The cost and scale for the LNG production in a Gas pressure regulating and measuring station is calculated through the model used in SGC report 167, as seen in table F1.

**Table F1: Calculation sheet for the specific costs for LNG production in a Gas pressure regulating and measuring station**

| Specific cost for LNG production in a GPRM station | | | |
|---|---|---|---|
| **Cost model as in SGC167 [33]** | | | |
| Pressure reduction from 60 to 28 bar | | | |
| | | | |
| Annual production volume | GWh | 100 | 200 |
| Flow of NG | $Nm^3/h$ | 3847 | 7694 |
| Electricity price | SEK/kWh | 0,8 | 0,8 |
| Methanol price | SEK/l | 7 | 7 |
| Average running time/day | h | 24 | 24 |
| Pressure of transmission | bar | 60 | 60 |
| Pressure of distribution | bar | 28 | 28 |
| Specific power cons. | $kWh/Nm^3$ | 0,198 | 0,198 |
| Specific methanol cons. | $l/Nm^3$ | 0,002 | 0,002 |
| | | | |
| Production of LNG | $Nm^3/h$ | 962 | 1923 |
| Scale factor | | 1 | 1 |
| Methanol consumption | l/h | 10 | 10 |
| Electricity needed | kW | 200 | 390 |
| Operating cost electricity | $SEK/Nm^3$ LNG | 0,166 | 0,162 |
| Operating cost methanol | $SEK/Nm^3$ LNG | 0,073 | 0,036 |
| **Operating cost total** | $SEK/Nm^3$ LNG | 0,239 | 0,199 |
| | | | |
| Specific investment cost | MSEK/plant | 16 | 16 |
| Investment cost | MSEK | 16 | 16 |
| Pay-back time | years | 15 | 15 |
| Interest | % | 0,1 | 0,1 |
| Annuity | | 0,131473777 | 0,131473777 |
| Total capital cost | Mkr/year | 2,104 | 2,104 |
| **Capital cost** | $SEK/Nm^3$ LNG | 0,2497 | 0,1248 |
| | | | |
| Specific production cost | $SEK/Nm^3$ LNG | 0,49 | 0,32 |
| Specific production cost | SEK/MWh | 41,18 | 27,25 |

# Appendix G: Peak-Shaving

To cover 25 MW of energy input at the power plant, two different solutions are studied: normal small-scale LNG distribution supplied by Gasnor (Kollsnes plant) and the LiquiTainer® portable LNG container options supplied by Liquiline. Liquiline offers two sizes of LiquiTainers®: 20- and 40-foot. Table G1 describes the assignment, possible solutions and the costs involved.

**Table G1: Problem description, solutions and costs for peak-shaving assignment**

| | | | | |
|---|---|---|---|---|
| **Problem description peak-shaving and possible solutions** | | | | |
| | | | | |
| **Need** | | | | |
| Power | 25 | MW | | Öresundskraft |
| Usage time | 24 | h/day | | |
| Energy need | 600 | MWh/day | | |
| Number of days | 1 | days/year | | |
| Annual need | 600 | MWh/year | | |
| | | | | |
| **Solutions** | | | | |
| *LiquiTainer® portable containers - rental costs* | | | | |
| | 20-foot | 40-foot | | |
| Capacity | 20 | 45 | $m^3$ | [44] |
| Capacity | 136 | 306 | MWh | |
| Containers/year | 4 | 2 | | |
| Containers /month | 0,4 | 0,2 | | |
| Rental cost/container | 0,30 | 0,46 | MSEK/year | (assumed)* |
| Specific rental cost | 515 | 772 | SEK/MWh | |
| | | | | |
| *Small-scale LNG – terminal costs* | | | | |
| Tank size (Näsl) | 20 | $m^3$ | | Usage/tank size table in [7] |
| Specific capital cost | 72,31 | SEK/MWh | | Appendix E |
| Specific operating cost, (1%) | 0,72 | SEK/MWh | | Appendix E |

***As no purchase price is available from Liquiline, an assumption based on the cost of rail wagon rental is made. A wagon consists of a 605 MWh cryogenic tank, support systems and the actual wheel system. A LiquiTainer® is a cryogenic tank with support systems. Therefore, the 40-foot container, which has half the loading capacity of a wagon and no wheels, but probably a reinforced body to withstand the rougher handling it would be exposed for, is assumed to cost 60 % of a wagon. The cost for the tank does not increase linearly with the size and this fact is also included in the assumption. For the 20-foot equivalent, which holds 136 MWh, the cost is assumed to be 40 % of a wagon. The operating cost is included in the rental cost.**
**It is also worth to mention that the specific capital cost for the terminal might be under-estimated for this size.**

The transport cost is calculated using the same model as in appendix B for road transport [33]. The parameters are altered for the LiquiTainer® case (table G2). Note that the investment cost for the LiquiTainer® is omitted from this section as the rental cost was previously calculated.

**Table G2: Transport costs involved in the peak-shaving solutions**

| Transport costs | | | | |
|---|---|---|---|---|
| | Trailer | LiquiTainer® | | |
| | | 20-foot | 40-foot | |
| Loading capacity | 312 | 136 | 306 | MWh |
| Loading capacity | 46 | 20 | 45 | m3 |
| | | | | |
| Annual transfer | 0,6 | 0,6 | 0,6 | GWh |
| Number of units | 1 | 1 | 1 | # |
| Distance one way | 1001 | 1001 | 1001 | km |
| Number of round trips per unit | 2 | 5 | 2 | |
| Transport time, round-trip | 32,60 | 32,60 | 32,60 | h |
| Working hours per unit | 138 | 336 | 134 | hrs/y |
| Hours/year | 8766 | 8766 | 8766 | hrs/y |
| Usage of each unit | 2% | 4% | 2% | % |
| | | | | |
| Investment cost per unit | 2,7 | N/A | N/A | MSEK |
| Pay-back time | 15 | | | years |
| Interest | 10% | | | % |
| Annuity | 0,131473777 | | | |
| *Investment cost* | 0,355 | | | MSEK/y |
| | | | | |
| Loading + unloading time | 4 | 2 | 2 | hrs |
| Hourly rate, loading/unloading | 550 | 550 | 550 | SEK |
| | | | | |
| Transport rate (forwarder) | 15 | 15 | 15 | SEK/km |
| *Operating cost* | 64460 | 155650 | 62260 | MSEK/year |
| | | | | |
| Total transportation cost | 419439 | 155650 | 62260 | MSEK/year |
| Specific transport cost | 699 | 259 | 104 | SEK/MWh |

The total costs are summarised in table G3. The Norwegian LNG purchase price as used is SGC report 167[33] is also utilised here.

**Table G3: Total costs for the peak-shaving solutions**

| Total costs peak-shaving | | | | |
|---|---|---|---|---|
| | Small-scale LNG | LiquiTainer® 20-foot | LiquiTainer® 40-foot | |
| LNG market price | 472 | 472 | 472 | SEK/MWh |
| Terminal | 73 | | | SEK/MWh |
| LiquiTainer® rental | | 515 | 772 | SEK/MWh |
| LiquiTainer® terminal | | 18 | 18 | SEK/MWh |
| Transport | 699 | 259 | 104 | SEK/MWh |
| | | | | |
| Total specific cost | 1244 | 1264 | 1366 | SEK/MWh |

## Alternative assignment

The same calculations are performed for an alteration of the assignment:
25 MW for 24 hours, **7 days** per year. See tables G4-G6.

**Table G4: Problem description, solutions and costs for the alternative peak-shaving assignment**

| **Problem description peak-shaving and possible solutions** | | | | |
|---|---|---|---|---|
| | | | | |
| **Need** | | | | |
| Power | 25 | MW | | Öresundskraft |
| Usage time | 24 | h/day | | |
| Energy need | 600 | MWh/day | | |
| Number of days | 7 | days/year | | |
| Annual need | 4200 | MWh/year | | |
| | | | | |
| *LiquiTainer® portable containers - rental costs* | | | | |
| | | | | |
| Capacity | 20-foot | 40-foot | | |
| Capacity | 20 | 45 | $m^3$ | [44] |
| Containers/year | 136 | 306 | MWh | |
| Containers /month | 31 | 14 | | |
| Rental cost/container | 2,6 | 1,1 | | |
| Specific rental cost | 0,30 | 0,46 | MSEK/year | (assumed) |
| Specific rental cost | 74 | 110 | SEK/MWh | |
| | | | | |
| *Small-scale LNG – terminal costs* | | | | |
| Tank size (Näsl) | 20 | $m^3$ | | Usage/tank size table in [7] |
| Specific capital cost | 72,31 | SEK/MWh | | Appendix E |
| Specific operating cost, (1%) | 0,72 | SEK/MWh | | Appendix E |

**Table G5: Transport costs involved in the peak-shaving solutions**

| Transport costs | | | | |
|---|---|---|---|---|
| | **Trailer** | **LiquiTainer®** | | |
| | | **20-foot** | **40-foot** | |
| Loading capacity | 319 | 136 | 306 | MWh |
| Loading capacity | 47 | 20 | 45 | m3 |
| | | | | |
| Annual transfer | 4,2 | 4,2 | 4,2 | GWh |
| Number of units | 1 | 1 | 1 | # |
| Distance one way | 1001 | 1001 | 1001 | km |
| Number of round trips per unit | 14 | 31 | 14 | |
| Transport time, round-trip | 32,60 | 32,60 | 32,60 | h |
| Working hours per unit | 969 | 2083 | 941 | hrs/y |
| Hours/year | 8766 | 8766 | 8766 | hrs/y |
| Usage of each unit | 11% | 24% | 11% | % |
| | | | | |
| Investment cost per unit | 2,7 | N/A | N/A | MSEK |
| Pay-back time | 15 | | | years |
| Interest | 10% | | | % |
| Annuity | 0,131473777 | | | |
| *Investment cost* | 0,355 | | | MSEK/y |
| | | | | |
| Loading + unloading time | 4 | 2 | 2 | hrs |
| Hourly rate, loading/unloading | 550 | 550 | 550 | SEK |
| | | | | |
| Transport rate (forwarder) | 15 | 15 | 15 | SEK/km |
| *Operating cost* | 451220 | 965030 | 435820 | MSEK/year |
| | | | | |
| Total transportation cost | 806199 | 965030 | 435820 | MSEK/year |
| Specific transport cost | 192 | 230 | 104 | SEK/MWh |

**Table G6: Total costs for the peak-shaving solutions for the alternative assignment**

| Total costs peak-shaving - alternative assignment | | | | |
|---|---|---|---|---|
| | **Small-scale LNG** | **LiquiTainer® 20-foot** | **LiquiTainer® 40-foot** | |
| LNG market price | 472 | 472 | 472 | SEK/MWh |
| Terminal | 73 | | | SEK/MWh |
| LiquiTainer® rental | | 74 | 110 | SEK/MWh |
| LiquiTainer® terminal | | 18 | 18 | SEK/MWh |
| Transport | 192 | 230 | 104 | SEK/MWh |
| | | | | |
| Total specific cost | 737 | 794 | 704 | SEK/MWh |

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