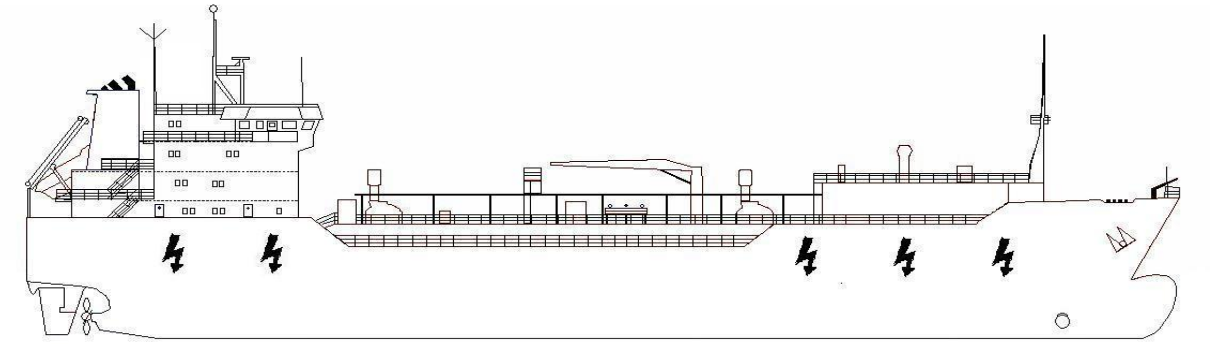
FACULTY MECHANICAL ENGINEERING
AND MARINE TECHNOLOGY
Section Ship Design, Production & Operation
Mekelweg 2
2628 CD Delft
Netherlands
Phone: 015-2782889

Bulk Electricity Sea Transport from Remotely Located Power Plants

Author: A.G.A. Hammoutene



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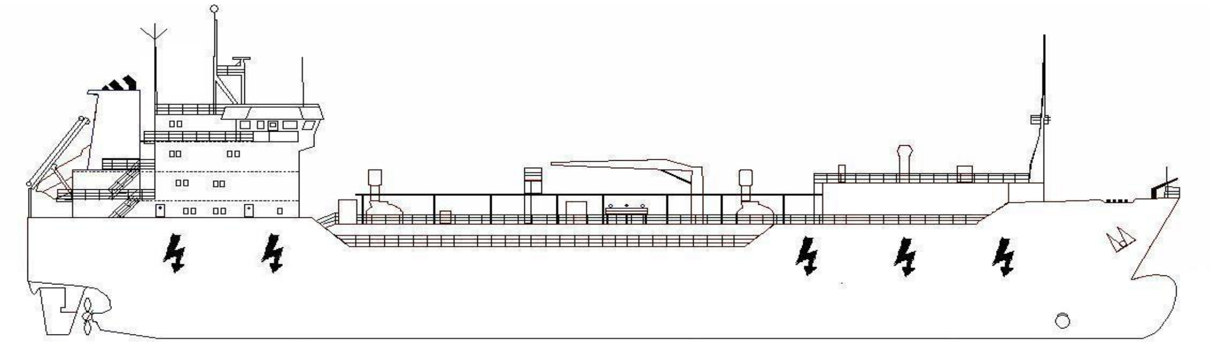

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Preface

Since the beginning of time humankind uses ship transport for the transport of people and goods. Nowadays it is not differently. Today ship transport is indispensable in our modern society. Ship transport is mainly used for the transport of a large variety of cargoes such as ore, rice, grain, containers, chemicals, etc. However, ship transport is not yet used for the bulk electricity transport, despite electricity is one of most utilized energy form in the world. Therefore the goal of the report is to develop and to analyse different electricity transport concepts to achieve bulk electricity transport across the sea in energy efficient and cost efficient manner. Furthermore bulk electricity transport across the sea would enable the transport of renewable energy from remotely located energy sources to electricity consumers. Currently the electricity transport across the sea is only done with submarine electrical power cables. The report is written in a period that the diminishing oil and natural gas resources and the increasing energy demand cause high energy prices. The author hopes that the thesis will provide insight into the different methods to achieve bulk electricity across the sea, so that the energy system becomes more sustainable in the future.

The thesis is written at Delft University of Technology for obtaining a master degree in Naval Architecture. The report has been written under the supervision of ir. J.W. Frouws and prof. ir. A. Aalbers. The author would like to thank ir. J.W. Frouws for his guidance and for improving the thesis. Moreover I am especially indebted to ir. J.W. Frouws for his very valuable criticism on my work. In addition, the author would like to thank prof. ir. A. Aalbers for his patience and the giving opportunity to graduate on this fascinating topic.

My sincere gratitude goes also out to my mother Ria, my brother Lyes, my sister Nadia, Ramdane Hammoutene and my family for their support.

The thesis is dedicated to my father Nazim Hammoutene, deceased on 6 October 2005. His compassion, his strive for perfection and his wisdom were of great value to his family, his friends, his colleagues and the Algerian community in the Netherlands. As person Nazim Hammoutene was very highly esteemed and respected in Algeria, France and the Netherlands.

Delft, Mai 2008

A.G.A. Hammoutene

Summary

Electricity is one of the most utilized energy carriers for energy transmission in the world. In recent years more electricity is generated from renewable energy sources. The main drawback of renewable energy sources is that renewable energy power plants are often connected to certain locations. Sometimes these renewable energy power plants are located in very long distant areas across the sea, so consequently bulk electricity transport to major electric power consuming areas across the sea is not done due to economical difficulties. Therefore the aim of the report is to develop and to analyse different electricity transport concepts to achieve bulk electricity transport across the sea in energy efficient and cost efficient manner. In this case the feasibility of bulk electricity transport between the hydroelectric and geothermal energy sources in Iceland and the electric power consuming areas such as Scotland and European mainland is investigated. During the development of the electricity transport concepts three electricity transport concepts emerged. The three electricity transport concepts are the submarine electric power transmission, the battery ship and the synthetic fuel. In the study the three electricity transport concepts are further developed and analysed. The three electricity transport concepts are analysed by investigating the energetic performance and the cost performance of the three electricity transport concepts for the distances from 0 nautical miles till 6000 nautical miles. In addition the influence of the cost per MWh of power plants on the three electricity transport concepts is examined for the distances of 500 nautical miles and 1000 nautical miles. Currently the electric power transmission with submarine electrical power cables is the only way to deliver electrical energy across the sea. The electric power transmission system is composed of two converter stations and one or two submarine power cables. The other electricity transport concept consists of a battery ship and two small offshore terminals. The battery ship is a 300.000 dwt ship with integrated redox flow batteries. The battery ship is charged and discharged at small offshore terminals. In this report the battery ship is developed till conceptual design.

The last electricity transport concept consists mainly of a production plant for the conversion of electricity into synthetic fuel, a cargo ship and a power plant. In the thesis different synthetic fuels are compared. The different synthetic fuels are hydrogen, ammonia, methanol, ethanol, dimethyl ether (DME), sodium borohydride and zinc. The results of the investigation are that the synthetic fuels hydrogen and ammonia are attractive synthetic fuels for bulk electricity sea transport. Hence follows that the bulk electricity sea transport by means of compressed hydrogen and ammonia is examined in more details and afterwards the two synthetic fuels are compared. The comparison shows that ammonia is a more energy efficient and cost efficient synthetic fuel than hydrogen, so ammonia is the appropriate synthetic fuel for the purpose of bulk electricity sea transport.

Finally, all electricity transport concepts are compared with each other and evaluated.

The main conclusions of the comparison between the electricity transport concepts are:

- The bulk electricity transport with submarine power cable link is the most cost efficient and energy efficient solution till approximately 2500 nautical miles.
- Beyond approximately 2500 nautical miles the bulk electricity sea transport with ammonia fuel is the most attractive solution.
- The submarine power cable link is the most attractive solution for the bulk electricity transport between Iceland and Scotland and the bulk electricity transport between Iceland and European mainland and bulk electricity transports are profitable with the current market prices of electricity in Scotland and European mainland.
- The bulk electricity transport with battery ship could be an attractive solution till approximately 1000 nautical miles, when the costs of batteries are significantly lower.

Table of Contents

1 Introduction

Electricity is one of the most utilized energy carriers for energy transmission in the world. It is a convenient clean flexible energy carrier. Electricity is a convenient energy carrier, because electrical energy can be transformed into mechanical energy, thermal energy, magnetic energy, radiant energy and chemical energy. Besides that the different forms of energy such as mechanical energy, thermal energy, magnetic energy, electromagnetic radiation, chemical energy and nuclear energy are transformed into electrical energy. Electricity has become indispensable for the existence of our modern human society. Electricity enables lighting, entertainment, communication, medical services, computers, internet, medical services, mechanical work, heating and electric vehicles such as train, metro and tram, etc. Summarized electricity is required for operating factories, homes, offices and public transport [43]. The power plants generate electricity from various energy sources such as coal, oil, natural gas, nuclear, waste, wind, hydro, solar, geothermal and biomass.

The electricity from the power plants is transported with transmission lines and distribution systems to the consumer, because electricity is often not produced in the same place that it is consumed. In recent years more electricity is generated from renewable energy sources, because fossil fuels such as coal, oil and natural gas are not sustainable.

The important drawbacks of renewable energy sources are that renewable energy power plants are sometimes connected to certain locations and renewable energy power plants do not often provide for constant energy supply. Moreover the growing world population, the higher living standards and the shortage of fossil fuel resources in the world increase the demand for electricity. Unfortunately, the ‘stranded’ renewable energy sources are often located in very long distant areas across the sea. An example of ‘stranded’ renewable electrical energy sources in a remote long distant area across the sea is the hydroelectric and geothermal energy sources in Iceland. The electricity in Iceland is needed in the electric power consuming areas such as Scotland and European mainland.

However, transporting bulk electricity from remote long distant areas to major electric power consuming areas across the sea is not yet common practice due to economical difficulties. Therefore in this report different bulk electricity transport concepts are developed and investigated to unlock the ‘stranded’ renewable energy sources in very long distant areas across the sea. The goal of the report is to develop and to analyse different bulk electricity transport concepts to achieve bulk electricity transport across the sea in energy efficient and cost efficient manner. The report does not examine the different methods of electric power generation and the grid connection between substation and households. The report consists of 7 chapters. The electricity transport concepts are explored and determined in chapter 2.

The three electricity transport concepts are the submarine electric power transmission, the battery ship and the synthetic fuel. The submarine electric power transmission is described and investigated in chapter 3. The battery ship is developed and investigated in chapter 4. The last electricity transport concept synthetic fuel is investigated in chapter 5. Finally, the electricity transport concepts are compared and evaluated in chapter 6. During the comparison the influence of parameters such as distance and cost per MWh of power plants are determined. In the chapter 7 the conclusions and recommendations are presented.

2 Exploration of Electricity Transport Concepts

In this chapter electricity transport concepts are explored and determined.

2.1 Direct Physical Connection

In our modern society energy transmission over long distances is often accomplished by a direct physical connection from one point to another point. The direct physical connection enables conducting continuous energy in an efficient manner over long distances and the direct physical connection protects often the energy transmission against the environment.
In addition the physical connection protects the environment against the energy transmission.
The direct physical connection is a conducting medium such as electrical copper cables or pipelines. Some conducting mediums like pipeline transport both energy and matter.
Other conducting mediums like optical fibers transport energy without transporting matter.
The medium has consequences for the energy losses, speed, sensitivity to environment, reliability and the cost of energy transmission. An overview of different mediums based on different forms of energy for long distances is presented in table 2.1.

Medium	Form of Energy
Electrical Cables	**Electrical Energy**
Synthetic Fuel like Hydrogen in Pipelines	**Chemical Energy**
Hot Matter like Hot Water in Pipelines	**Thermal Energy**
Light in Optical Fibers	**Radiant Energy**

Table 2.1 The different conducting mediums with associated form of energy

Among the four conducting mediums two conducting mediums are attractive for long distance energy transmission. The two conducting mediums are electrical cables and synthetic fuel in pipelines. The two other mediums are less attractive for energy transmission.
The energy transmission by means of transporting hot matter like hot water in pipelines is less attractive, because the energy transmission is sensitive to the environment temperature.
The energy transmission with light in optical fibers is less attractive, because the energy losses per km are very high [121]. The energy losses per km for the two remaining conducting mediums are lower. The energy losses per km of transporting synthetic fuel such as hydrogen, ammonia, etc in pipelines depend on the properties of synthetic fuel such as energy density, viscosity, etc. In certain cases the energy losses per km of transporting synthetic fuel in pipelines are even lower than the energy losses per km of energy transmission with electrical cables. Furthermore the costs per km of pipelines and electrical cables are of the same magnitude. Another major difference between the remaining conducting mediums is the speed. The speed of energy transmission with electrical cables is close to the speed of light [43]. Therefore the benefit of energy transmission with electrical cables is that it is possible to react quickly on fluctuations in energy demand. The main drawback of electricity is that it cannot be directly stored. The speed of transporting matter in a pipeline depends on the characteristics of synthetic fuel and economical issues, but the speed should be around 2 m/s. The benefit of synthetic fuel is that it is easily storable. Thus energy transport by means of synthetic fuel in pipelines is interesting, when both energy transmission and energy storage are required. The main drawback of synthetic fuel is that the energy losses associated with the conversion of electricity into synthetic fuel and synthetic fuel into electricity are very high [71]. Therefore the direct physical connection for energy transmission across the sea consists of electrical cables.

2.2 No Direct Physical Connection

As stated before energy transmission over long distances is often accomplished by a direct physical connection, but there are other general solutions for energy transmission or energy transfer over long distances. The other general solutions for energy transmission are:

1) Wireless energy transmission
2) Transporting matter, which contains energy

The two general solutions have in common that there is no direct physical connection between electric power plants and electricity consumers. The wireless energy transmission is defined as the process that takes place in any system, where electrical energy is transmitted from a power plant to electricity consumers without interconnecting wires or cables [122].
The advantages of wireless energy transmission are instantaneous energy on demand to inaccessible locations and no requirement for energy infrastructure. Today wireless energy transmission for long distances has not been implemented. Over time different wireless energy transmission technologies are investigated. The following wireless energy transmission technologies are developed [122]

- Energy transmission with inductive coupling/mutual induction
- Energy transmission with radio waves
- Energy transmission with resonant inductive coupling
- Energy transmission with microwaves
- Energy transmission with laser light
- Electrical conduction through naturally existing conductors such as air and water

Among the wireless energy transmission technologies energy transmission with microwaves and energy transmission with laser light are feasible for long distance energy transmission. Both well-proven technologies convert electrical energy into radiant energy and vice versa. The energy transmission with laser light is accomplished by converting electricity into a laser beam, which is directed at a solar cell receiver. The solar cell receiver converts the light into electricity. The drawback of laser light is that atmospheric absorption causes energy losses. The energy transmission with microwaves is accomplished by converting electricity into microwaves with transmitting antenna, which is directed at a rectenna. The rectenna converts the microwaves into electricity. Both energy transmission technologies require a direct line of sight to the receiver, so very long distance energy transmission is only feasible with orbiting power satellites or hovering vehicles. Among the two power transmission technologies the energy transmission with microwaves is now the most attractive technology due to safety reasons and high efficiency of power transmission between antenna and rectenna [123]. Despite the high efficiency of microwave power transmission, it is not suitable for long distance energy transmission across the sea, because the microwave power transmission cannot transmit beyond the horizon. Similarly as microwave power transmission, laser light power transmission is not suitable for long distance energy transmission across the sea, because it cannot transmit beyond the horizon. Perhaps in the future long distance energy transmission beyond the horizon is achievable with reflectors. However laser light power transmission and microwave power transmission are feasible for transferring energy to the surface of the Earth from solar power satellites or transferring energy from the surface of the Earth to satellites, because there is a direct line of sight [122].

The other general solution is transporting matter, which stores electrical energy.

This solution requires energy storage. Energy storage is the storage of an energy form that can be recovered in a later stadium. Energy storage is a process, which takes everywhere place. Energy storage has several advantages. Energy storage enables the decoupling of energy demand and energy supply. Energy storage prevents energy supply interruptions. Energy storage maximizes the efficiency of the energy distribution system and finally the energy storage provides for stability in energy prices. Energy storage is especially used for electricity storage, because as stated before electricity cannot be directly stored. This drawback means that electricity must always be consumed, when the electricity is produced.

Today electrical energy storage is becoming important, because more renewable energy sources are utilized. In addition energy savings and emission reductions are more an issue. Several renewable energy sources have the disadvantage that they do not provide for a constant energy supply or the energy supply is difficult to couple to the energy demand.

This problem can be solved by utilizing electrical energy storage devices, so called electrical storage devices. The electrical storage device is an equipment or installation that receives electrical energy, converts the electrical energy into a form of energy suitable for storage and after a time period the stored energy is converted back to electrical energy. The electrical storage devices have basically three different operations: charging/converting, storing and discharging/converting. The electrical storage devices can only discharge energy, when energy is stored. Therefore the solution consists of transporting electrical storage devices with a vehicle. The most appropriate vehicle for transporting electrical storage devices across the sea is a ship. Furthermore the electrical storage devices must be coupled in series connection, to achieve energy transfer or energy transport by ship. The electrical storage devices must be coupled in series connection, because the electrical energy must go through the electrical storage device. It should be noted that the electrical storage devices can be connected to distribution system in series connection or in parallel connection [1].

Generally the electrical storage devices are applied for three different functional applications such as power quality, bridging power and energy management [82]. The power quality electrical storage devices are applied to ensure the continuity and the quality of the power for some seconds. The bridging power electrical storage devices are applied to deliver power for some minutes. This makes switching from one energy supply to an alternative energy supply possible. The energy management electrical storage devices are used to store a lot of electrical energy for long periods such as many hours or days. These devices have the ability to be decoupled from the distribution system or grid for long periods. Normally the electrical storage devices can be used for all three functional applications, but the electrical storage device is best suited for the designed functional application based on economical reasons.

In this case energy management electrical storage devices should be utilized, because electrical storage devices in the ship must store electricity for several days.

Next the general features of electrical storage devices are explained.

2.2.1 General Features of Electrical Storage Devices

Over time a wide variety of different electrical energy storage technologies and devices are developed and new different electrical energy storage technologies are in development.
The electrical storage devices come in different sizes, different functional applications and different storage technologies. The electrical storage device may mainly consist of solid or/and liquid materials. These reasons make direct comparison of electrical storage devices complex. Still all electrical storage devices have same general features and key parameters in common. The key parameters for comparison are presented below.
The key parameters of electrical storage devices can be summarized thus [1][2][3][82]:

- Energy density by mass in Wh/kg or kWh/ton
- Energy density by volume in Wh/l or Wh/m^3 or kWh/m^3
- Energy efficiency or cycle efficiency in %
- Output energy density by mass in Wh/kg
- Output energy density by volume in Wh/m^3
- Density in kg/m^3 or ton/m^3
- Lifetime in years
- Cycle Life
- Power density by mass in W/kg or kW/ton
- Power density by volume in W/m^3
- Response time in seconds or minutes
- Capital cost per unit power in USD/kW
- Capital cost per unit energy in USD/kWh
- Cost per cycle in USD/kWh
- Site requirement

The most relevant key parameters are energy density, output energy density, energy efficiency, cycle life, power density by mass and capital cost per unit energy.
The energy density by mass or gravimetric energy density is the amount of stored energy in electrical storage device divided by the mass of the device. Similarly, the energy density by volume or volumetric energy density is the amount of energy in electrical storage device divided by the volume of the device. In the literature theoretical values of energy densities are often presented, but for comparison the practical values of energy densities are used.
The energy efficiency also called cycle efficiency is the useful electrical energy extracted from an energy storage device divided by the total electrical energy put into an energy storage device for one charge/discharge cycle. The energy efficiency or cycle efficiency is often expressed in %. The depth-of-discharge is the percentage withdrawn from an electrical storage device in a given discharge, related to the total capacity [3]. The cycle life is the number of cycles normally for depth-of-discharge of 100%. The cycle life limits basically the lifetime of electrical storage device. The lifetime of some electrical storage devices is not limited by the cycle life. The lifetime of electrical storage device is determined by the cycle life and the aging process. If during the lifetime of electrical storage device the cycle life is less than the maximum cycle life, the aging process prescripts the lifetime of electrical storage device. At lower percentage DOD, the cycle life could increase. Another relevant parameter is SOC. The state-of-charge indicates how much capacity remains in the electrical storage device [3]. The density in ton/m^3 or in kg/m^3 of electrical storage device is obtained by dividing the energy density by volume in kWh/m^3 by the energy density by mass in kWh/ton, which is presented in the equation below.

Most electrical storage devices have densities higher than 1000 kg/m^3 [82]. In this case the density of electrical storage device should be close to the density of seawater 1250 kg/m^3.

$$\textbf{Density} = \frac{\textbf{Energy Density by Volume}}{\textbf{Energy Density by Mass}} \tag{2.1}$$

Although the density of an electrical storage device is relevant, the energy density is more relevant. As previously mentioned, the energy density is the amount of stored electrical energy in the electrical storage device divided by the mass, but it is not the amount of electrical energy that comes out of the electrical storage device. During the storage energy could be lost due to heat, chemical reactions within the electrical storage device or self-discharge. During long storage times such as months and years, the self-discharge gives lower cycle efficiency. Some electrical storage devices require to be kept at an extreme temperature to store the energy. These electrical storage devices require energy to maintain the extreme temperature. If the extreme temperature is not kept, the energy in the electrical storage device will be lost or/and the electrical storage device could be damaged. The extreme temperature is not maintained, when electrical storage device contains or receives no energy. These electrical storage devices are not suited for off-grid application, because the risk of cargo loss or electricity loss is very high and these electrical storage devices require energy to maintain the extreme temperature. These electrical storage devices are best suited for back-up applications or power quality applications. The output energy density is the product of energy density and energy efficiency. The product of energy density and efficiency is used, because it reflects the realistic energy content better. Similarly as energy density, the output energy density is presented in output energy density by mass and in output energy density by volume.
The output energy density by mass expressed in Wh/kg is obtained with the following equation [82].

$$\textbf{Output Energy Density by Mass} = \textbf{Energy Density by Mass} \cdot \textbf{Efficiency} \tag{2.2}$$

Furthermore the output energy density by volume expressed in Wh/m^3 is obtained with the equation below [82].

$$\textbf{Output Energy Density by Volume} = \textbf{Energy Densityby Volume} \cdot \textbf{Efficiency} \tag{2.3}$$

For comparisons the output energy density by mass is preferred than output energy density by volume. In addition the output energy density of the electrical storage device will be preferred instead of the energy density in this report. Furthermore it should be mentioned that the energy unit kWh is equal to 3.6 MJ. Besides the output energy density the power density is relevant. The power density is the amount of power discharged by the electrical storage device divided by mass or volume [3]. The power density is expressed in W/kg. The power density could also be expressed in W/m^3. The power density in W/m^3 is obtained by multiplying the power density in W/kg with the density in kg/m^3, which is reflected in the following equation.

$$\textbf{Power Density by Volume} = \textbf{Power Density by Mass} \cdot \textbf{Density} \tag{2.4}$$

In general high power densities are required for quality power applications [82]. A parameter relevant for the power density is the specific capacity. The specific capacity is the capacity delivered per unit volume or per unit mass [3]. The specific capacity is expressed in Ah/kg.

The rated capacity is the product of the nominal current with time. The specific capacity in Ah/m^3 is calculated by multiplying the specific capacity in Ah/kg with the density in kg/m^3.

$$\textbf{Specific Capacity by Volume} = \textbf{Specific Capacity by Weight} \cdot \textbf{Density} \qquad (2.5)$$

The specific capacity of some electrical storage device is related to the electrochemical equivalent of the material in Ah/g [3]. The other relevant parameter is the response time. The response time is the time between the signal for discharging and the start of discharging. The electrical storage devices have response times ranging from milliseconds till several minutes. Response times of several minutes present problems for some applications.
Most electrical storage devices have response times of seconds.
For energy management electrical storage device is the response time is not crucial.
The technical parameters are discussed till now, but the economical parameters are even so relevant. The relevant economical parameters are capital cost per energy unit, capital cost per power unit, capital cost per unit mass, capital cost per unit volume and cost per cycle.
The capital cost of electrical storage devices determines mainly the total costs, but most electrical storage devices have also maintenance costs. It is preferred to use maintenance free electrical storage devices. The capital cost per unit mass or capital cost per unit energy is often used. The capital cost per unit mass is normally expressed in USD/kg. The capital cost per unit volume in USD/m^3 is acquired with the formula below.

$$\textbf{Capital Cost per Unit Volume} = \textbf{Capital Cost per Unit Weight} \cdot \textbf{Density} \qquad (2.6)$$

The capital cost per unit energy is often utilized to compare electrical storage devices.
The capital cost per unit energy is calculated with the following formula with the energy density in kWh/kg. The capital cost per unit energy is expressed in USD/kWh [82].

$$\textbf{Capital Cost per Unit Energy} = \frac{\textbf{Capital Cost per Unit Weight}}{\textbf{Energy Density}} \qquad (2.7)$$

The capital cost per unit energy is a parameter that should be applied for the comparison of energy management electrical storage devices. For quality power applications, the parameter capital cost per unit power should be used instead of capital cost per unit energy. The capital cost per unit power is obtained with the following equation with the power density in kW/kg.

$$\textbf{Capital Cost per Unit Power} = \frac{\textbf{Capital Cost per Unit Weight}}{\textbf{Power Density}} \qquad (2.8)$$

Although the capital cost per unit energy could be used for a comparison of the electrical storage devices. In general the cost per cycle is the appropriate way to compare electrical storage devices for energy management applications. The capital cost per cycle takes account for the influence of the maximum cycle life and the energy efficiency/cycle efficiency.
The cost per cycle is calculated with the following equation with the capital cost per unit energy in USD/kWh. The cost per cycle is expressed in USD/kWh [82]:

$$\textbf{Cost per Cycle} = \frac{\textbf{Capital Cost per Unit Energy}}{\textbf{Cycle Life}} \qquad (2.9)$$

If the energy losses during the cycle should be taken into account the cost per cycle is obtained with the following equation [82]. The equation should only be used for comparing the cost per cycle of different electrical storage devices.

$$\textbf{Cost per Cycle} = \frac{\textbf{Capital Cost per Unit Energy}}{\textbf{Cycle Life} \cdot \textbf{Efficiency}} \qquad \textbf{(2.10)}$$

The cost is a complex subject. The cost of the electrical storage device is not only the manufacturing cost of the electrical storage device. The cost can be broken down into the manufacturing cost, disposal cost, interest cost, operating cost, maintenance cost, insurance cost and replacement cost and other cost associated with the ownership of the electrical storage device. The cost of electrical storage device is not so straight forward. The cost of electrical storage device could drop, when the electrical storage device is manufactured in very large quantities. Furthermore the cost of electrical storage device could likewise drop, because the manufacturing of the electrical storage device is optimized. The cost of some electrical storage devices could decrease, when the electrical storage device is sized up. The cost of some electrical storage devices could likewise drop, because they are becoming more mature. Therefore the cost of electrical storage device is more variable than expected.

2.2.2 Electrical Energy Storage Technologies

Over time a large variety of electrical storage devices are developed based on different physical principles. Almost all electrical storage devices convert electrical energy in different forms of energy. An overview of different electrical storage devices based on different electrical energy storage technologies are presented in table 2.2. Each electrical energy storage technology is developed and based on a different form of energy.

Electrical Energy Storage Technologies	Form of Energy
Flywheels, Pumped Hydro and Compressed Air Energy Storage (CAES)	**Mechanical Energy**
Pumped Hydro and Compressed Air Energy Storage (CAES)	**Potential Energy**
Flywheels	**Kinetic Energy**
Superconducting Magnetic Energy Systems (SMES)	**Magnetic Energy**
Supercapacitors	**Electrical Energy**
Batteries	**Electrochemical Energy**
Hydrogen or other synthetic fuel	**(Thermo-)Chemical Energy**
Hot water, steam, ice, ceramics, molten salt, hot rocks and phase change materials	**Thermal Energy**

Table 2.2 The different electrical energy storage technologies with associated form of energy [1][23][24][25]

The electrical energy storage in nuclear energy is not considered in table 2.2, because this technology is not accessible. The energy form and the associated electrical energy storage technologies will be examined now more closely to determine the suitability for the energy transport or energy transfer by ship. The different electrical energy storage technologies are now explained.

Pumped Hydro Storage

The pumped hydro storage is one of the most utilized electrical energy storage technologies for long term energy storage. The electrical energy storage technology is based on the use of two large water reservoirs located on different heights. The electrical energy storage technology is illustrated in figure 2.1. The lower water reservoir collects the water from upper water reservoirs. During off-peak hours water from the lower reservoir is pumped to the upper reservoir. The water is stored till energy is required. During high energy demand the upper water reservoir provides the head to drive the hydropower turbines similar as a hydroelectric power plant. Pumped hydro storage systems are designed to deliver over 1000 MW. They are very cost-effective. The disadvantages of pumped hydro storage are long construction times, high construction costs, large amounts of land, long response times and mountainous relief. The pumped-hydro storage is not suitable for mobile applications. The characteristics of the pumped hydro storage are listed in table 2.3.

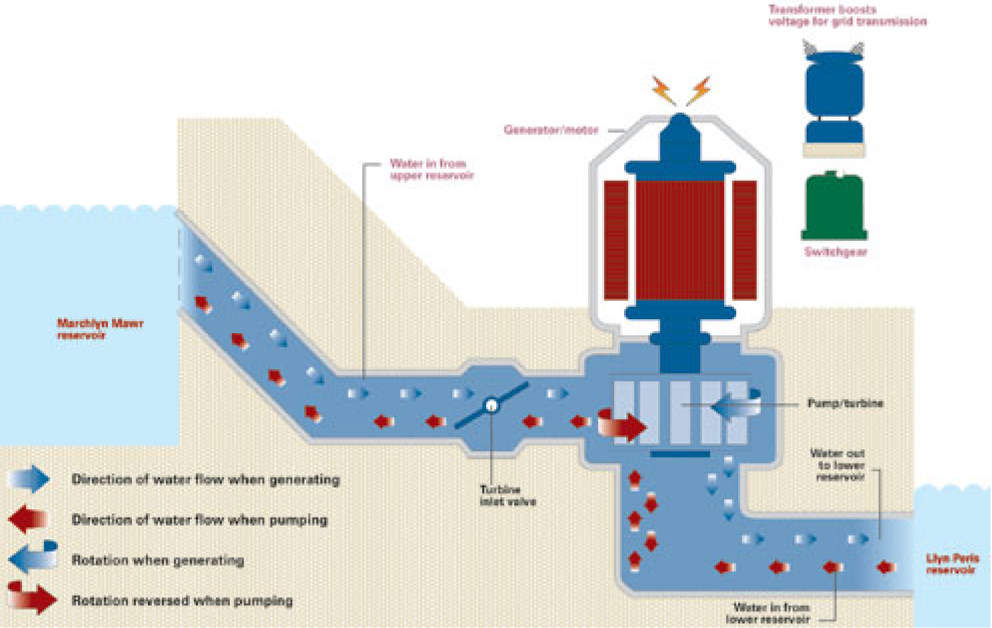

Figure 2.1 Pumped hydro storage [83]

Description	Characteristics
Power	**0.1 - 2.7 GW**
Energy	**10 - 100000 MWh**
Efficiency	**70 - 85%**
Discharge Time	**several hours**
Self-discharge	**no**
Cycle Life	**15000 - 30000**
Lifetime	**30 - 50 years**
Energy Density	**0.1 - 1.0 Wh/kg**
Capital Costs per Energy	**4.2 USD/kWh**
Capital Costs per Power	**720 - 2160 USD/kWh**

Table 2.3 The characteristics of the pumped hydro storage [25][83].

Compressed Air Energy Storage (CAES)

Compressed air energy storage is an electrical energy storage technology for long term energy storage, which converts electrical energy into pneumatic energy. The pneumatic energy is stored in a man-made storage tanks, man-made rock cavern, salt cavern, porous rock or empty gas field. There are two conceptual different types of storage reservoirs such as constant volume reservoirs and constant pressure reservoirs. The compressed air energy storage comes in different sizes. In very large CAES above 100 MW units the air is compressed by compressors in underground reservoirs, which is illustrated in figure 2.2. The air is compressed at constant pressure ranging 45 bar till 100 bar [24]. The compressed stored air in the CAES unit is used to drive the compressor of the gas turbine system, which generations the electricity. The compressed air is often mixed with natural gas in the gas turbine system to achieve higher efficiencies. The large CAES units are very cost-effective.
The other advantages are quick charging, quick discharging and very low self-discharge. Till now there are few large size units built in the world. The disadvantages of large scale CAES are the limited suitable locations with underground reservoirs and high construction costs. In general the large scale CAES is more expensive than pumped hydro storage.
The large scale CAES is not suitable for mobile applications, but compressed air storage systems are suitable for mobile applications. The compressed air storage (CAS) systems are based on compressing air in man-made storage tanks such as vessels and bottles. The CAS is a new development. The pneumatic energy of the compressed air in the pressure vessels can be recovered by a gas turbine system or an air engine or another system. The air engine is based on a piston engine. The air engine is developed by Guy Nègre. Other people such as Armando Regusci, Angelo Di Pietro and Chul-Seung Cho are also working on the air engine [26][124]. The energy density of the system depends on the maximum allowable pressure of the pressurized holding tank and the material of the pressurized holding tank. A pressurized holding tank of fiber-reinforced or superior steel has a higher energy density than a pressurized holding tank of normal steel. The current maximum pressure for CAS applications is around 250 bar. All bottles must comply with legal safety codes. In the future the energy density could increase, because the 700 bar carbon fiber bottle is under development [124]. The disadvantages of compressed air energy storage are medium efficiencies, variable power levels and safety concerns about ruptures of vessels.
The advantages of compressed air energy storage are long lifetimes of pressure vessels, very low self-discharge, very long cycle life, quick charging and low costs. The CAS is still in the research stage. The technology could be used to propel small vehicles. The characteristics of the compressed air energy storage are listed in table 2.4.

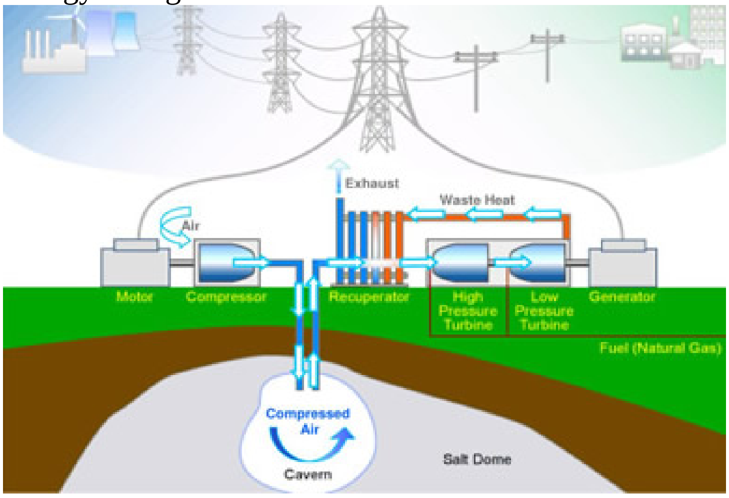

Figure 2.2 Compressed air energy storage (CAES) [84]

Description	Characteristics CAES	Characteristics CAS
Power	**0.1 - 1 GW**	**1 - 1000 kW**
Energy	**100 - 3000 MWh**	**1 kWh - 1 MWh**
Efficiency	**60 - 70%**	**40 - 73%**
Discharge Time	**several hours**	**several hours**
Self-discharge	**no**	**no**
Cycle Life	**10000 - 20000**	**10000 - 20000**
Lifetime	**30 years**	**25 years**
Energy Density by Volume	**4.17 kWh/m^3**	**3 - 50 kWh/m^3**
Energy Density by Mass	**-**	**3 - 50 Wh/kg**
Capital Costs per Energy	**40 - 80 USD/kWh**	**360 - 960 USD/kWh**
Capital Costs per Power	**500 - 1000 USD/kW**	**-**

Table 2.4 The characteristics of the compressed air energy system CAES [2][25][27][82]

Flywheel Energy Storage

The flywheel energy storage is a technology based on mechanical kinetic energy for short term energy storage such as several minutes. The inertial kinetic energy is stored in the rotating mass of a flywheel, which rotates at very high speeds. The speed is an indicator of the energy in the flywheel. During charging an electric motor/generator spins the mass to a higher speed and during discharging the motor/generator converts the kinetic energy into electricity. There are two flywheel groups namely the conventional steel flywheels and advanced flywheels. The advanced flywheels are made of fibre-reinforced plastics. They rotate at very high speeds in a vacuum enclosure with magnetic bearings. The advanced flywheels are illustrated in figure 2.3. The advanced flywheels are more expensive and they have higher energy densities. Manufacturers of flywheel energy storage systems are AFS Trinity, Hitec Power Protection, Active Power, Beacon Power, Powercorp, Pentadyne and Piller [82].

The advantages of flywheels are quick charging, quick discharging, high efficiency, high energy densities, very high cycle life, low maintenance and long lifetimes. In addition power and energy are not directly related and relative low costs. The disadvantages of flywheels are short energy storage times, very large stand-by losses, danger of explosion and susceptible for accelerations and motions. Flywheels are limited in power and energy size.

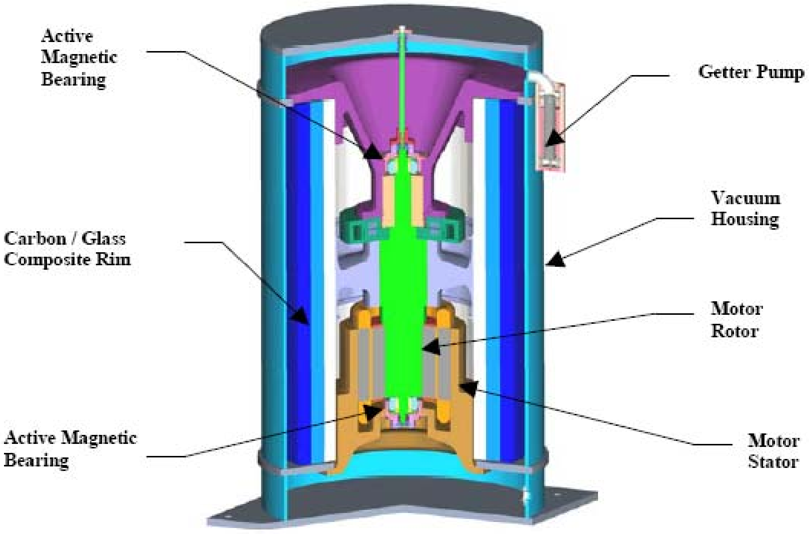

Figure 2.3 Flywheel energy storage [85]

Flywheels are suitable for mobile applications, especially for short term energy storage.
The characteristics of the flywheel energy storage are presented in table 2.5.

Description	Characteristics
Power	**1 - 100 kW**
Energy	**1 - 10 kWh**
Efficiency	**90 - 96%**
Discharge Time	**several minutes**
Self-discharge	**30 - 40%/hour**
Cycle Life	**5000 - 100000**
Lifetime	**30 years**
Energy Density by Volume	**5 - 210 kWh/m^3**
Energy Density by Mass	**5 - 130 Wh/kg**
Power Density	**200 - 1500 W/kg**
Capital Costs per Energy	**840 - 1200 USD/kWh**
Capital Costs per Power	**240 - 1200 USD/kW**

Table 2.5 The characteristics of the flywheel energy storage [25][27][82]

Superconducting Magnetic Energy Storage (SMES)

The superconducting magnetic energy storage (SMES) system is an electrical energy storage technology for short term energy storage, which converts electrical energy into magnetic energy. Electrical energy is stored in the very strong magnetic field of a coil. The coil is composed of superconducting wire. The superconducting magnetic energy storage system consists of cooling system, power electronics system, containment structure and a conductor coil of superconducting material. The superconducting magnetic energy storage system is shown in figure 2.4. The direct electric current in low temperature superconducting materials at very low temperatures has almost no resistance. The coil is cooled cryogenically.
The cooling requires energy. The SMES systems are still in research stage. The SMES systems find there application in use for power quality and voltage stability. The advantages of superconducting magnetic energy storage system are very high power, high efficiency, quick discharging and quick charging.

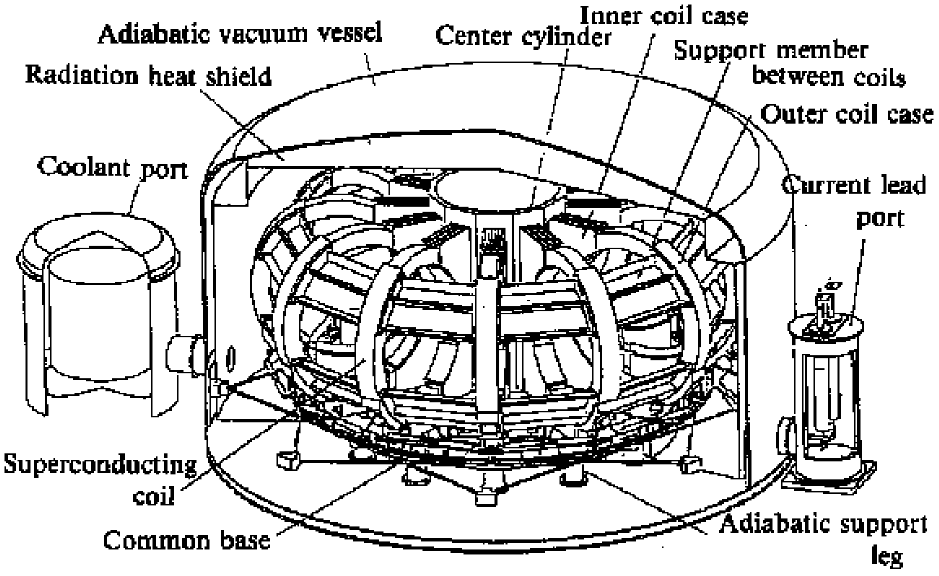

Figure 2.4 Superconducting Magnetic Energy Storage (SMES) system [86]

The disadvantages of superconducting magnetic energy storage system are low energy densities, parasitic losses and high costs. The technology is not interesting for mobile applications, because the cooling requires external energy and technology has low energy densities. The characteristics of the superconducting magnetic energy storage system are presented in table 2.6.

Description	Characteristics
Power	**10 - 5000 MW**
Energy	**1 kWh - 5000 MWh**
Efficiency	**95%**
Discharge Time	**several seconds**
Self-discharge	**no**
Cycle Life	**10000 - 100000**
Lifetime	**20 years**
Energy Density by Volume	**2 kWh/m^3**
Energy Density by Mass	**4 - 75 Wh/kg**
Power Density	**1000 - 100000 W/kg**
Capital Costs per Energy	**800 - 1800 USD/kWh**
Capital Costs per Power	**300 - 2000 USD/kW**

Table 2.6 The characteristics of the superconducting magnetic energy storage system [25][27][82]

Supercapacitor

The supercapacitor or ultra capacitor is a technology based on electrical energy for short term energy storage such as several hours. In fact, the supercapacitor is a capacitor.
The capabilities of supercapacitors are by two orders of magnitude greater than conventional capacitors. A conventional capacitor consists of two metal plates separated by a non-conducting layer so called dielectric. The capacitor is charged by direct current.
The conventional capacitor is limited in capacity, so consequently the supercapacitor or electrochemical capacitor was developed to have larger capacity. The electrochemical capacitor consists of two electrodes and electrolyte, which creates an electric double layer. The electric double layer is shown in figure 2.5. The electrodes are made with porous carbon material and the electrolyte is either aqueous or organic. The organic supercapacitor has higher energy density and it is more expensive. The manufacturers of supercapacitors are ESMA, NESS, SAFT, ELIT, PowerCache (Maxwell) and PowerSystem Co..
Presently electrochemical capacitors with higher energy densities are under development.
The advantages of supercapacitors are high cycle life, no maintenance, high cycle efficiency, long lifetime, very high power density and wide operating temperature. The disadvantages of supercapacitors are low energy densities, relative high costs, short term energy storage and the requirement of electronic control equipment. Supercapacitors are suitable for mobile applications, especially for short term energy storage such as energy storage during braking. The characteristics of the supercapacitors are listed in table 2.7.

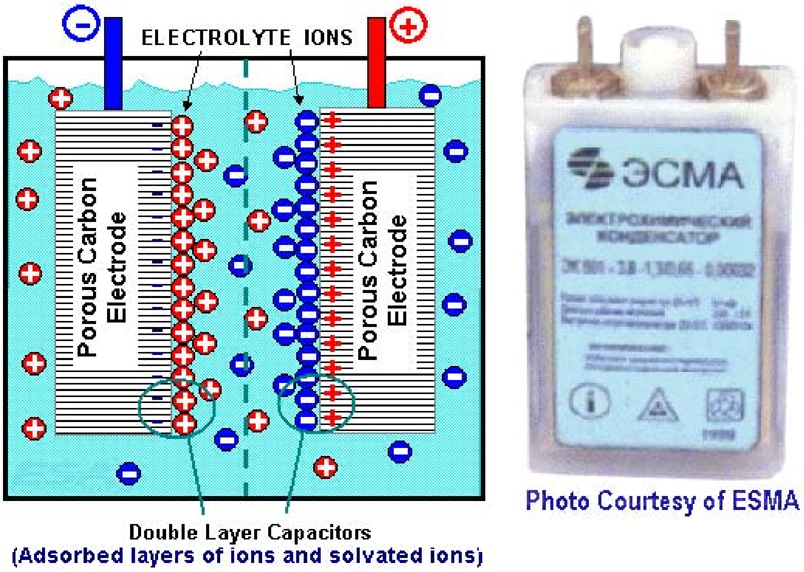

Figure 2.5 Supercapacitor [82]

Description	Characteristics
Power	**100 kW -10 MW**
Energy	**1 - 100 Wh**
Efficiency	**85 - 100%**
Discharge Time	**several seconds**
Self-discharge	**20 - 50%/month**
Cycle Life	**50.000 - 500.000**
Lifetime	**10 years**
Energy Density by Volume	**4 - 20 kWh/m^3**
Energy Density by Mass	**4 - 20 Wh/kg**
Power Density	**100 - 10000 W/kg**
Capital Costs per Energy	**60000 - 180000 USD/kWh**
Capital Costs per Power	**240 - 1200 USD/kW**

Table 2.7 The characteristics of the supercapacitor [25][27][82]

Batteries

The batteries are a technology based on electrochemical energy for short term and long term energy storage. The use of batteries is the most established and oldest way of storing electricity. Most batteries are used for small scale applications. The electrochemical energy storage can be categorized into batteries and fuel cells. The difference between the fuel cells and batteries is that fuel cells get the chemical energy from synthetic fuel, which comes from outside the fuel cell [27][125]. The fuel cells can be classified into two categories: normal fuel cells and metal fuel cells. This classification is based on what is oxidized at the anode.
In normal fuel cells such as SOFC and PEM the current is created by the removal of electrons from the hydrogen atoms. After that process hydrogen ion passes through the electrolyte and it reacts with the other chemical. The product of the reaction goes out the fuel cell.
By metal fuel cells the current is produced by oxidizing a metal atom such as aluminum or zinc. During oxidizing the metal ion goes through a liquid electrolyte. The batteries can be classified into primary type batteries and second type batteries [3].

All batteries and fuel cells have in common that they deliver direct current and they are based on electrochemical reactions. The direct current must often be converted to alternating current. The primary type batteries are not rechargeable, so they have one discharge. Secondary type batteries are designed to be recharged. The secondary type batteries are only suitable for energy storage. Batteries consist of two electrode systems suspended in electrolyte. The negative metal electrode or oxidizing electrode is called anode. The positive metal electrode is called cathode. During discharging the battery, electrochemical oxidation-reduction reactions take place at the two electrodes between the electrodes and the electrolyte, which creates a current through an external circuit. During recharging the battery, the electrochemical reactions are reversed. The most mature and known battery is the lead acid battery. Over time different secondary batteries are developed [3][4][25][27].
The most common secondary batteries are presented in table 2.8.
Special batteries are the high temperature batteries and the redox flow batteries.
The high temperature batteries are batteries, which work only at high temperatures.
The redox flow battery is a battery type, which consist of two or more electrolytes with dissolved electroactive parts. The electrolytes go through a power cell or battery stack to generate electricity. The advantages of batteries for electricity storage are very high efficiency, instantaneously constant power, reliable and low/medium costs.
The disadvantages of batteries for electricity storage are medium lifetimes, parasitic losses, medium cycle life and medium energy densities. Batteries are suitable for mobile applications. The characteristics of the batteries are listed in table 2.9. The batteries are likewise presented in Appendix F Batteries.

Figure 2.6 Batteries [87]

Battery	Efficiency (AC to AC)	Cycle Life	Energy density (Wh/kg)
Lead-acid	**75%**	**500-1500**	**25-40**
Ni/Cd	**65%**	**2500**	**10-60**
NaS	**70%**	**2500**	**100-200**
Li-Ion	**85%**	**1000-10000**	**100-200**
Zn/Br	**60%**	**2000**	**70-90**
V-redox	**70%**	**12000**	**15-20**
Metal/Air	**40%**	**100**	**100-500**

Table 2.8 Secondary type batteries [3][4][25][27][82]

Description	Characteristics
Power	**100 kW -10 MW**
Energy	**0.5 Wh - 500 MWh**
Efficiency	**70 - 90%**
Discharge Time	**several hours**
Self-discharge	**2 - 10%/month**
Cycle Life	**100 - 2000**
Lifetime	**10 years**
Energy Density by Volume	**30 - 500 kWh/m^3**
Energy Density by Mass	**30 - 500 Wh/kg**
Power Density	**75 - 300 W/kg**
Capital Costs per Energy	**100 - 2500 USD/kWh**
Capital Costs per Power	**50 - 4000 USD/kW**

Table 2.9 The characteristics of the batteries [3][4][25][27][82]

Synthetic Fuel

The synthetic fuel is a technology based on chemical energy or thermochemical energy for short term and long term. Synthetic fuels are not very different from oil fuels and natural gas. Most synthetic fuels are gases and liquids. The synthetic fuel is produced in a chemical reactor or/and electrolyzer with electrical energy from chemicals such as water, CO_2, waste and biomass. In chemical reactor or/and electrolyzer electrical energy is used to drive chemical reactions towards the production of synthetic fuel. In addition the synthetic fuel could also be produced with thermochemical or photochemical processes using concentrated solar energy. The synthetic fuel is the energy carrier. The synthetic fuel is normally stored in vessels or storage tanks. Some synthetic fuels may impose safety problems and storage problems. The energy in the synthetic fuel is recovered with a generator system.
The generator system converts the stored chemical energy back to electrical energy.
The generator system may consist of a fuel cell system or an internal combustion engine with alternator. The fuel cell system has a higher conversion efficiency compared with internal combustion systems. After the conversion the residue of the synthetic fuel could be recycled to produce again synthetic fuel. The size of production, storage and generator system are independent of each other. The use of synthetic fuel depends on safety, energy density, storability, transportability, costs, pollution of the environment and other factors.
Most synthetic fuels are hydrogen related fuels. The energy densities of some synthetic fuels are presented in table 2.10.

Synthetic Fuel	Density kg/m^3	Energy Density Wh/kg	kWh/m^3
Methanol	**791**	**6300**	**4983**
Ethanol	**789**	**7850**	**6100**
Dimethyl Ether	**668**	**8000**	**5344**
Sodium Borohydride	**1030**	**7100**	**7314**
Ammonia (liquid)	**680**	**6240**	**4243**
Hydrogen (gas)	**0.08988**	**39700**	**3.568**

Table 2.10 The energy densities of synthetic fuels [5][6][125][126]

The main problem with some synthetic fuels is the harmful emissions to environment. The advantages of synthetic fuel for electricity storage are very high energy density, good transportability and large operating temperature range. The disadvantages of synthetic fuel for electricity storage are very low efficiency (in the range of 10% - 50%), low power density and only "one cycle". It should be noted that the mentioned advantages and disadvantages do not apply to all synthetic fuels. Synthetic fuels are very good suitable for mobile applications due to very high energy density. The characteristics of the synthetic fuel for electricity storage are listed in table 2.11.

Description	Characteristics
Power	**1 kW - 1000 MW**
Energy	**0.1 - 1000 MWh**
Efficiency	**10 - 50%**
Discharge Time	**several hours**
Self-discharge	**no**
Cycle Life	**1**
Lifetime	**20 - 30 years**
Energy Density by Volume	**1000 - 7314 kWh/m^3**
Energy Density by Mass	**1000 - 38890 Wh/kg**
Power Density	**100 - 1400 kW/kg**
Capital Costs per Energy	**0.05 - 0.50 USD/kWh**
Capital Costs per Power	**500 - 2000 USD/kW**

Table 2.11 The synthetic fuel for electricity storage [1][2][3][25]

Thermal Energy Storage

The thermal energy storage (TES) is an electrical energy storage technology based on thermal energy for short term energy storage such as several hours. Some thermal energy storage systems store thermal energy for long term. Thermal energy storage system consists of a storage medium, which is a solid or a fluid. The solid or fluid is often stored in insulated containers. The thermal storage systems range from low temperatures to high temperatures. Low temperature thermal storage systems have a temperature ranging from -10 ºC till 150 ºC and these low temperature systems are used for HVAC. Medium temperature thermal storage systems have a temperature ranging from 150 ºC till 500 ºC. These systems are applied for thermo solar storage and industrial processes. High temperature thermal storage systems have a temperature above 500 ºC. High temperature thermal storage systems are used for electricity storage and industrial processes. In these systems thermal energy is mainly recovered as heat. The recovered heat could be utilized in industrial processes or in heat engines. The heat engines could be based on steam Rankine cycle or other heat engine cycles. The mechanical energy of heat engines is converted to electricity with the assistance of generators. The heat for thermal energy storage is created by electrical resistance heating. The electrical resistance heats the storage medium (refractory elements) above 500 ºC. The thermal storage system for electricity storage is illustrated in figure 2.7. The thermal storage system consists of an electric oven, an insulated tank with storage medium or refractory elements, a regenerator, a turbine and an alternator. The thermal storage system for electricity storage is not yet constructed in the world. The electricity storage by this way has a low efficiency. Thermal energy storage is best suitable to store only heat (or cold).

Thermal energy storage can be based on three main storage mechanisms [1]:

1. Latent heat storage, based on the energy associated with a change of phase for the storage medium (melting, evaporation or structural change)
2. Sensible heat storage, based on the heat capacity of the storage medium
3. Physicochemical reaction heat storage, based on bond energy

The energy density of thermal energy storage systems depends on the material, storage mechanism, temperature level and other factors. The energy densities of different thermal energy storage systems are listed in table 2.12. The main problems with thermal energy storage systems are the heat transfer from and to the thermal energy storage system and the heat loss to the environment. The heat loss is influenced by the surface area of the insulated container, the time, the temperature level and the properties of the container. The containers for thermal energy storage are normally steel vessels, pre-stressed concrete pressure vessels and pre-stressed cast-iron vessels. The well-known thermal energy storage systems have the following storage mediums such as pressurized water, ice, concrete, thermal oil, molten salt, salt and eutectic mixtures. The advantages of thermal energy storage for electricity storage are very high cycle life, low maintenance, long lifetimes and relative low costs.
The disadvantages of thermal energy storage for electricity storage are low efficiency, high self-discharge, low power density and susceptible for surrounding temperature. Thermal energy storage could be used for mobile applications. The characteristics of the thermal energy storage are presented in table 2.13.

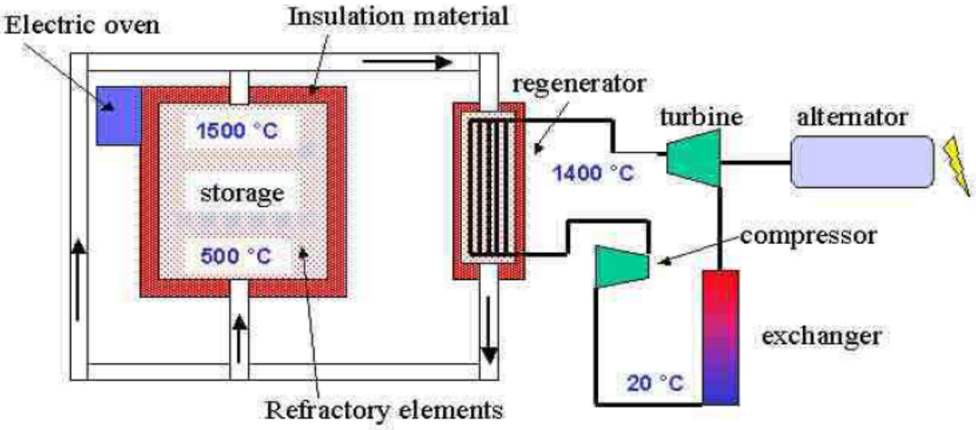

Figure 2.7 Thermal energy storage system for electricity storage [27]

Working Body	Storage Mechanism	Working Temperature °C	Energy Density	
			Wh/kg	kWh/m^3
Water in steel tank	**Heating**	**500**	**611.11**	**611.11**
Hot rocks	**Heating**	**20 - 100**	**11.11**	**27.78**
Iron	**Heating**	**20 - 350**	**5.83**	**50.0**
Ice	**Phase change**	**0**	**93.1**	**91.7**
Paraffin	**Phase change**	**55**	**47.2**	**38.9**
Salt hydrates	**Phase change**	**30-70**	**55.6**	**83.3**
Water	**Phase change**	**100**	**630.6**	**630.6**
Lithium hydride	**Phase change**	**686**	**1305.6**	**1305.6**
Lithium fluoride	**Phase change**	**850**	**305.6**	**758.3**

Table 2.12 The energy densities of different thermal energy storage systems [1]

Description	Characteristics
Power	**100 kW -100 MW**
Energy	**1 kWh-1000 MWh**
Efficiency	**50 - 60%**
Discharge Time	**several hours**
Self-discharge	**-**
Cycle Life	**10000 - 20000**
Lifetime	**20 years**
Energy Density by Volume	**25 - 250 kWh/m^3**
Energy Density by Mass	**30 - 40 Wh/kg**
Power Density	**3 - 4 W/kg**
Capital Costs per Energy	**120 USD/kWh**
Capital Costs per Power	**1200 USD/kW**

Table 2.13 The characteristics of thermal energy storage for electricity [1][27]

2.2.3 Electrical Energy Storage Technologies Selection

The investigation of the different electrical energy storage technologies is carried out so far has mainly been focused on the technical and economical performances of the electrical energy storage technology. Nevertheless, the appropriate electrical energy storage technologies should be chosen from the discussed electrical energy storage technologies.
The selection of the appropriate electrical energy storage technologies depends strongly on the special requirements of the application. In this case the application is the energy transport by ship, which is an energy management application.
The requirement for the application is defined as follows:

- long term storage (from 3 days till a month)
- long lifetime
- long cycle life (from 400 cycles till 2000 cycles)
- high energy density
- large scale energy storage (comparable with load leveling)
- low costs
- high power density
- suitable for mobile application
- off-grid application

The requirements such as long term storage, high energy density, suitable for mobile application and off-grid application are critical. The most appropriate electrical energy storage technologies are selected with an approximate comparison. The approximate comparison knows only three levels: better (+) or equal (=) or less (-). The method checks for each specification whether the electrical energy storage technologies meets the required specification. In this manner the strong points and weak points of each electrical energy storage technologies for energy transport by ship will be clarified. The approximate comparison between different electrical energy storage technologies is presented in table 2.14.

Specifications	**Long Term Storage**	**High Energy Density**	**Suitable for Mobile Application**	**Off-grid Application**	**Score**
Pumped Hydro Storage	+	-	-	+	**0**
Compressed Air Energy Storage (CAES)	+	-	-	+	**0**
Compressed Air Storage (CAS)	+	=	+	+	**+3**
Flywheel Energy Storage	-	=	+	+	**+1**
Superconducting Magnetic Energy Storage (SMES)	-	-	-	-	**-4**
Supercapacitor	-	-	+	+	**0**
Batteries	+	=	+	+	**+3**
Synthetic Fuel	+	+	+	+	**+4**
Thermal Energy Storage	-	=	+	+	**+1**

Table 2.14 The approximate comparison of electrical energy storage technologies

The result of the approximate comparison is that compressed air storage (CAS), batteries and synthetic fuel are identified as most suitable solutions from the approximate comparison.
The most attractive solution according to the approximate comparison is synthetic fuel.
The energy storage technologies flywheel energy storage, superconducting magnetic energy storage (SMES), supercapacitor and thermal energy storage are not suitable for energy transport by ship, because they do not meet the criterion of long term energy storage and off-grid application. The large scale compressed air energy storage (CAES) and pumped hydro storage have special site requirements and they are not suited for the mobile application, so consequently they cannot be used for the bulk electricity sea transport.
The resulting electrical energy storage technologies are compressed air storage (CAS), batteries and synthetic fuel. The electrical energy storage technologies compressed air storage (CAS) and batteries are both electrical storage devices. However the batteries are a better electrical energy storage technology than compressed air storage (CAS), because compressed air storage (CAS) has variable power levels and lower efficiencies. Perhaps the efficiency of compressed air storage could improve in the future. Therefore the electrical energy storage technologies batteries and synthetic fuel are investigated for bulk electricity sea transport.

2.3 Most Attractive Electricity Transport Concepts

In the previous text the most attractive concepts for long distance bulk electricity sea transport are identified. In this report the three electricity transport concepts will be developed to investigate the technical, energetic and economical performances. Hereafter the electrical energy transport concepts will be compared to determine the most energy efficient and most cost efficient manner to achieve bulk electricity transport across the sea. The three electricity transport concepts are summarized below:

1. **Submarine Electric Power Transmission** The energy transmission across the sea is accomplished with high voltage electrical cables between power plants and electricity consumers.

2. **Battery Ship** The energy transport across the sea is accomplished by ship, which transports batteries between power plants and electricity consumers. The batteries store the electrical energy.

3. **Synthetic Fuel** The energy transport across the sea is accomplished by ship, which transports synthetic fuel from power plants to the electricity consumers. The electricity is converted into synthetic fuel close by the power plants. Afterwards synthetic fuel is converted into electricity near the electricity consumers.

These bulk electricity transport concepts will serve power plants. The power plants will mainly be renewable energy power plants, because the renewable energy power plants are connected to the location of the renewable energy source. Another characteristic feature of renewable energy power plants is that renewable energy power plants are often intermittent energy sources. The other power plants such as fossil fuel power plants, waste burning power plants, biomass power plants and nuclear power plants are not connected to the location of the energy source, because the fuel for those power plants is transported to the power plants.
The renewable energy power plants could be onshore power plants or offshore power plants. The onshore renewable energy power plants are power plants such as wind turbines, geothermal power plants, hydroelectric power plants, solar thermal power plants, photovoltaic power plants and salt-powered osmotic power plants. The offshore renewable energy power plants are power plants such as offshore wind turbines, floating wind turbines, floating geothermal power plants, ocean thermal energy conversion (OTEC) power plants, wave power plants, tidal power plants and submerged current turbines.
In this case the renewable energy power plants are situated in Iceland. The power plants are hydroelectric power plants and geothermal power plants. The cost per MWh of power plants in Iceland is estimated 30 USD/MWh [132]. The cost per MWh of power plants is defined as the levelized cost of produced electricity from the power plants in site A. The other important electricity costs are the cost per MWh of delivered energy and the cost per MWh for energy transport. The cost per MWh of delivered energy is defined as the total costs for bulk electricity sea transport and power generation during the whole project period divided by the delivered energy in site B during the whole project period. Furthermore it should be noted that the project period for all electricity transport concepts is 30 years. The cost per MWh for energy transport is the difference between the cost per MWh of delivered energy and the cost per MWh of power plants. The electricity from power plants in Iceland will be transported to the electric power consuming areas Scotland and mainland Europe. The distance between Iceland and Scotland is approximately 500 nautical miles. Furthermore the distance between Iceland and European mainland is approximately 1000 nautical miles.

3 Submarine Electric Power Transmission Overview

In this chapter the bulk electricity transport with submarine power cables across the sea is investigated.

3.1 Electric Power Transmission

Nowadays all electrical energy is transported with electrical power cables.
Besides that the electric power transmission with submarine electrical power cables is currently the only way to deliver electrical energy across the sea. The electrical power transmission enables the electric power transmission from power plants to the consumers.
In general the electric power transmission from power plant to substation is carried out with high voltage electrical power cables, because the distance between power plant and substation is normally a long distance. Besides that the power losses in the cables are very low at high voltage levels. The location of a power plant is determined by the issues associated with fuel logistics, energy demand and cooling. The electric power transmission from substation to the houses is done with low voltage electrical power cables. The low voltage levels are used due to safety reasons and short distances. In the world electricity is utilized, because it is applicable for most consumer appliances such as lighting, computers, motors, etc and it is a relative safe flexible energy carrier. Furthermore electricity requires no oxygen and it creates no emissions. The electricity allows easy energy distribution with minimum power losses. The main drawback of electricity is that electrical energy is difficult to store. The first power transmission lines started with direct current in 1882, because voltage conversion was only accomplished with rotating DC machines [127]. These power transmission lines were not suitable for long distance transmission. The high voltage alternating current transmission system was presented by Nikola Tesla in 1888. The high voltage alternating current transmission system is composed of two AC transformers and a three phase transmission line. The three phase transmission line consists of three power cables. The high voltage is accomplished with AC high voltage transformers, which convert the low voltage from generators to high voltage. The transformers convert likewise the high voltage back to low voltage. Today European grids are divided in the following four groups of voltage levels [28]:

- Extra High Voltage 750 kV to 220 kV
- High Voltage 150 kV to 60 kV
- Medium Voltage 50 kV to 10 kV
- Low Voltage 400 V to 200 V

The benefit of AC transformers is low power losses. In addition the transformers require little maintenance. The benefit of high voltage levels are smaller currents, which result in small ohmic losses and less heat. The first AC three phase power transmission lines were introduced in Frankfurt in 1891. The first working transmission line was a 25 kV 175 km long transmission line between Frankfurt, Neckar and Frankfurt in Germany [127].
The next development was the disc insulator. The disc insulator has replaced the porcelain pin-and-sleeve insulator. The disc insulator allows higher voltage levels. Till that time the high voltage level was limited till 40 kV. In the 20th century the high voltage levels increased from 110 kV till 1200 kV. Present day high voltage levels are 110 kV and above. Moreover in the 20th century national grids were realized. These grids are based on AC technology. During begin of 20th century three phase AC technology was considered as the only feasible technology for electric power transmission lines.

Nevertheless the AC technology has the following disadvantages [7][44][127][128]:

- The reactive currents cause additional losses in the power transmission lines, so the distance of AC transmission lines are limited.
- The three phase power transmission lines are composed of three power cables, which make the transmission lines for long distances expensive.
- The synchronisation of the grids requires the same grid frequency, the same voltage level, the same phase sequence and the same phase angle.

As a solution to those problems associated with the AC technology the high voltage direct current HVDC technology was developed. The HVDC transmission system is composed of two converter stations and one HVDC transmission line. The converter stations consist of rectifiers and AC transformers. The HVDC transmission line consists of one or two power cables. The first HVDC system was constructed in Berlin in 1945 [128]. The 200 kV HVDC underground transmission line was 115 km long. The alternating current was converted into high voltage direct current by means of mercury arc valves. The first converters were line-commutated current sourced converters. The first HVDC link with a submarine power cable was a 20 MW transmission line between the island of Gotland and Sweden in 1954 [129]. Over time the mercury arc valves were replaced with high power electronic semiconductor devices such as thyristors and insulated gate bipolar transistors.
The IGBTs with high power ratings find their application in self-commutated voltage sourced converters (VSC). The gate turn-off thyristors are likewise utilized in self-commutated voltage sourced converters. The operation of the voltage sourced converters is achieved by pulse width modulation (PWM), so there is no need for AC commutation voltage. The electricity converters based on voltage sourced converters have the following advantages [33]:

- The voltage sourced converters have smaller footprint and compacter design
- The voltage sourced converters have lower costs
- The voltage sourced converters have four-quadrant operation capability
- The voltage sourced converters have black-start capability
- The voltage sourced converters are self-commutated, so the electricity converters are capable to convert electrical power from an isolated DC voltage source

Besides the advantages the electricity converters based on voltage sourced converters have the drawback of higher energy losses due to the switching losses. The self-commutated voltage sourced converters are mainly utilized for offshore wind farms, offshore oil and gas platforms and subsea equipment. These offshore platforms and subsea equipment get their electrical energy from the shore. In general the HVDC VSC system is used for short distances and low power ratings. The HVDC VSC system is known under the names HVDC PLUS (Power Link Universal System) and HVDC Light [127][128]. The self-commutated voltage sourced converters are not preferred for long distance HVDC systems between two grids.
These HVDC systems use line-commutated current sourced converters with thyristor valves. The first thyristor valves were oil-immersed thyristors with electromagnetic firing systems. These thyristor were connected in parallel and in serie. The thyristor valves were improved over time. The cooling of thyristor valves has changed from air-insulated air-cooled thyristor valves to air-insulated water-cooled thyristor valves. Furthermore the power ratings of thyristors have been sized up. This development has reduced the number of thyristor valves in the converter station. The introduction of light-triggered thyristors has also reduced the number of thyristors [44].

The HVDC power transmission line has the following advantages over the HVAC power transmission line [7][44][46][127][128]:

- Beyond 50 km HVDC power transmission line has lower investment costs, especially for submarine power transmission line across the sea. The costs of two DC cables instead of three AC cables compensate the costs of converter stations.
- The HVDC power transmission line has no additional power losses due to reactive power, so the reactive power does not reduce the transmission capability. Therefore the length of HVDC power transmission is not limited by reactive power.
- The power cables of HVDC transmission line has no skin effect, so the entire cross section of the power cables conduct the current and less insulation is required.
- The HVDC power transmission line connects two grids with different frequencies.
- The HVDC power transmission line allows accurate rapid control of power flow in quantity and in both direction, so the HVDC transmission link is more stable.
- The cost of wiring, pylons and ground of HVDC overhead transmission line are lower than HVAC overhead transmission line.

Summarized the HVDC system is the most attractive power transmission technology for long distances and high power ratings due to the mentioned economical and technical reasons. Presently the longest HVDC link with submarine power cables in the world is the 580 km 700 MW link between Eemshaven in Netherlands and Fedafjord in Norway. The operating voltage of the HVDC NorNed is ±450 kV [45][129]. The engineering companies ABB, Siemens and Alstom design and install HVDC systems everywhere in the world.

3.2 Configurations

There are several HVDC configurations to make a DC circuit of a HVDC link complete. The different configurations for HVDC schemes are presented below [7][29][44][66][67][127][128]:

- Back-to-Back
- Monopole with earth return
- Monopole with metallic return
- Bipole with earth return
- Bipole with metallic return
- Tripole

The different configurations will be now discussed in detail, except the tripole configuration. The tripole configuration is a HVAC configuration, but the configuration is utilized in a different manner. The tripole configuration is not yet applied [128].
Most submarine power transmission lines have monopolar and bipolar configurations.
The different configurations for HVDC schemes allow bi-directional power flow.

3.2.1 Back-to-Back

The back-to-back configuration is a station with the inverter and rectifier located at the same location. The back-to-back scheme is illustrated in figure 3.1. The conductor between the inverter and the rectifier is limited to a few metres. The HVDC back-to-back station is used for connection between two adjacent large AC grids with different grid frequencies, different phase sequences or different phase angles.

3.2.2 Monopole with Earth Return

The monopole with earth return configuration is a monopolar configuration.
The monopole with earth return configuration consists of one DC power cable between two converter stations. The two converter stations are connected to the earth potential with earth electrodes. The monopole with earth return is illustrated in figure 3.1. The current flows from one converter station through the single DC power cable to the other converter station.
The current flows back via the earth/sea electrodes in the earth. The benefit of monopole with earth return path is very low costs for the power transmission line. The main drawback of monopole with earth return path is larger effect of faults and lower availability. The monopole with earth return configuration is used for very long distance transmission lines, especially very long submarine transmission lines. Sometimes the electrodes cannot be used due to environmental conditions. The earth/sea electrodes may affect the water chemistry and magnetic navigational equipment of ships. In that case monopole with metallic return configuration is utilized.

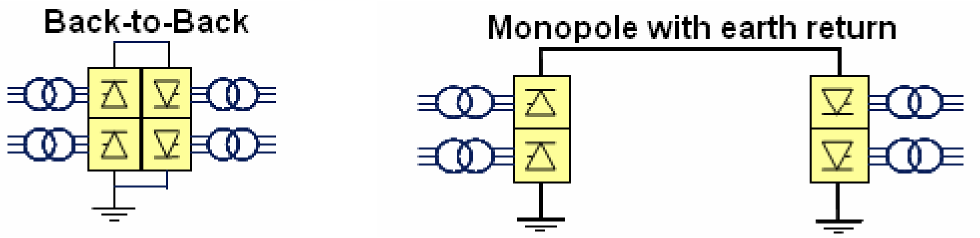

Figure 3.1 The back-to-back and monopole with earth return [66]

3.2.3 Monopole with Metallic Return

The monopole with metallic return configuration is a monopolar configuration. The monopole with metallic return configuration consists of two DC power cables between two converter stations. One converter station is connected to the earth potential with earth electrodes. The monopole with metallic return is illustrated in figure 3.2. The current flows from one converter station through high voltage direct current power cable to the other converter station. The current flows back via a cheap non-insulated low voltage direct current power cable. The benefit of monopole with metallic return is higher availability. Nevertheless the power transmission line is more expensive than the monopole with earth return.

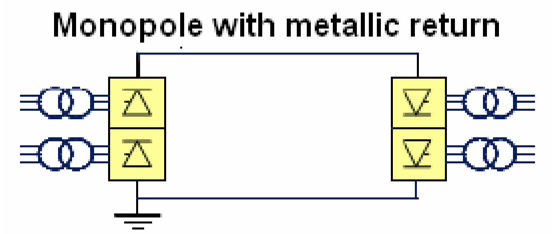

Figure 3.2 The monopole with metallic return [66]

3.2.4 Bipole with Earth Return

The bipole with earth return configuration is a bipolar configuration. The bipole with earth return is the most common bipolar configuration. The bipole with metallic return configuration consists of two HVDC power cables between two converter stations.
Both converter stations are connected to the earth potential with earth electrodes. The bipole with earth return is illustrated in figure 3.3. The first HVDC power cable operates at positive potential and the second HVDC power cable operates at negative potential. Both power cables have reference to the ground. In the case that the two both cables have the same polarity, the configuration is homopolar. The current flows from one converter station through two HVDC power cables to the other converter station. A small unbalance current flows back via the earth/sea electrodes in the earth. The advantages of the bipolar configuration are higher transmission capacity, higher energy availability, half rate transmission capacity during maintenance or power outage of one cable, lower power losses and reduced costs of HVDC power cables.

3.2.5 Bipole with Metallic Return

The bipole with metallic return configuration is likewise a bipolar configuration. The bipole with metallic return configuration consists of two HVDC power cables and one low cheap non-insulated low voltage direct current power cable between the two converter stations.
Both converter stations are connected with each other via the non-insulated low voltage direct current power cable. The bipole with metallic return is illustrated in figure 3.3. The current flows from one converter station through two HVDC power cables to the other converter station. A small unbalance current flows back via the non-insulated low voltage direct current power cable. The bipole with metallic return configuration is mainly used for short distances.

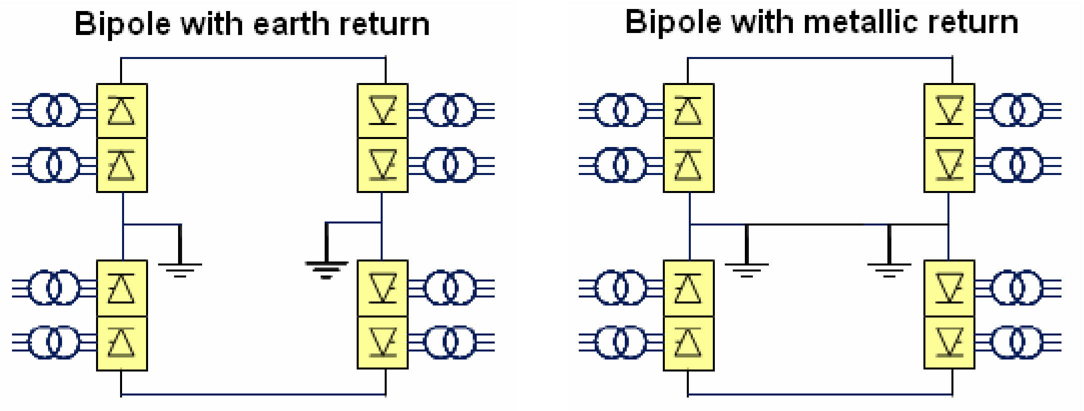

Figure 3.3 The bipole with earth return and the bipole with metallic return [66]

3.2.6 Bipole without Return

The bipole without return configuration is also a bipolar configuration. The bipole with metallic return configuration consists of two HVDC power cables between two converter stations. One converter station is connected to the earth potential with earth electrodes. The bipole without return is illustrated in figure 3.4. The current flows from one converter station through two HVDC power cables to the other converter station. The bipole without return configuration is rarely used.

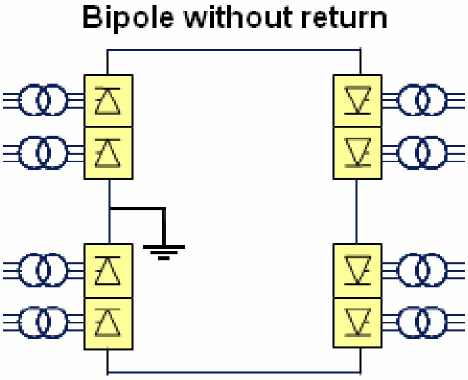

Figure 3.4 The bipole without return [66]

3.3 Power Transmission Cable

The power transmission cable is an essential part of the power transmission line. The power transmission cable is build up from conductor and insulation. The insulation, conductor, power rating and electric field requirements determine the design of the power transmission line. The insulation is the most critical part of the power transmission cable. The voltage level of the power transmission cable depends on the insulation design [44]. The insulation design of DC power transmission cables is better than the insulation design of AC power transmission cables. The insulation of submarine power cable is superior to the normal overhead power cable due to the environmental conditions in the seabed. In addition the mechanical strength and the fatigue of submarine cable are superior to the normal overhead power cable, because the submarine cable must withstand the tensional loads and the torsional loads during installation, operation and retrieval. Other cable design considerations are protection against chafe, corrosion, thermal conductivity and heat dissipation of the submarine cable. The different type power cables for submarine power transmission lines are listed below:

- Oil-filled Cable
- Solid Dielectric Cable
- Mass Impregnated Cable
- Mass Impregnated Cable with Integrated Return Conductor
- PPLP Solid Cable
- Gas Insulated Line
- High Temperature Superconducting (HTS) Cable

The mass impregnated cables and oil filled cables were the first high voltage submarine power cables. Today oil filled cables and mass impregnated cables are replaced by lapped thin film insulation cables and XPLE cables. In the future the submarine power cables might exist of gas insulated lines/cables and high temperature superconductivity power (HTS) cables. The manufactures of power cables are Pirelli Energy Cables, NKT Cables, ABB, Sumitumo Electric Industries, Hitachi Cable, Furukawa, Southwire, LG Cables, Nexans, JDR Cable Systems, Prysmian Cables & Systems and Condumex [28][67][88].

3.3.1 Oil-filled Cable

There are different type oil-filled cables [44][46][89]. The different type oil-filled cables are high pressure pipe-type fluid-filled cable, high pressure pipe-type gas-filled cable and low pressure oil-filled cable. All power cables are covered by oil impregnated paper. The oil-filled cables are applicable for HVAC and HVDC transmission lines. The high pressure pipe-type fluid-filled cable and high pressure pipe-type gas-filled cable are rarely used as submarine power cable, because they are complex to install and they require pressurization systems. The low pressure oil-filled cable or self contained fluid-filled cable was one of the first submarine power cables. The low pressure oil-filled cable is shown in figure 3.5. The conductor of low pressure oil-filled cable is manufactured of the material copper. The layers of copper are stranded around a longitudinal duct. The longitudinal duct enables low viscosity oil flow along the cable. The conductor is covered by oil impregnated paper insulation. The remaining insulation equals to the insulation of mass impregnated cables. The disadvantages of oil-filled cable are the requirement of pressurization system, risk of oil leakage, oil refreshing, requirement for flat trench and limited length. The length of oil-filled cable is limited up to 100 km. Currently the maximal voltage of oil-filled cables is 600 kV. The oil-filled cable is applicable in great water depths.

Figure 3.5 The self contained fluid-filled power cable [67]

3.3.2 Solid Dielectric Cable

The solid dielectric power cables are referred as XLPE power cables [28][44][46][89].
The conductor of solid dielectric cable is likewise made of copper. The insulation of the solid dielectric power cable is normally extruded cross-linked polyethylene (XLPE) or ethylene-propylene rubber (EPR). The cable is hermetically sealed with a lead or aluminium sheath with extruded polyethylene or polyvinyl chloride jacket. The jacket protects the XLPE cable from water penetration and moisture. The XLPE power cable is illustrated in figure 3.6.
The solid dielectric cables are applicable for HVAC and HVDC transmission lines. Most dielectric solid cables are used up to the high voltages of 132 kV.
The dielectric solid cables for extra high voltage are under development. Today XLPE cables are utilized for umbilicals for offshore oil platforms and for offshore wind farms.
The benefits of XLPE cables are lightness, strength, flexibility, low costs, lower power losses and lower maintenance costs. The main drawback of XLPE cables is the sensitivity to quick voltage reversal.

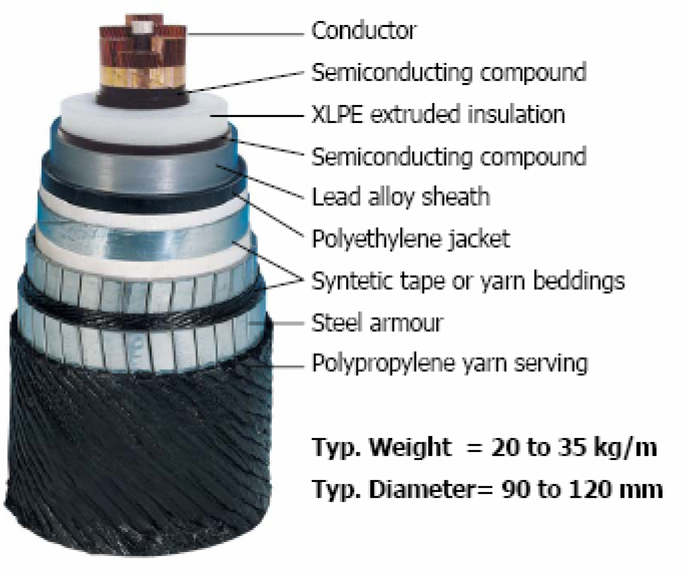

Figure 3.6 The XLPE power cable [67]

3.3.3 Mass Impregnated Cable

The mass impregnated cable is one of the most utilized power cable [44].
The conductor is manufactured of the material copper. The layers of copper are stranded around a central circular rod. Around the copper conductor oil and resin-impregnated papers are applied. The surface of conductor is covered by the carbon papers. Over the paper insulation a conductive layer of metallized and carbon papers are applied.
The impregnated cable is hermetically sealed lead sheath with extruded polyethylene jacket. The jacket protects the fully impregnated cable from water penetration and moisture.
The mass impregnated power cable is illustrated in figure 3.7. The power cable is reinforced with galvanized steel tapes to avoid torsional stress. The steel tapes are protected with a polypropylene string and galvanized steel wire armour. Currently the maximal voltage of mass impregnated cables is 500 kV. The maximal transmission capacity of mass impregnated cables is 800 MW. The transmission capacity is limited by the temperature of the conductor. The maximal water depth of the mass impregnated cable is 1000 m. Furthermore the transmission lengths of mass impregnated cables are almost unlimited.

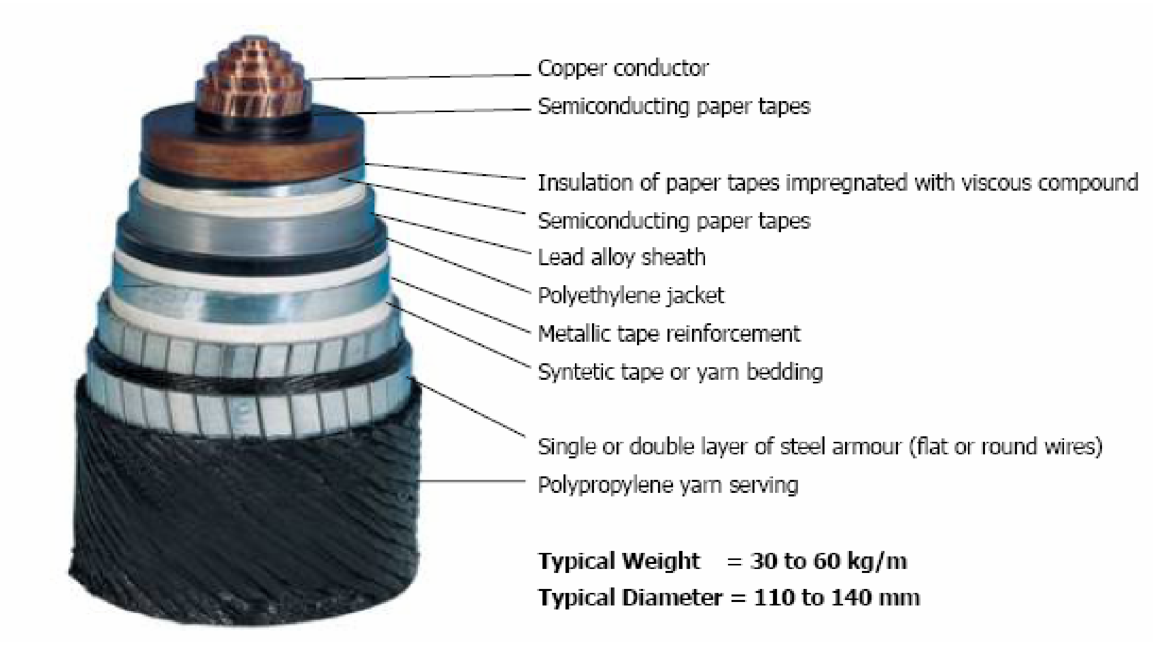

Figure 3.7 The mass impregnated power cable [67]

3.3.4 Mass Impregnated Cable with Integrated Return Conductor

The mass impregnated cable with integrated return conductor is a traditional mass-impregnated cable with the return conductor [44]. Around the lead sheath the return conductor is applied concentrically. On the outside of the return conductor insulation balance armour is used. The balanced armour is made from flat steel wire layer. The mass impregnated cable with integrated return conductor is developed for monopolar transmission lines. The maximal voltage is 250 kV. The maximal power is 250 MW. In the future the power transmission capacity and voltage could increase.

3.3.5 PPLP Solid Cable

The PPLP solid cables are similar as the mass impregnated cables, except the PPLP solid cables use non-impregnated polypropylene laminated paper as insulation material [44][47]. The lapped non-impregnated thin PP film replaces mainly the resin-impregnated paper. The polypropylene laminated paper is illustrated in figure 3.8.

The advantages of PPLP solid cables are higher allowable operating temperature of the conductor, higher voltage and power ratings. In addition the PPLP solid cables are more compact than mass impregnated cables. Currently the maximal voltage of PPLP solid cables is 800 kV. The PPLP solid cable is suitable for large power, very long and deep water submarine cables. The PPLP solid cables are not yet applied in submarine HVDC links.

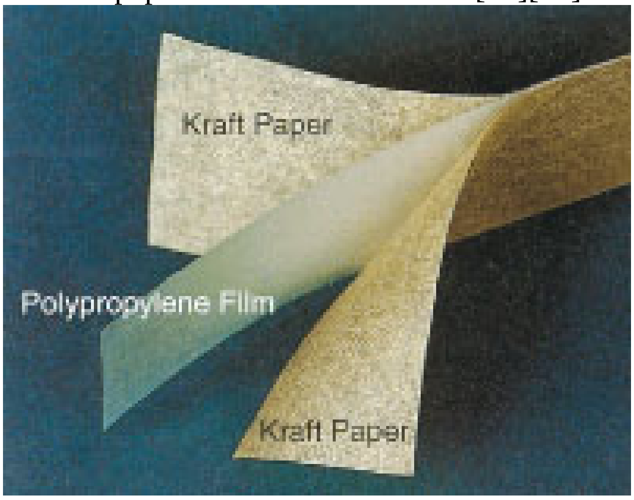

Figure 3.8 Polypropylene Laminated Paper [90]

3.3.6 Gas Insulated Line

The gas insulated line is built from an aluminium tube [28]. In the middle of the aluminium tube lays the conductor. The conductor is held in place by regular spacers. The tube is filled up with insulating greenhouse gas SF_6 and insulating gas nitrogen. The gas mixture is pressured in the tube. The aluminium tube is protected with anticorrosion coating.
The advantages of gas insulated line are low power losses, very high transmission capacity, very low electromagnetic field and low maintenance costs. The disadvantages of gas insulated line are short distances, higher costs and complex installation. The gas insulation line is installed with pipe laying techniques. The gas insulation line is interesting for underground power transmission lines in urban areas. Today the maximal voltage of gas insulated lines is 550 kV and the maximal transmission capacity of gas insulated lines is 2000 MW.
The maximal voltage and maximal transmission capacity could increase in the future.

3.3.7 High Temperature Superconducting (HTS) Cable

The superconducting materials have the ability to conduct electricity without electric losses, when the materials are cooled to very low temperatures [28][91]. The temperatures are around 4 K or -269 ºC. The discovery of high temperature superconducting materials (HTS) made possible that high temperature superconducting materials conduct electricity without electric losses at liquid nitrogen temperatures. The nitrogen temperatures are around 77 K or -196 °C. The cooling of HTS material is less expensive than cooling of other superconducting materials. The current material density of superconducting materials is higher than the current material density of copper. The advantages of HTS power cable are very low energy losses, very high current material density, high power rating, no thermal interaction with environment and no magnetic interaction with environment. The HTS power cable is illustrated in figure 3.9. The disadvantages of HTS power cable are very high cost of HTS material and the internal liquid nitrogen cooling. Current research about HTS materials is mainly focused on reducing the cost of HTS power cables. To date several demonstration projects with HTS power cables are carried out. Today the HTS power cable is interesting for underground power transmission lines in very compact urban areas. In the future HTS power cable might be used for large power long distance power transmission lines.

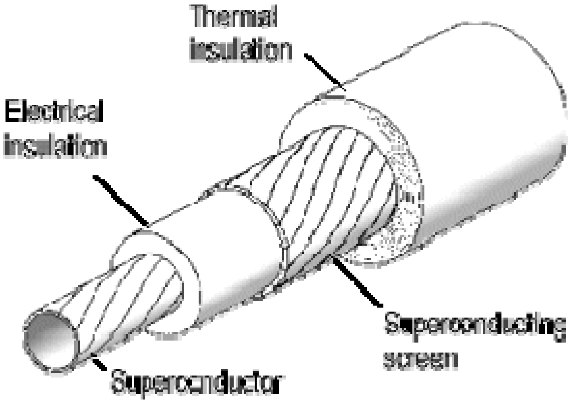

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Figure 3.9 The HTS cryogen dielectric power cable [91]

3.4 Converter Station

The converter station is also an essential part of the HVDC system [7][29][44][66][128]. The converter station is usually used at both ends of the direct current submarine power line or direct current overhead line. The converter station performs the following functions:

- Converting direct current into three phase alternating current or vice versa
- Converting high voltage into lower voltage or vice versa
- Keeping the voltage and frequency stable
- Controlling the power flow

The converter station is normally located on shore. However the converter station could also be placed on a fixed structure as a jacket or a floating structure as a weather-vaning barge, when the power plant is located on open sea. There are two configuration types for the converter station. The configuration types for the converter station are:

- Voltage Sourced Converter (VSC)
- Current Sourced Converter (CSC)

Since the beginning of HVDC systems CSC converter stations are used. The first VSC converter stations emerged in 1990s due to technological improvement in turn-off devices such as Insulated Gate Bipolar Transistors (IGBTs) and Integrated Gate-Communtated Thyristors (IGCTs). Today the HVDC converter station can be a CSC converter station or a VSC converter station.

3.4.1 Voltage Sourced Converter Station

The VSC converter stations are preferred for submarine power lines between a large strong grid and a weak small grid due to high level of power quality control.
The circuit of the VSC converter station is illustrated in figure 3.10.
The VSC converter stations are characterized by [7][44][66]:

- Small AC filters on AC side for higher harmonic elimination
- DC filters on DC side
- Inductors as electrical energy storage device on AC side
- Capacitors as electrical energy storage device on DC side
- Self-commutated
- Switching frequency at higher frequency
- Higher switching losses
- Current or voltage reversal
- Polarity of DC voltage is unidirectional
- Large DC filter keeps DC voltage constant
- Smoothing reactor on DC side

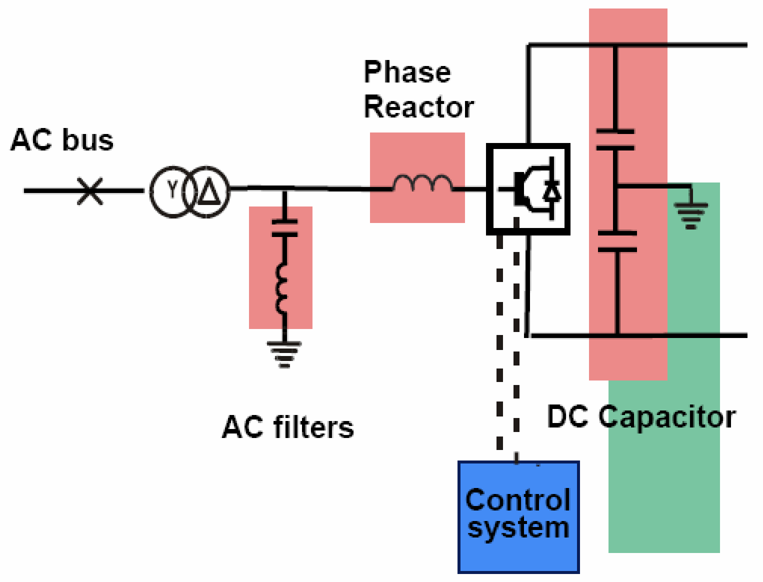

Figure 3.10 The voltage sourced converter station [66]

3.4.2 Current Sourced Converter Station

The CSC converter stations are preferred for long distance submarine power lines between two strong grids due to lower switching losses. The circuit of the CSC converter station is shown in figure 3.11. The CSC converter stations are characterized by [7][44][66]:

- Large AC filters on AC side for harmonic disturbance elimination
- DC filters on DC side
- Reactive equipment on AC side for power factor correction
- Capacitors as electrical energy storage device on AC side
- Inductors as electrical energy storage device on DC side
- Line commutated (with commutation capacitors)
- Switching frequency at line frequency
- Lower switching losses
- Only voltage reversal
- Polarity of DC current is unidirectional
- Large smoothing reactor keeps DC current constant
- DC filter on DC side

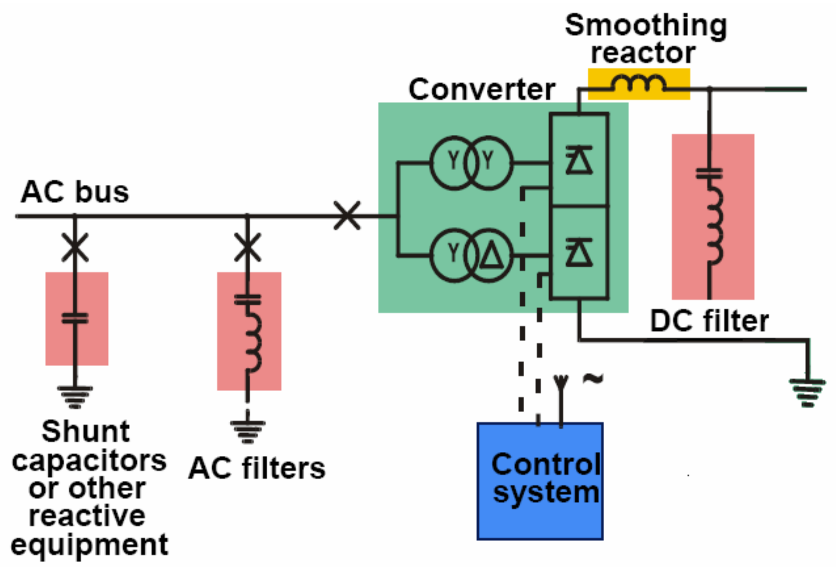

Figure 3.11 The current sourced converter station [66]

3.4.3 Lay-out of Converter Station

The lay-out of the converter station depends mainly on the configuration type of the three phase converter. The lay-out of a CSC converter station is illustrated in figure 3.12.
In general the converter station is composed of the following parts:

- Shunt capacitor banks
- AC filter banks
- AC switchyard
- Converter building
- DC switchyard

As mentioned before the shunt capacitor banks or other reactive equipment compensate the reactive power. The shunt capacitor banks have circuit breakers.
The AC filter banks are applied for eliminating of higher harmonics.
The AC filter banks are passive AC filters and/or active AC filters. The AC switchyard provides the interface with AC grid. The AC switchyard is comprised of converter transformers, surge arresters and circuit breakers. The surge arresters in the AC switchyard protect the AC switchyard against overvoltages from the AC side. The converter transformers are single phase transformers. The converter transformers convert the voltage of the AC grid to the voltage level of the converter. The converter building contains the high power semiconductors valves, control system and cooling system. The converter building resembles at a warehouse building. The converter building provides for weather protection, high frequency shielding and noise reduction. The high frequency shielding is achieved by steel enclosures. The most relevant components of the converter building are the high power semiconductor valves. The valves are suspended or standing in the converter building.
The valves contain high power semiconductors.

There are three types of high power semiconductors [48]:

- Diodes
- Thyristors
- Turn-Off Devices

The diodes block or pass the current according to applied voltage.
The thyristors such as fast switching thyristors, triacs pass the current when triggered, but they block the current according to applied voltage. The turn-off devices such as IGBTs, GTOs, IGCTs, MOSFETs and Darlingtons pass or block the current at will. The thyristors are applied in current sourced converter stations. The turn-off devices find their application in voltage sourced converter stations. The DC switches and DC filters are located in the DC switchyard. The DC filters eliminate harmonic frequencies.

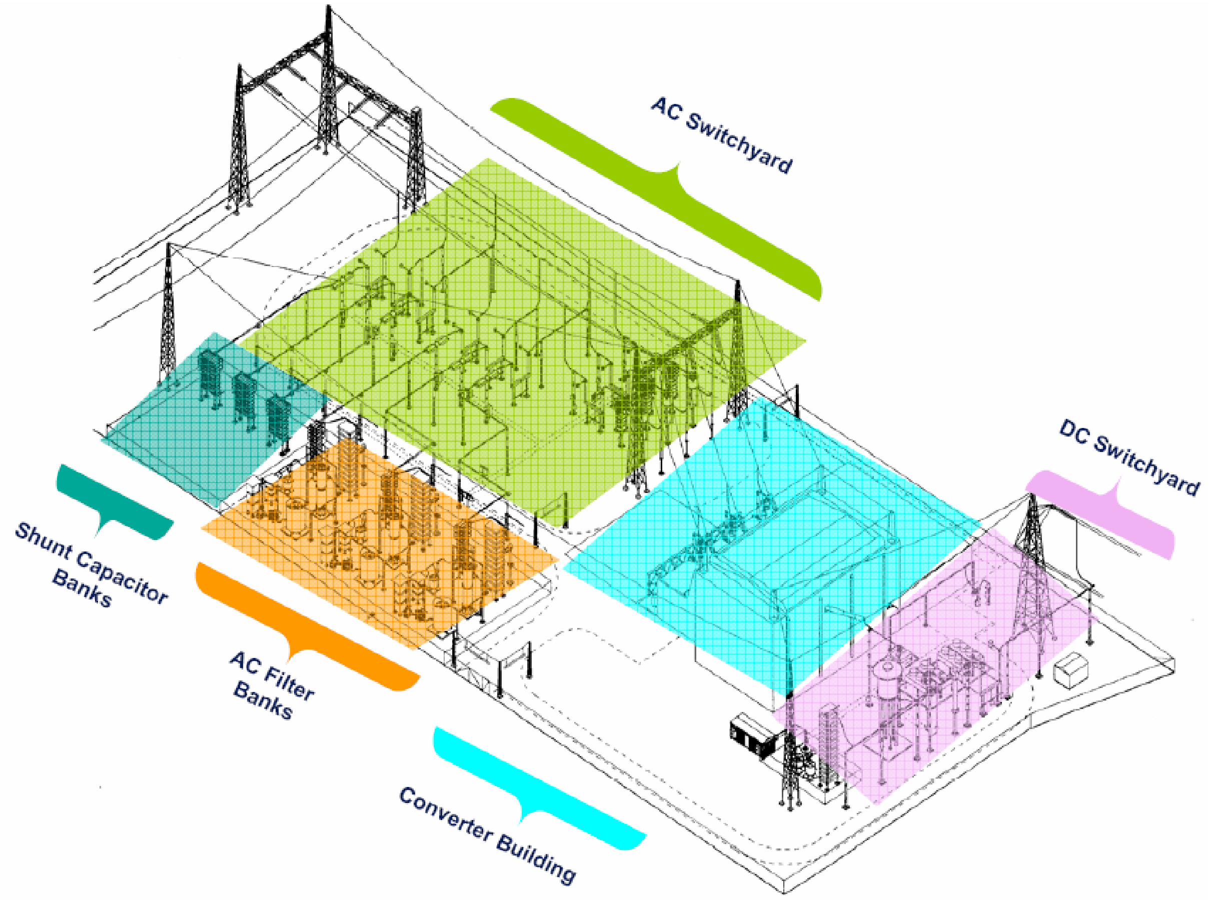

Figure 3.12 The lay-out of the typical current sourced converter station [66]

3.5 Installation

The first commercial electrical cable across the sea was laid by John Watkins Brett's Anglo-French Telegraph Company in 1850. The first electric cable was a submarine communication cable. The first transatlantic communication cable was laid by Cyrus West Field in 1858.
As mentioned before the first submarine power cable was laid between the island of Gotland and Sweden in 1954 [130]. The cables are laid with a ship. The first cable laying ships were normal cargo ships. Nowadays cable laying ships are dedicated cable ships.

3.5.1 Cable Layer

Figure 3.13 The cable layer [92]

The dedicated cable ships use specialized techniques to lay cables.
The ship owners with cable laying ships are Global Marine Systems Limited, FT Marine, Elettra, ASN Marine, NSW, TYCO, S.B. Submarine Systems, IT International Telecom Inc., Subsea 7, E-Marine, YIT Primatel Ltd, NTT World Engineering Marine Corporation (NTT-WEM), LD TravOcean and Oceanteam Power & Umbilical [92][93][130]. The ship owners have often contracts with cable manufacturers or telecommunication companies. The cable ships have in common that they have cable tanks and cable engines. The cable tanks store the cables in static coil below the tank. Sometimes the cables are stored in a revolving turn carousel or static coil on the deck. The submarine cable is led out at a predetermined rate. This is accomplished with cable engines or cable tensioners. Next the submarine cables go over the stern or the bow of the ship by means of sheaves. Hereafter the submarine cable is finally led over board via a cable chute or cable stinger in a safe way. The cable stinger is installed at the bow or at the stern of the cable layer. The cable stinger is normally installed at the stern of the vessel. In general the cable laying ships are designed to carry large cable lengths. The installation of submarine cables is a complex and hazardous work. The cable must be laid exactly according to a predetermined route without being damaged or broken, so that the submarine cable works underwater. The cable installation under sea is more difficult than cable installation on land. In addition the cable laying ships have systems for repairing a cable. The submarine cable can be damaged or broken by anchoring, earthquakes, hurricanes, undersea avalanches, volcanic activity and fishing trawlers. Before the submarine cable is repaired the damage cable is cut into two parts on the seabed. The two ends of submarine cable are lifted separately to the cable layer by means of a grapple. The systems of the cable ship hold the ends of cable, so that a new section of submarine cable is spliced between the two ends of the submarine cable. Afterwards the repaired submarine cable is laid back on the seafloor. During the cable laying or cable repair on the seabed a remotely operated vehicle is used [29][92][130]. Besides that the ROV is used for the surveys of the submarine cable. The surveys are carried out to minimize the unavailability of submarine cable. The surveys are likewise carried out for determining the optimal route of the submarine cable on the seabed.

3.5.2 Cable Routing

The ideal route on the seafloor is a flat and unbroken path. In practice the following issues determine the route of the submarine power cable [29][49][130][131]:

- The cultural considerations such as existing infrastructure, communication cables, gas and oil pipelines, offshore mining, hydrocarbon exploration and production, offshore dumping grounds, military grounds, dumping grounds, marine parks, fishing grounds, anchoring grounds, etc.
- The political considerations such as territorial boundaries and international boundaries
- The physical considerations such as water depths, excessive seabed slopes, soil conditions, seismic and volcanic activities, sand waves, high currents and coastline stability
- The physical and cultural limitations at the landing site locations

The route of submarine power cable determines the diameter of the power submarine cable and the protection of the cable. In general the diameter of the cable is wider for rocky and coral soil conditions and near landing sites. The submarine power cable is protected, when submarine power cable is vulnerable to damage by fishing nets, anchors and high water currents. The submarine power cable is protected particularly in shallow waterdepths.
In shallow waters submarine power cable can be damaged by ship anchoring or trawling or other bottom-fishing techniques. In particular the installed submarine power cables in soft soils are vulnerable. Sometimes armoured power cable is applied, where the cable is vulnerable and burial is very difficult due to the hard bottom soil [29][30][130].
In certain circumstances the submarine power cable on seabed can be replaced by other solutions as offshore overhead lines or floating submarine power cables. The offshore overhead lines are feasible in very shallow water of roughly ten metres [29].
The pylon installation in sea is more expensive and complex than pylon installation on shore. The offshore overhead lines are a solution for short distances near the shore or at the shoreline, when the visual intrusion and the obstruction for ships are not a problem.
The floating submarine cables could be feasible in deep water of hundred metres.
The submarine cables are floating far beneath the surface. The submarine cables float by means of submersible buoys. The submarine cables are connected to the seabed with a large number of mooring lines. The solution is attractive, when the seabed morphology is difficult or the cable is required to pass an ocean through or the ocean seabed is too deep (> 1000 metres). Moreover the floating submarine cables are less vulnerable to anchors.
In addition the floating submarine cables avoid huge hydropressure acting on the submarine cables. In general floating submarine power cables could be a solution for very long power cables in very deep water. The vulnerable power cable on seabed is protected with the following measures [29][30][75][92][94][130][131]:

- Cable burial by ploughing
- Cable trenching by jetting or cutting
- Cable conduits by directional drilling
- Cable protection by rock dumping or mattresses or bags

The various techniques to protect the vulnerable power cable are now discussed in detail.
Most protection techniques are based on burial the power submarine cable in the seabed.

However in certain conditions like hard bottom soil other protection techniques are preferred for vulnerable submarine power cables. It should be noted that the burial of submarine power cables is expensive, because specialized equipment is required.

3.5.3 Cable Burial by Ploughing

The cable burial by ploughing is performed in shallow waterdepths up to 100 metres with soft soils such as sand soils and clay soils [29][30][130][131]. In order to provide for adequate protection the burial depths of the power cable range from 1 metre to 2 metres [29].
The burial depth depends on the properties of the soil. The soft soils require deeper burial depth. The cable burial by ploughing is achieved by towing a plough. The plough is illustrated in figure 3.14. The vessel pulls the plough through the seafloor soils. The cable ships should have adequate power and adequate bollard pull to tow the plough on the seafloor. The plough makes a trench. Simultaneously the submarine power cable is laid in the trench and the trench is closed and smoothed out with the same plough. Sometimes the trench closes already by natural forces. The cable burial by ploughing is a continuous process. The installation rates with cable burial by ploughing are quiet high, especially in sand and loose clays. In certain situations the laying and burying of the submarine cable cannot be performed out in one operation due to the cable design or seabed soil conditions or other issues.
In these circumstances the post burial method is used. In this method the cable is first laid on the seafloor. Hereafter the cable is buried with a plough. The cable could likewise be buried with other dredging techniques such as water jetting. The post burial method is more expensive than the previous method simultaneous laying and burying of the cable. In addition the post burial method is more difficult, because the towing of the plough requires very accurate navigation of the large vessel.

Figure 3.14 The cable burial with a plough [92]

3.5.4 Cable Trenching by Jetting or Cutting

In certain situations the cable burial by ploughing is very difficult due to the soil conditions of seabed. In those circumstances a trench is first made in, which the submarine cable is laid. Next the submarine cable is laid and buried in the trench. The trench can be excavated with the different trenching technologies such as water jetting or soil cutting [30][94][131].
The trenching by water jetting is achieved with a hydraulic jet plough. The hydraulic jet plough uses high velocity pressurized water to make the trench.
The hydraulic jet plough or towed jetting vehicle is used for several soils such as clay, chalk and gravel. The hydraulic jet plough or towed jetting vehicle is illustrated in figure 3.15.
In soft rocks such as limestone and sandstone rock cutting saw or rock trencher is used to create the trench. The rock cutting saw or rock trencher has a cutting wheel or digging chain to excavate the trench. The rock cutting saw or rock trencher is shown in figure 3.16.
During trenching with hydraulic jet plough or rock trencher the loose sediments soil remains in the trench. After trenching the submarine cable is laid in the trench.
The submarine cable settles between the loose sediments soil. Finally, the trench closes by natural sediment moves and the submarine cable is buried in the seabed. The use of hydraulic jet plough and rock trencher requires very accurate navigation. The cable trenching is feasible in waterdepths up to 100 metres.

Figure 3.15 The hydraulic jet plough/ towed jetting vehicle [75]

Figure 3.16 The rock cutting saw/ rock trencher [94]

3.5.5 Cable Conduits by Directional Drilling

The cable conduits by directional drilling are often applied at landing locations [29][30][75][131]. The cable conduits are drilled from shore into the sea. The cable conduits go under the beach and shoreline. The protection method minimizes the impact of submarine cable on the environment like the beach and the reef near the shore. In addition the submarine cable is protected against the tidal waters and high currents near the shore.
The cable conduit by directional drilling is illustrated in figure 3.18.
Another method at landing locations is the shore pull of the submarine cable.
The disadvantages of shore pull are that the cable is not protected and the visual intrusion of the cable at the shoreline. The shore pull is illustrated in figure 3.17. The methods cable conduits by directional drilling and shore pull require specialized equipment.


Figure 3.17 The shore pull [75]


Figure 3.18 The directional drilling [75]

3.5.6 Cable Protection by Rock Dumping or Mattresses or Bags

The cable protection by rock dumping or concrete block mattresses or sand/cement bags is performed, when burying of the submarine cable is very difficult due to the hard seafloor. In those circumstances the submarine power cable is laid on the seafloor. Hereafter the submarine power cable is covered by rocks or concrete block mattresses or sand/cement bags. The rock dumping is the most utilized protection measure among the three protection measures [30][67]. The rock dumping is achieved with a fall pipe vessel, which drops rocks and sand on the submarine cable by means of a fall pipe. The rock dumping requires very accurate navigation [95]. The concrete block mattresses are installed on the submarine cable. The concrete block mattresses are difficult to install. In addition the concrete block mattress is an expensive solution. The cable protection by block mattresses is illustrated in figure 3.19. The installation of sand/cement bags on the submarine cable is achieved with divers, which guide the sand/cement bags on the submarine cable. The sand/cement bags are only feasible in very shallow water. The cable protection by sand/cement bags is illustrated in figure 3.20. In comparison with rock dumping it is an expensive solution.

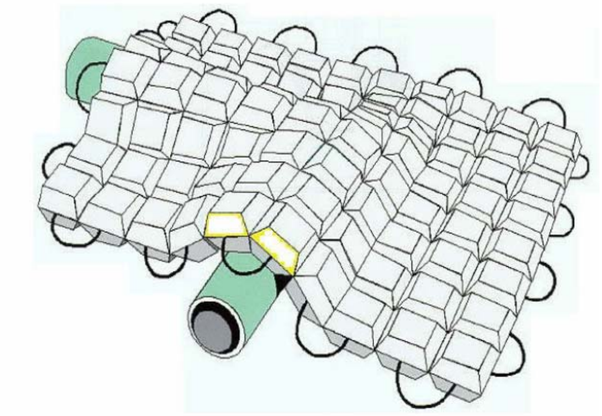
Figure 3.19 The concrete block mattresses [67]

Figure 3.20 The sand/cement bags [67]

3.6 Cost Analysis Submarine Power Link

Nowadays most submarine power lines are laid for connecting the shore with offshore applications such as wind farms, oil and gas platforms and subsea equipment.
The transmission capacity of submarine power lines for offshore applications is several hundred megawatts. Besides that submarine power lines are utilized for interconnection links. The transmission capacity of interconnection links across the sea is above 500 megawatts. The total costs of the submarine HVDC power line are determined by the following costs:

- The construction cost of two HVDC submarine power cables including installation
- The construction cost of two HVDC converter station
- The interest costs
- The costs due to energy losses
- The operating costs such as maintenance and repair cost

The construction costs of the submarine HVDC power line are the largest costs.
These costs are influenced by the metal prices like the price of copper, the demand for submarine power lines, the availability of cable manufacturing capacity, the availability of cable laying ships, the cable route, permits, studies and protection measures. The realization time of submarine interconnection link is at least 10 years. Still the submarine power lines are cheaper than underground lines on shore, because the installation requires less labour and the transport from factory to the cable route is easier. In addition the submarine power cable is smaller, because heat dissipation in the sea is less a problem.
In comparison with the construction costs the operating costs and the costs due to energy losses are almost negligible. The construction costs of the submarine HVDC power line are estimated with the following figures [32]:

- Two submarine power cables: 1000 USD/km·MW or 1852 USD/nm·MW
- One HVDC converter station: 110400 USD/MW

The figures are based on the several interconnection links across the sea in Europe.
The exchange rate between Euro and US Dollar in 2005 is 1 Euro = 1.2 US Dollar.
The construction costs of the submarine power line are financed with a loan with the interest of 8% for the period of 30 years. Furthermore it is worth noting that all electricity transport concepts are financed with a loan with the interest of 8% for the period of 30 years.
The annual operation and maintenance costs such as repair costs and operating costs of the submarine power line are assumed 0.3% of the construction costs of the submarine power line [33]. The availability factor of submarine power cable link is assumed 85% during the project time of 30 years, so consequently the submarine power cable link operates 310.25 days in one year [66]. The design life of the submarine power cable link is higher than 30 years. During operation electrical energy is transported over the submarine power cable link. The energy transmission causes energy losses. Most energy losses are ohmic losses, which are lost as heat. Therefore heat is generated during the energy transmission. The energy losses of the submarine HVDC power line are estimated with the following figures [31][32][47][66]:

- Full load one converter station losses: 0.75%
- Full load submarine cable losses: 7% / 1000 km

The mentioned figures will be used to calculate the total ownership costs of the submarine power cable link. The total costs of a 1200 MW submarine HVDC power line for the distance 500 nautical miles is calculated in table 3.1. As mentioned before the distance of 500 nautical miles is the distance between Iceland and Scotland. The energy losses or power losses of the submarine power line for the distance 500 nautical miles are 7.982%.

Description	Quantity	Unit Rate	Cost
HVDC Converter Station	**1200 MW**	**110400 USD/MW**	**132480000 USD**
1200 MW Submarine Power Cable	**500 nm**	**2222400 USD/nm**	**1111200000 USD**
HVDC Converter Station	**1200 MW**	**110400 USD/MW**	**132480000 USD**
Investment	**1376160000 USD**		
Annuity (8% for 30 years)	**122240761 USD/year**		
CAPEX	**3667222822 USD**		
Energy Costs	**268056 GWh**	**30000 USD/GWh**	**8041680000 USD**
Energy Losses Costs 7.982%	**21396.23 GWh**	**30000 USD/GWh**	**641886898 USD**
Operation and Maintenance Costs	**30 years**	**4128480 USD/year**	**123854400 USD**
OPEX	**8807421298 USD**		
Total Costs	**12474.64 million USD**		

Table 3.1 The calculation total ownership costs of 1200 MW 500 nm submarine power line

The capital expenditures of the 1200 MW submarine power line are 3667.22 million USD. The capital expenditures (CAPEX) are expenditures by a company to acquire or to upgrade physical assets. The operating expenditures of the 1200 MW submarine power line are 8807.42 million USD. The operating expenditures (OPEX) are the on-going costs for running a product, business or system. The submarine power cable link delivers 246659.77 GWh during 30 years. The cost per MWh of delivered energy in Scotland is 50.574 USD/MWh. Thus the cost per MWh for energy transport is 20.574 USD/MWh. The total ownership costs of 1200 MW submarine HVDC power line for 1000 nautical miles are calculated in table 3.2. The distance of 1000 nautical miles represents the distance between Iceland and European mainland. The energy losses or power losses of the submarine power line for the distance 1000 nautical miles are 14.464%.

Description	Quantity	Unit Rate	Cost
HVDC Converter Station	**1200 MW**	**110400 USD/MW**	**132480000 USD**
1200 MW Submarine Power Cable	**1000 nm**	**2222400 USD/nm**	**2222400000 USD**
HVDC Converter Station	**1200 MW**	**110400 USD/MW**	**132480000 USD**
Investment	**2487360000 USD**		
Annuity (8% for 30 years)	**220945805 USD/year**		
CAPEX	**6628374141 USD**		
Energy Costs	**268056 GWh**	**30000 USD/GWh**	**8041680000 USD**
Energy Losses Costs 14.464%	**38771.62 GWh**	**30000 USD/GWh**	**1163148595 USD**
Operation and Maintenance Costs	**30 years**	**7462080 USD/year**	**223862400 USD**
OPEX	**9428690995 USD**		
Total Costs	**16057.07 million USD**		

Table 3.2 The calculation total ownership costs of 1200 MW 1000 nm submarine power line

The capital expenditures of the 1200 MW submarine power line are 6628.37 million USD. The operating expenditures of the 1200 MW submarine power line are 9428.69 million USD. The submarine power cable link delivers 229284.38 GWh during 30 years. The cost per MWh of delivered energy in Europe is 70.031 USD/MWh, so consequently the cost per MWh for energy transport is 40.031 USD/MWh. The total ownership costs of the submarine power cable link for two distances are now determined.

Now the influence of the parameters distance and cost per MWh of power plants on the cost per MWh of delivered energy will be more profound examined.
The influence of each parameter is determined by varying the parameter. The first parameter that will be investigated is the distance. The next parameter that will be investigated is the distance. The distance is varied from 0 nautical miles till 6000 nautical miles. The delivered energy in GWh versus the distance in nautical miles is illustrated in figure 3.21.

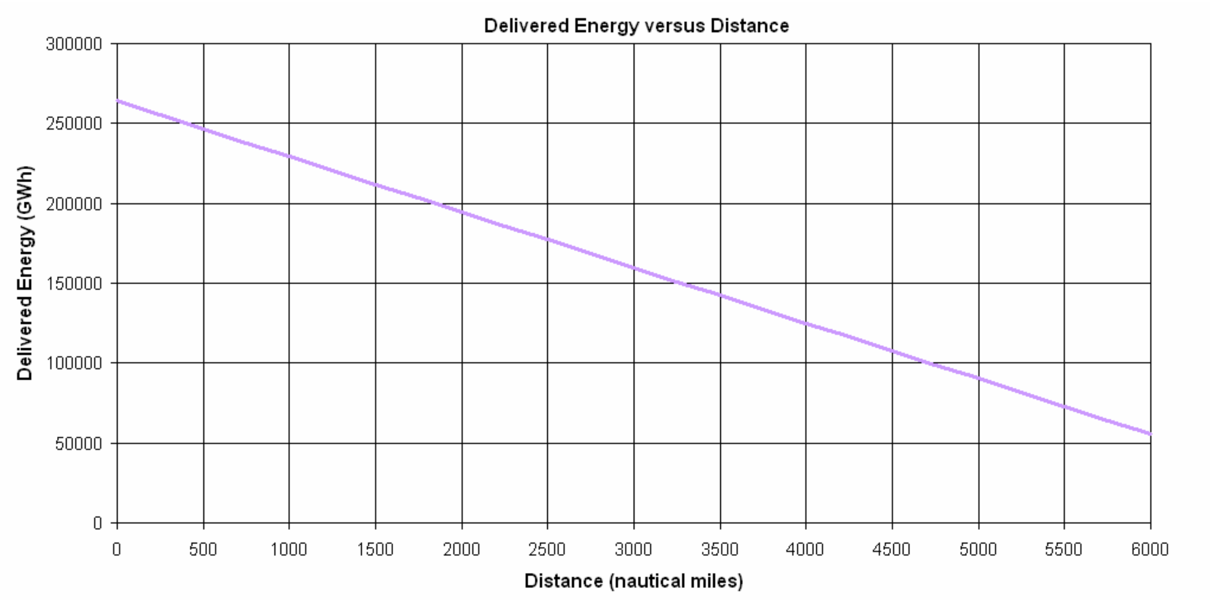

Figure 3.21 The delivered energy in GWh for 30 years versus the distance in nautical miles

The energy losses versus the distance are shown in figure 3.22. The energy flows of submarine power cable link are shown in figure 3.23. The Sankey diagram illustrates that the largest energy losses are the energy losses in the submarine cables. It should be noted that the energy losses in submarine cables increase, when the length of the submarine cable rises.

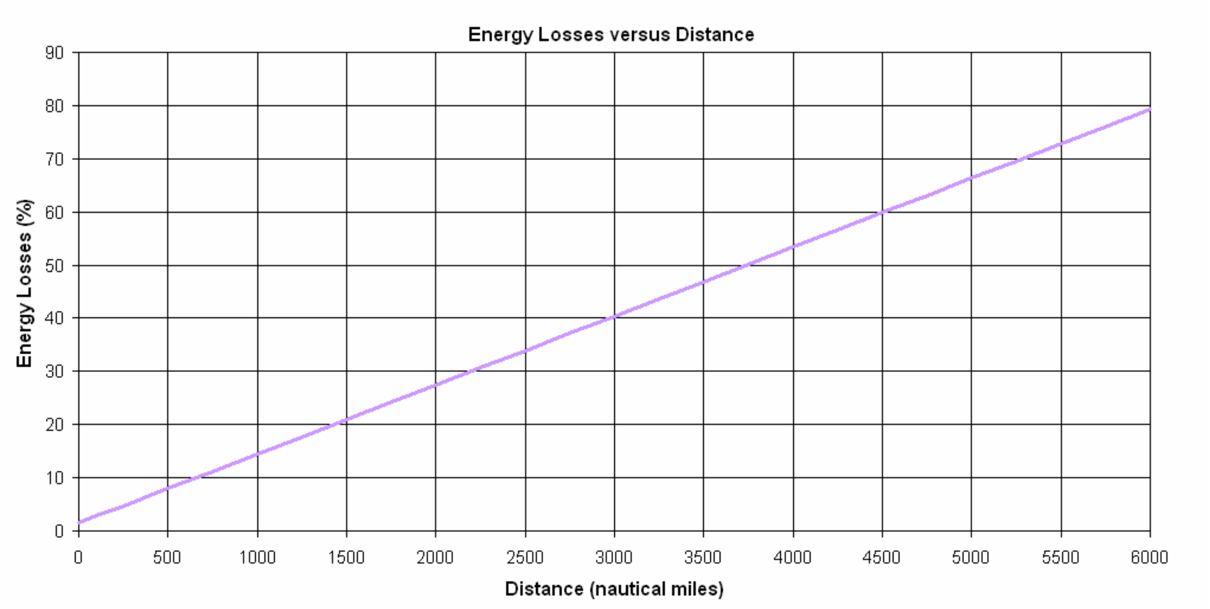

Figure 3.22 The energy losses in % versus the distance in nautical miles

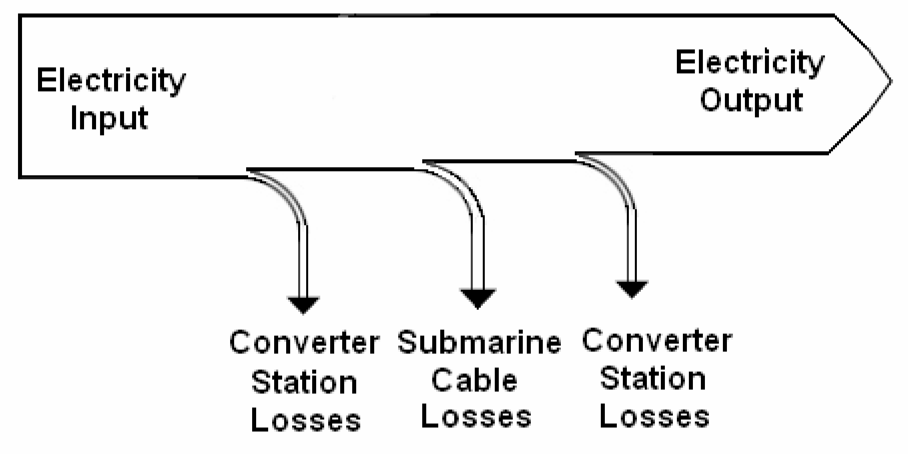

Figure 3.23 The energy flows of submarine power cable link

The cost per MWh of delivered energy in USD/MWh and the cost per MWh for energy transport in USD/MWh versus the distance in nautical miles are illustrated in figure 3.24. During the distance variation the cost of power plants is 30 USD/MWh.

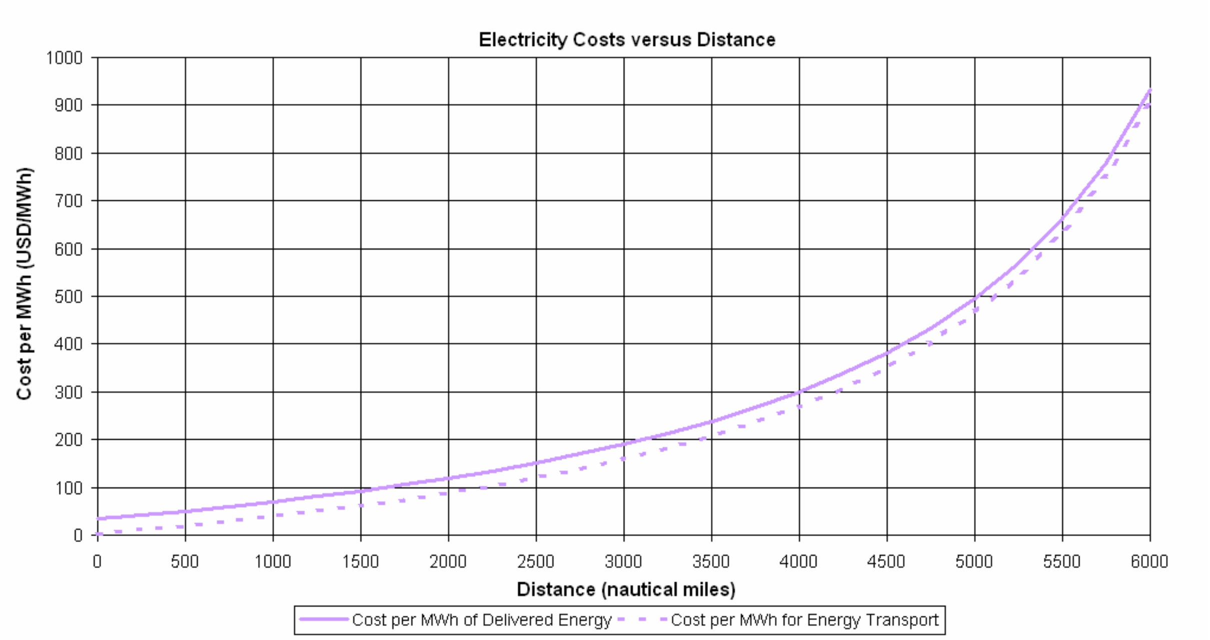

Figure 3.24 The cost per MWh of delivered energy and the cost per MWh for energy transport in USD/MWh versus the distance in nautical miles

The capital expenditures in million USD versus the distance in nautical miles are shown in figure 3.25. The rise of capital expenditures is caused by the increase of the submarine power cable length. The capital expenditures of submarine power cable link are very high for long distances.

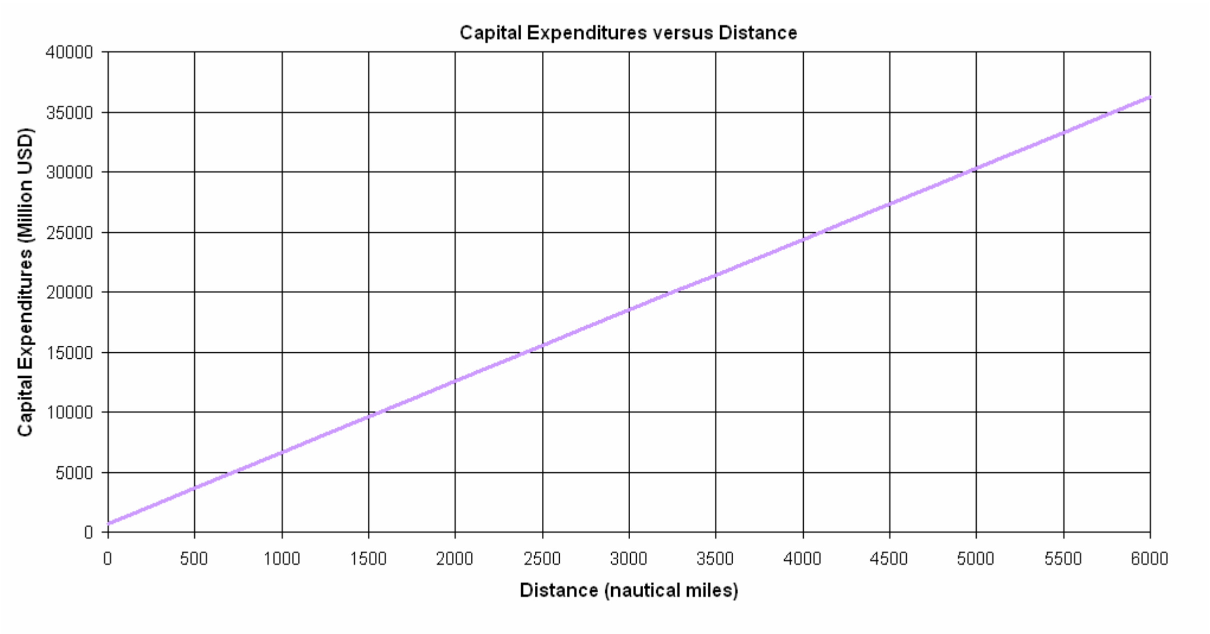

Figure 3.25 The capital expenditures in million USD versus the distance in nautical miles

The next parameter that will be investigated is the cost per MWh of power plants.
The cost per MWh of power plants is estimated 30 USD/MWh, but the cost per MWh of power plants could be lower or higher than 30 USD/MWh. Therefore the cost per MWh of power plants is varied from 0 USD/MWh to 150 USD/MWh to determine the influence of the parameter cost per MWh of power plants on the cost per MWh of delivered energy.
The influence of the cost per MWh of power plants in USD/MWh on the cost per MWh of delivered energy in USD/MWh for the submarine cable length 500 nautical miles is shown in figure 3.26. The influence of the cost per MWh of power plants in USD/MWh on the cost per MWh of delivered energy in USD/MWh for the submarine cable length 1000 nautical miles is illustrated in figure 3.27.

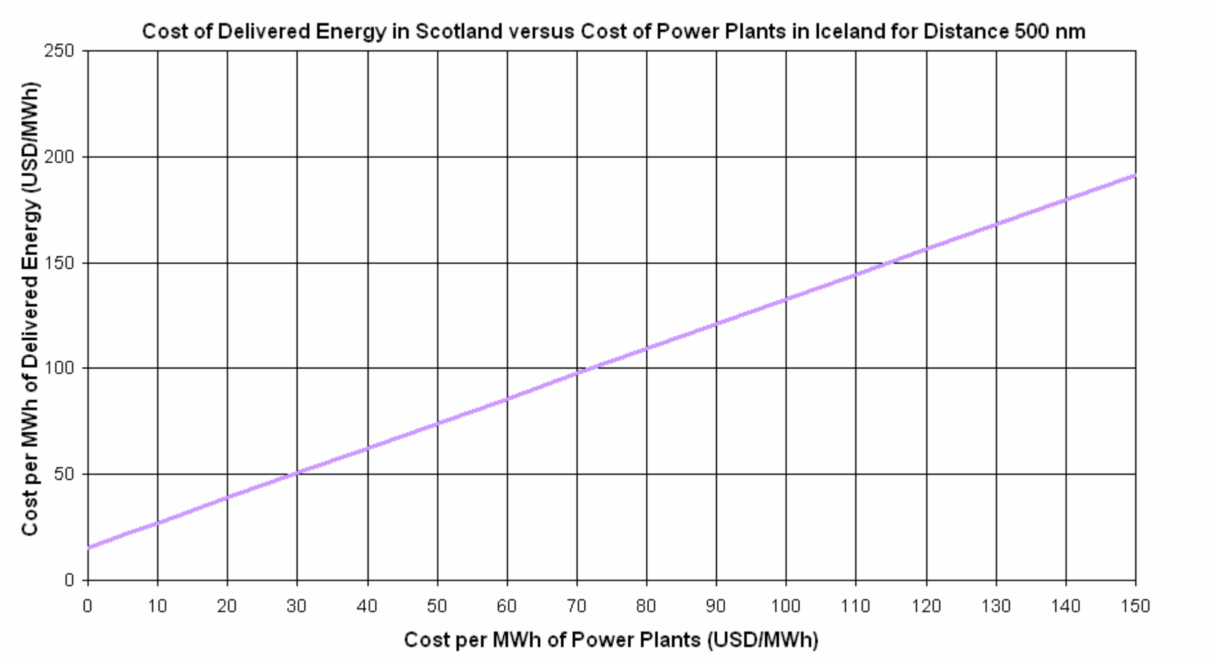

Figure 3.26 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance 500 nautical miles

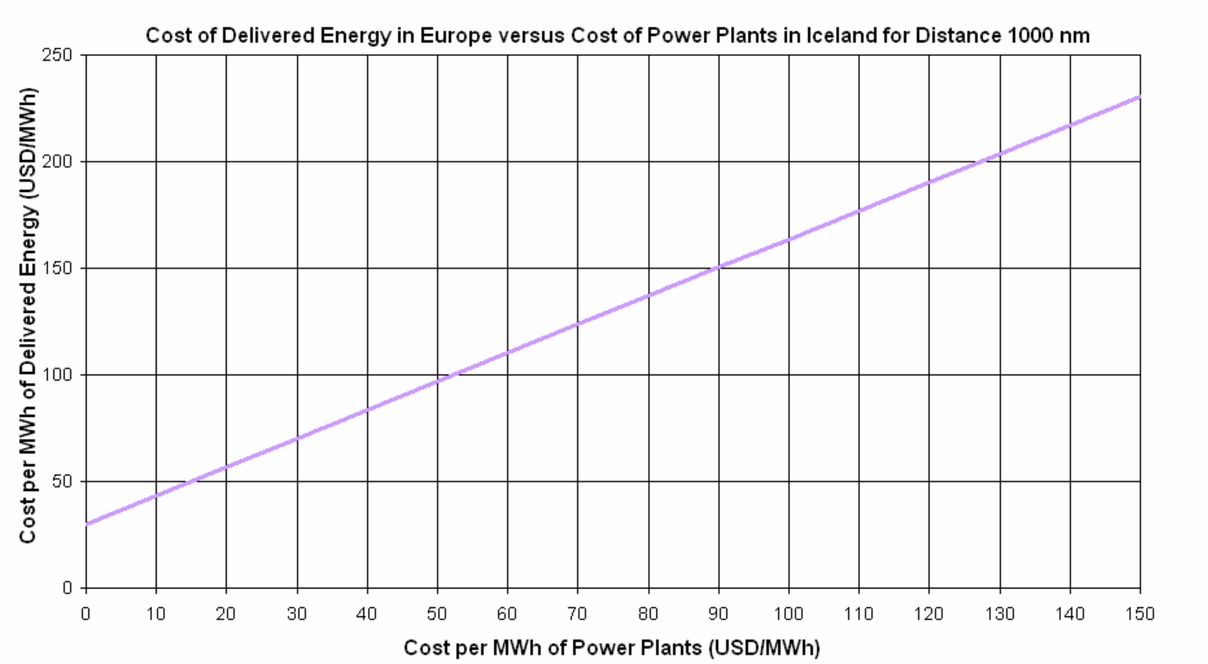

Figure 3.27 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance 1000 nautical miles

4 Battery Ship Development

In this chapter the battery ship is developed and analysed.

4.1 Feasibility of Battery Ship

The battery ship is technically feasible, because the current existing cargo ships are capable to carry and to transport batteries from origin A to destination B. This is not the fundamental problem, but is the battery ship attractive from the energetic perspective? The battery ship should always transport more energy than required to move the vessel from origin A to destination B. If the ship consumes more energy to transport the batteries than the recoverable stored electrical energy in the batteries the energy transport should not take place. The recoverable stored electrical energy in the batteries depends on the output energy density of batteries, allowable size of cargo space and allowable cargo deadweight. The gravimetric energy density of most batteries ranges from 10 kWh/ton till 100 kWh/ton [82]. Although the energy density is an important parameter, the density of the batteries in other words the cargo density is also relevant. When the cargo density is more than 0.77 ton/m^3, the ship is weight limited. If the cargo density is less than 0.77 ton/m^3, the vessel is volume limited [8]. The density of batteries varies from roughly 1.4 ton/m^3 till 2.5 ton/m^3, so the battery ship should be a weight limited ship [82]. The consumed energy for shipping the cargo depends on energy consumption of the vessel. Therefore the energy consumption of the cargo ship and the output energy density of the batteries are decisive for the energetic feasibility of the battery ship.

4.1.1 Energy Consumption

The energy consumption is the energy use over time. The energy consumption of a cargo ship is mainly connected with the energy consumption of the propulsion plant. Furthermore it is worth noting that the energy consumption of life support is very small. The energy consumption of life support is connected with the individual characteristics and the size of the vessel. The energy for life support is produced by diesel alternators and boilers. In first instance the energy consumption of the life support is neglected. The energy for propulsion is mainly produced by main engine or main engines. The other important parameter from energetic perspective is the energy intensity. The energy intensity of a cargo ship is defined as the energy consumption for shipping a cargo weight over a certain distance. The energy intensity depends on the individual characteristics of the ship. The energy intensity of a cargo ship is obtained with the following equation:

$$\textbf{Energy Intensity} = \frac{\textbf{Required Installed Power}}{\textbf{Cargo Deadweight} \cdot \textbf{Speed}} \qquad \textbf{(4.1)}$$

The energy intensity in Wh/(ton·nautical mile) is calculated with the required installed power in W for a certain speed, the cargo deadweight in metric ton and the speed in knots.
The energy intensity of a cargo vessel is expressed in Wh/ton·nautical mile or MJ/ton·km.
The measurement unit Wh/ton·nautical mile is equal to 1943.85 MJ/ton·km.
Besides the energy intensity enables to compare the energy consumption of different existing cargo ships.

In order to have a good comparison the ships should have the same speed, but the required installed power at different speeds for each ship can often not be found in literature, so consequently the energy intensity of a cargo ship is based on the energy consumption at design speed. In addition it is assumed that the cargo capacity is entirely utilized.
During the operational life the cargo capacity utilization could vary, which results in different energy intensities. The energy intensity increases as the capacity utilization declines.
The energy intensity depends also on the speed and the required installed power.
Between those two parameters there is a relation. The required installed power is a function of the speed. Therefore energy intensity and the required installed power decrease, when the speed declines. The relation between the required installed power in kW and the speed in knots is approximated with formula (4.2) with the resistance coefficient in kW·h^3/(nautical mile)^3. The relation between the required installed power in kW and the speed in knots is likewise approximated with the displacement in ton, the speed in knots and the admiralty constant. The values for coefficients and constants are obtained from the dataset of similar cargo vessels.

$$\textbf{Required Installed Power} = \textbf{Resistance Coefficient} \cdot \textbf{Speed}^3 \tag{4.2}$$

$$\textbf{Required Installed Power} = \frac{\textbf{Displacement}^{2/3} \cdot \textbf{Speed}^3}{\textbf{Admiralty Constant}} \tag{4.3}$$

The energy intensity is obtained by substituting the function (4.2) in equation (4.1) or by substituting the function (4.3) in equation (4.1).

$$\textbf{Energy Intensity} = \frac{\textbf{Resistance Coefficient} \cdot \textbf{Speed}^2}{\textbf{Cargo Deadweight}} \tag{4.4}$$

$$\textbf{Energy Intensity} = \frac{\textbf{Displacement}^{2/3} \cdot \textbf{Speed}^2}{\textbf{Cargo Deadweight} \cdot \textbf{Admiralty Constant}} \tag{4.5}$$

The equations (4.4) and (4.5) are simplified to formula (4.6) with the parameter energy intensity coefficient in W·h^3/ton·(nautical mile)^3.

$$\textbf{Energy Intensity} = \textbf{Energy Intensity Coefficient} \cdot \textbf{Speed}^2 \tag{4.6}$$

The equation (4.6) illustrates that the value of the energy intensity decreases, when the vessel speed decreases. The drawback of lower vessel speed is that the travel time will increase. Of course, the question is now, whether the longer travel time is acceptable.
The answer is on the question is related to the ship costs.

4.1.2 Existing Cargo Vessels

Since the beginning of the 20th century the shipping business has witnessed the development of different cargo vessel types. Each type of cargo vessel type is designed for a dedicated cargo, for example, the oil tanker is developed to transport crude oil. In general the existing predominated cargo vessel types can be summarized as follows: oil tanker, bulk carrier, chemical tanker, LPG carrier, LNG carrier, product tanker, multipurpose/general cargo ship and containership. It should be noted that there are more cargo vessel types. Each cargo vessel type will be examined to determine, whether the cargo vessel type is suitable for the battery ship. The investigation will highlight the energy intensity of the cargo vessel type and the cargo density. The energy intensity is important for the battery ship, because the vessel will transport energy in stead of commodities. Naturally during the energy transport the energy losses should not be accepted, because the loss of cargo for a commodity based vessel is likewise not accepted. In this case the energy losses are inevitable, otherwise the transport cannot take place, but the loss can be minimized through the use of a cargo vessel with low energy intensity. The aim of this investigation is to find the cargo vessel type with the lowest energy intensity and an acceptable cargo density. The calculation of the energy intensity requires the cargo deadweight. The cargo deadweight is a large part of the total deadweight. In publications the cargo deadweight is not always listed. The cargo deadweight can be estimated with the coefficient Ccdwt = Cargo Deadweight / Total Deadweight. The coefficient Ccdwt between the cargo deadweight and the total deadweight depends both on the cargo vessel type and the vessel size. The coefficient is relative small for small vessels and increases with the size. In this case the coefficient Ccdwt is fixed based on the average of the range of coefficient Ccdwt for the similar cargo vessel type.
The coefficient Ccdwt for different cargo vessel types are presented in table 4.1

Vessel Type	Ccdwt Ranges	Ccdwt Fixed
Containership	**0.80-0.81**	**0.81**
General Cargoship	**0.79-0.81**	**0.81**
Chemical Tanker	**0.97-0.99**	**0.98**
Product Tanker	**0.97-0.99**	**0.98**
Gas Carrier	**0.97-0.99**	**0.98**
Bulk Carrier	**0.95-0.97**	**0.96**
Oil Tanker	**0.97-0.99**	**0.98**

Table 4.1 Cargo deadweight coefficients [50]

The investigation of existing cargo ship types starts with the oil tanker. The oil tanker is a tanker for the transport of crude oil. A tanker is a cargo ship for the transport of liquids in bulk. The crude oil has a specific gravity of approximately 0.90 ton/m^3, so the design of an oil tanker is weight limited. The admiralty constant of oil tankers versus the froude number is illustrated in figure 4.1. The froude number is obtained with the following equation:

$$\textbf{Froude Number} = \frac{\textbf{Speed}}{\sqrt{\textbf{Acceleration of Gravity} \cdot \textbf{Length waterline}}} \qquad \textbf{(4.7)}$$

The length of waterline is assumed similar as the length between perpendiculars.
The displacement of oil tankers versus the total deadweight is illustrated in figure 4.2.
The energy intensity of the oil tankers versus the total deadweight is illustrated in figure 4.3.
The energy intensity of ships is calculated at the design speed. The energy intensity coefficient versus the total deadweight is illustrated in figure 4.4.

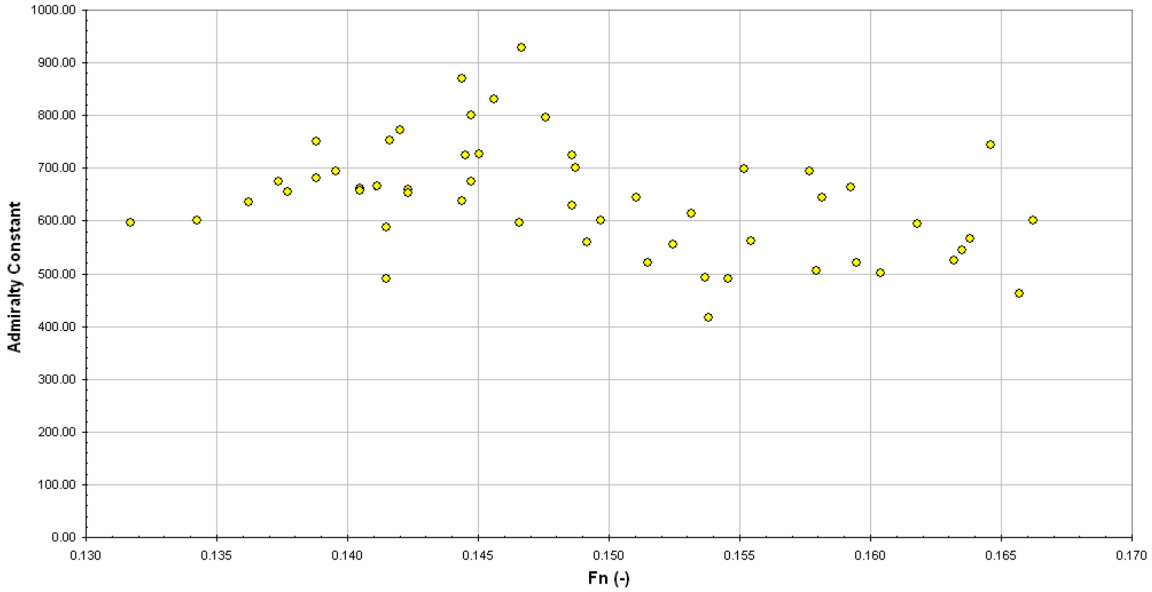

Figure 4.1 The admiralty constant of oil tankers versus the froude [50]

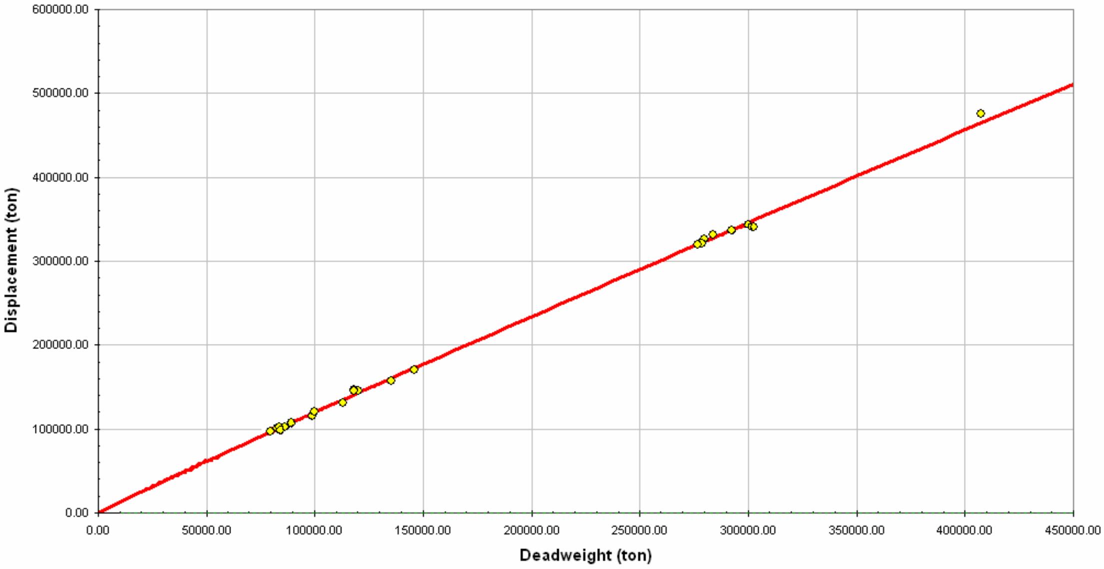

Figure 4.2 The displacement of oil tankers versus the deadweight with function **Displacement = 1.82·Deadweight** $^{\mathbf{0.96}}$ [50]

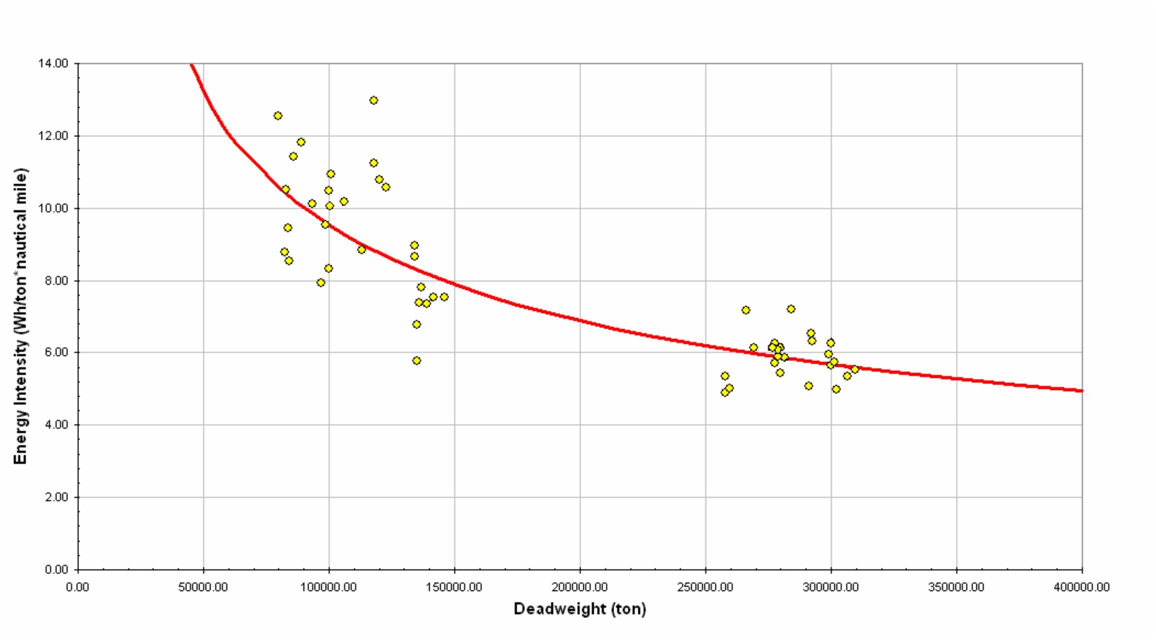

Figure 4.3 The energy intensity of oil tankers versus the deadweight with function **Energy Intensity = 218·Deadweight** $^{-0.47}$ [50]

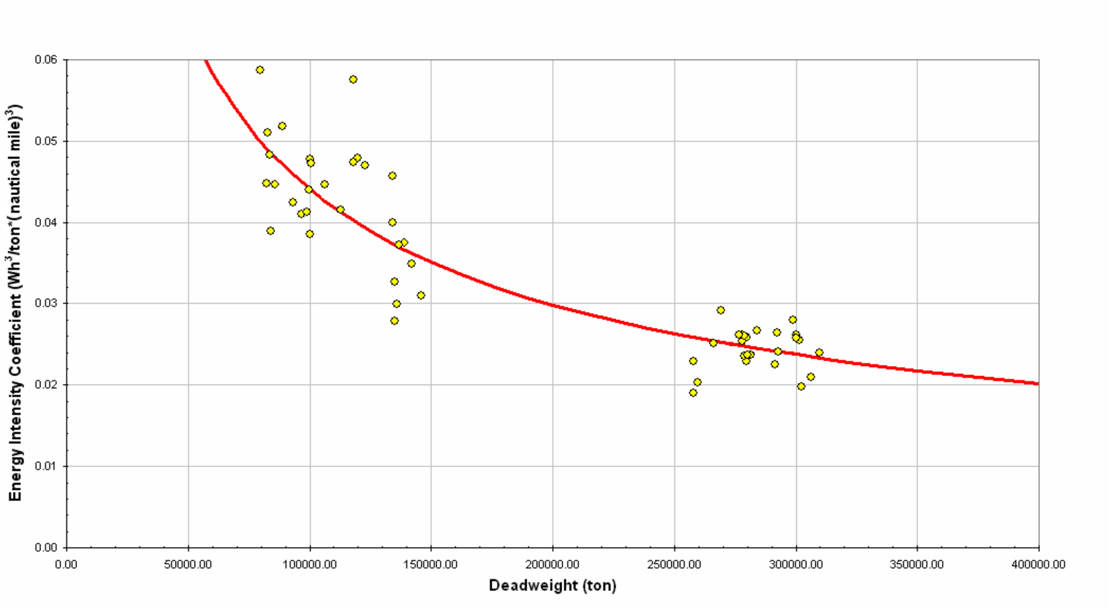

Figure 4.4 The energy intensity coefficient of oil tankers versus the deadweight with function **Energy Intensity Coefficient = 28.8· Deadweight** $^{-0.56}$ [50]

The description of remaining cargo ship types bulk carrier, chemical tanker, LNG carrier, LPG carrier, product tanker, multipurpose/general cargo ship and containership with their associated figures are presented in Appendix A Energy Intensity.
The results from figures 4.1 till 4.4 and the figures from Appendix A Energy Intensity are presented in table 4.2. The energy intensity range and design speed range of different existing cargo vessel types are listed in table 4.2. The energy intensity coefficient range and admiralty constant range of different cargo vessel types are listed in table 4.3.

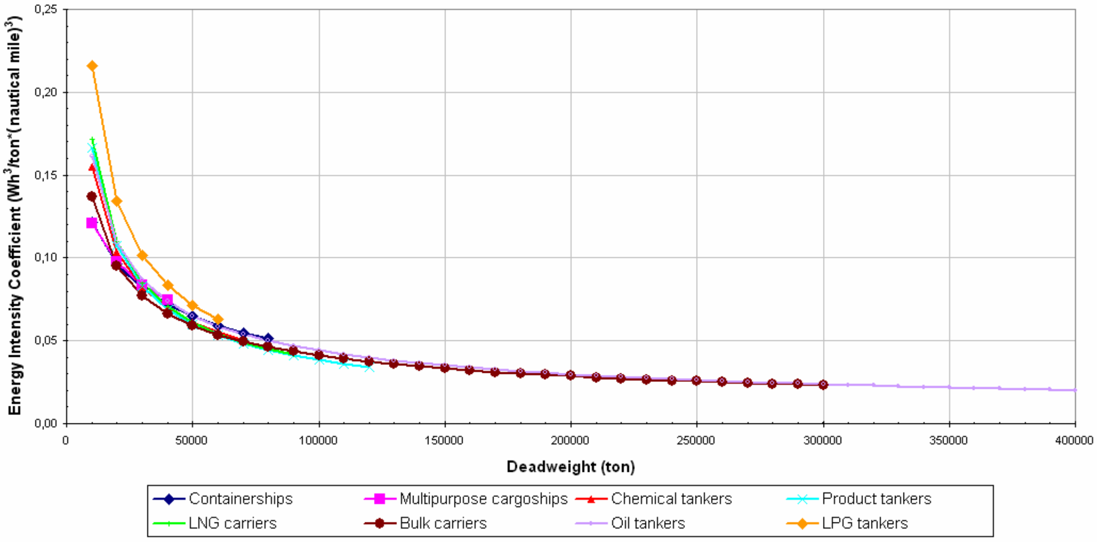

Figure 4.5 The energy intensity coefficient of 8 different cargo vessel types versus the deadweight

Vessel Type	Energy Intensity Range in Wh/ton·nautical mile	Design Speed Range in knots
Containership	**30-95**	**12.5-26.0**
Multipurpose Cargoship	**20-80**	**12.0-19.5**
Chemical Tanker	**12-50**	**12.5-16.5**
Product Tanker	**10-60**	**11.5-16.5**
LNG Carrier	**16-40**	**15.0-22.0**
LPG Carrier	**17-80**	**14.5-18.0**
Bulk Carrier	**5.6-25**	**13.5-16.0**
Oil Tanker	**5.0-13**	**13.8-16.5**

Table 4.2 The energy intensity range and design speed range of different ships

The impact of the increase of ship size is illustrated in the figures 4.1 till 4.5, that is to say the energy intensity decreases with the rise of the deadweight. The benefit of a big ship size is lower energy intensity.

Vessel Type	Energy Intensity Coefficient Range	Admiralty Constant Range
Containership	**0.050-0.600**	**250-750**
Multipurpose Cargoship	**0.090-0.400**	**250-550**
Chemical Tanker	**0.051-0.280**	**300-750**
Product Tanker	**0.045-0.500**	**200-650**
LNG Carrier	**0.035-0.181**	**450-850**
LPG Carrier	**0.060-0.350**	**200-550**
Bulk Carrier	**0.026-0.128**	**400-800**
Oil Tanker	**0.020-0.060**	**400-950**

Table 4.3 The energy intensity coefficient range and admiralty constant range of different cargo ships

According to table 4.2 and table 4.3 the largest oil tankers have relative the lowest energy intensity and the lowest energy intensity coefficient. After the oil tankers the largest bulk carriers have the lowest energy intensity and the lowest energy intensity coefficient due to the large deadweight and relative low speeds. The largest bulk carriers and the largest oil tankers are most attractive for the battery ship. The large product tankers and the large chemical tankers are less attractive, because they have higher energy intensities due to the limited deadweight of those cargo vessel types compared with the oil tankers and the bulk carriers. The containerships, multipurpose cargoships and gas carriers have the highest energy intensities due to relative high speeds. In addition they have far too low cargo densities. The cargo vessel types gas carriers, multipurpose cargoships and containerships are not suitable for the battery ship. The benefit of the largest bulk carriers compared with the largest oil tankers is that the largest bulk carriers have high cargo specific gravity. The high cargo specific gravity is almost comparable with the density of most batteries. The largest oil tankers have a lower cargo specific gravity. The benefit of the largest oil tankers compared with the largest bulk carriers is the lowest energy intensity due to the largest deadweight. The choice for the most suitable cargo vessel type cannot yet be made, because there are other important considerations such as ship costs. Still the vessel for the battery ship must have a very large deadweight and the design of vessel should resemble at an oil tanker or a bulk carrier.

4.1.3 Influence of Output Energy Density

Now the energy intensities of cargo vessels are known, the influence of the output energy density of batteries on the energy transport is investigated. As previously stated, the output energy density of the batteries defines the amount of energy that a vessel can carry from origin A to destination B. In the case the vessel uses the stored energy to propel it self, the ship can travel a certain distance until the batteries have no more energy. The travel distance is calculated with the following equation.

$$\textbf{Travel Distance} = \frac{\textbf{Output Energy Density}}{\textbf{Energy Intensity}} \qquad \textbf{(4.8)}$$

The parameters are the travel distance in nautical miles, the output energy density in Wh/kg and the energy intensity in Wh/ton·nautical mile. The influence of the output energy density on the maximal travel distance for different energy intensities is illustrated in figure 4.6. The figure 4.6 illustrates that the maximal travel distance increases, when the output energy density increases. In addition the maximal travel distance increases likewise, when the energy intensity declines. The figure 4.6 can be used to indicate how far you can travel with a certain output energy density and certain energy intensity, for example, a cargo ship with the energy intensity of 5 Wh/ton·nautical mile and batteries with an output energy density of 20 kWh/ton is capable to travel a distance of 4000 nautical miles. It should be stressed that the maximal travel distance is estimated. The maximal travel distance can be influenced by the weather, seaway and other factors.

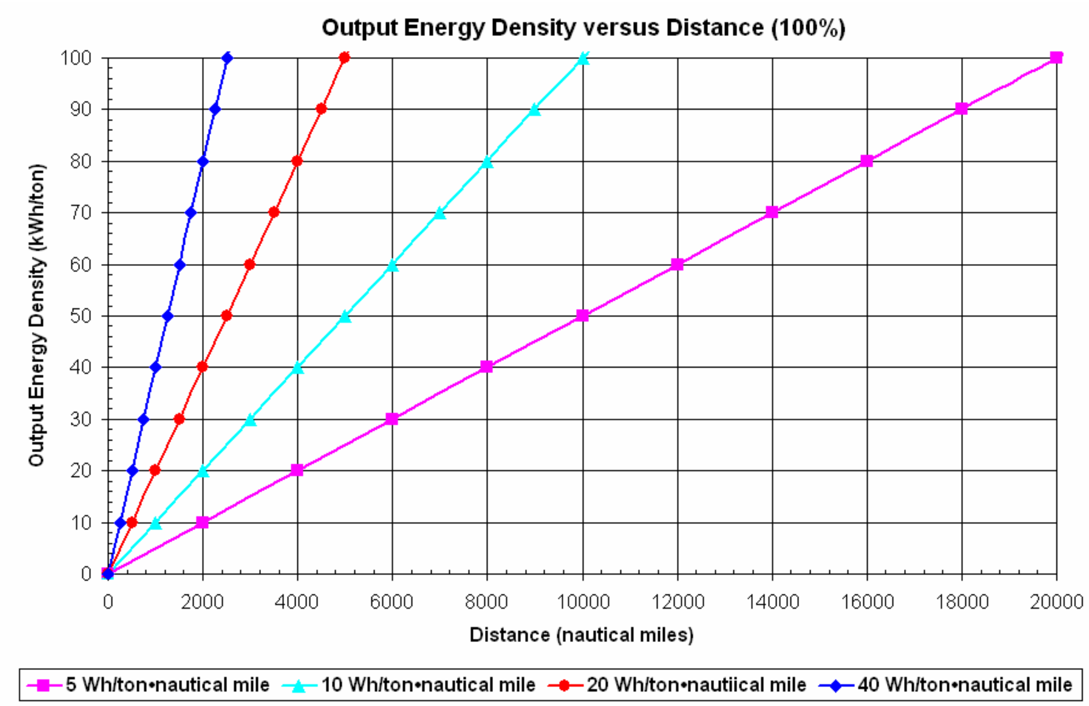

Figure 4.6 The influence of the output energy density in kWh/ton on the maximal travel distance in nautical miles

The battery ship starts to become feasible from energetic view point, when electrical energy is left after the voyage from origin A to destination B and back. The energy losses due to the unavoidable transport can be expressed as the ratio between the consumed energy for the transport and the stored energy. The ratio is here defined as transport energy losses.

$$\textbf{Transport Energy Losses} = \left(\frac{\textbf{Energy Intensity} \cdot \textbf{Traveled Distance}}{\textbf{Output Energy Density}} \right) \cdot \textbf{100} \qquad \textbf{(4.9)}$$

The parameters of equation (4.9) are the output energy density in kWh/ton, the travel distance in nautical miles, the energy intensity in Wh/ton·nautical mile and the transport energy losses in %. The output energy density versus the maximal travel distance for different energy intensities with transport energy losses of 50% is illustrated in figure 4.7. The transport energy losses should be as low as possible. The consumed energy for energy transport is considered as energy losses, because the energy is not delivered at destination B. The battery ship must perform two voyages. The first voyage is from origin A to destination B and the second voyage is from destination B back to origin A. The travel distance is twice the distance between origin A and destination B. The travel distance should be taken for the calculation of the transport energy losses, even in the case that on the voyage back the ship is used to transport other commodities. The transport energy losses versus the travel distance for the different output energy densities with energy intensity 5 Wh/ton·nautical mile are illustrated in figure 4.8. The similar figures with energy intensities 10 Wh/ton·nautical mile and 20 Wh/ton·nautical mile are illustrated in figure 4.9 and in figure 4.10. The same figures from 4.8 till 4.10 prove that for very low energy intensities the battery ship becomes feasible. According to the three figures the design energy intensities of the cargo vessel types oil tanker and bulk carrier are suitable for the battery ship.

Those cargo vessel types can be used till the travel distance of 10000 nautical miles or the distance of 5000 nautical miles. Moreover the same three figures prove that the output energy density has a large impact on the transport energy losses.

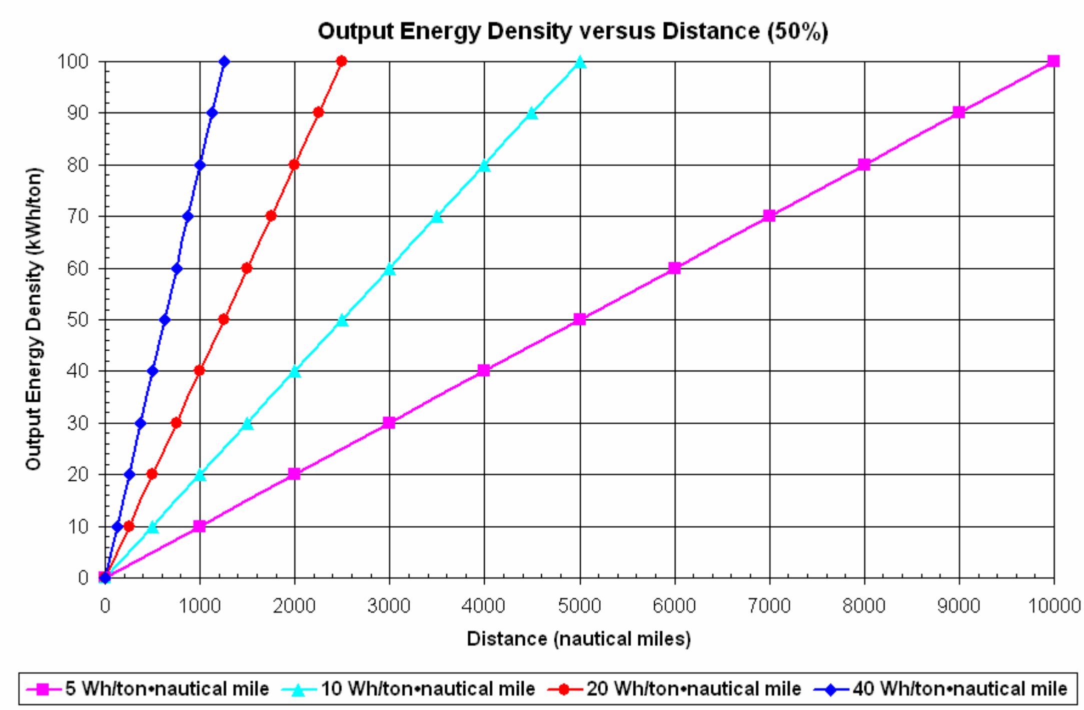

Figure 4.7 The output energy density in kWh/ton versus the travel distance in nautical miles for different energy intensities in Wh/ton·nautical mile with transport energy losses of 50%.

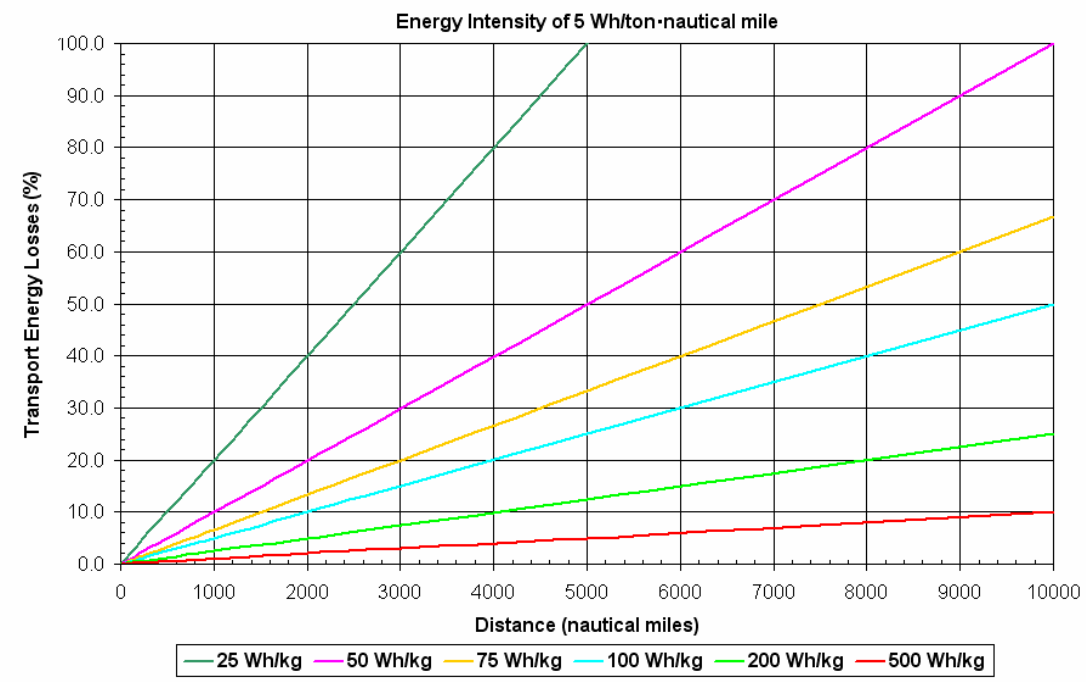

Figure 4.8 The transport energy losses in % versus the distance in nautical miles for different output energy densities in Wh/kg with the energy intensity of 5 Wh/ton·nautical mile

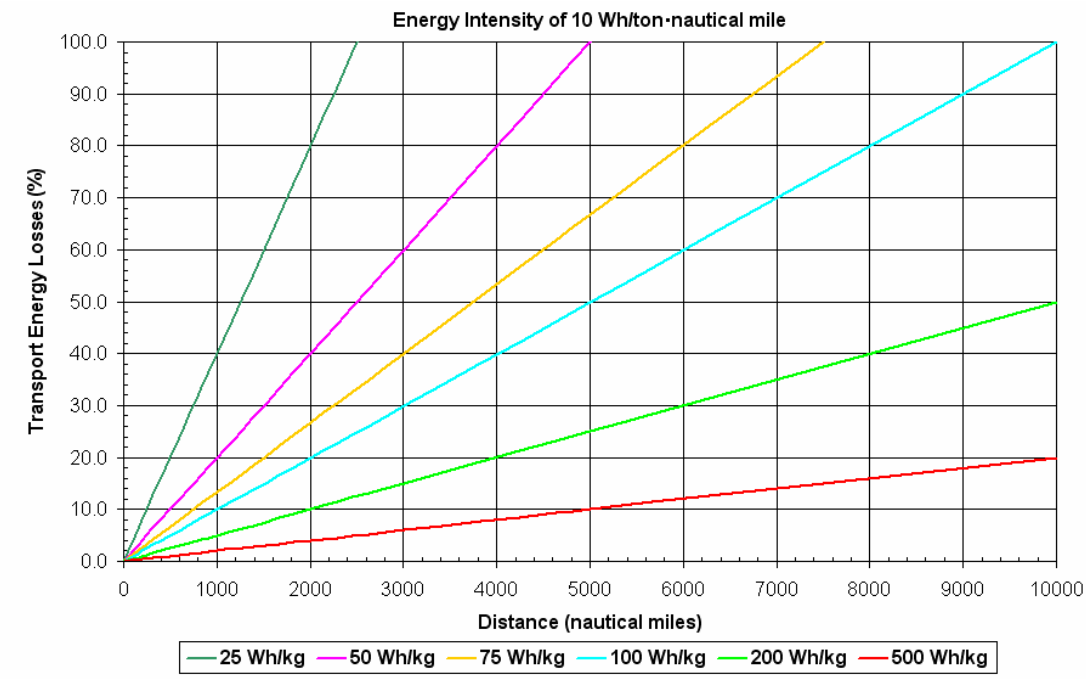

Figure 4.9 The transport energy losses in % versus the distance in nautical miles for different output energy densities in Wh/kg with the energy intensity of 10 Wh/ton·nautical mile

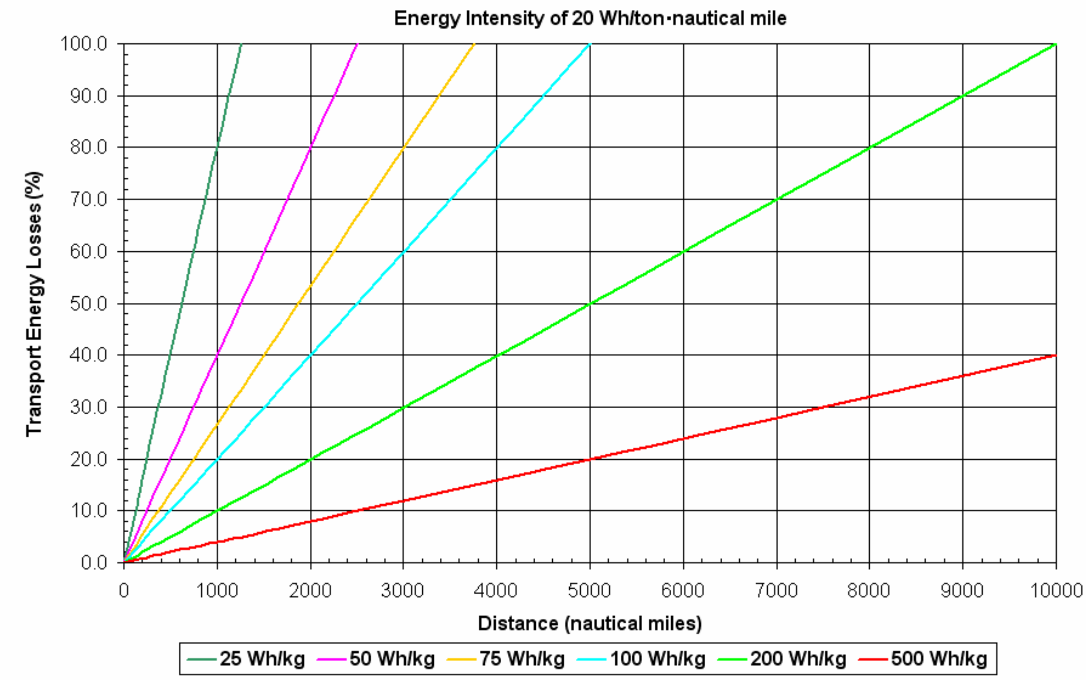

Figure 4.10 The transport energy losses in % versus the distance in nautical miles for different output energy densities in Wh/kg with the energy intensity of 20 Wh/ton·nautical mile

As mentioned before, the distance between Iceland and European mainland is approximately 1000 nautical miles, so the travel distance is about 2000 nautical miles.
The energy intensity versus the output energy density with different transport energy losses for the travel distance 2000 nautical miles is illustrated in figure 4.11.
According to figure 4.11 the battery ship for the electrical energy transport between Iceland and European mainland becomes feasible from energetic perspective with the design energy intensities of largest bulk carriers and largest oil tankers above the output energy density of 30 kWh/ton. The gravimetric energy density of most batteries ranges from 10 kWh/ton till 100 kWh/ton, so consequently the battery ship is capable to transport electrical energy from Iceland to European mainland. It should be noted that the output energy density is still a limiting factor. On the contrary the energy intensity is not a limiting factor, the lower energy intensities are achieved by sailing at lower speeds. The disadvantages of the lower speeds are longer travel times and less delivered electrical energy during the project time.

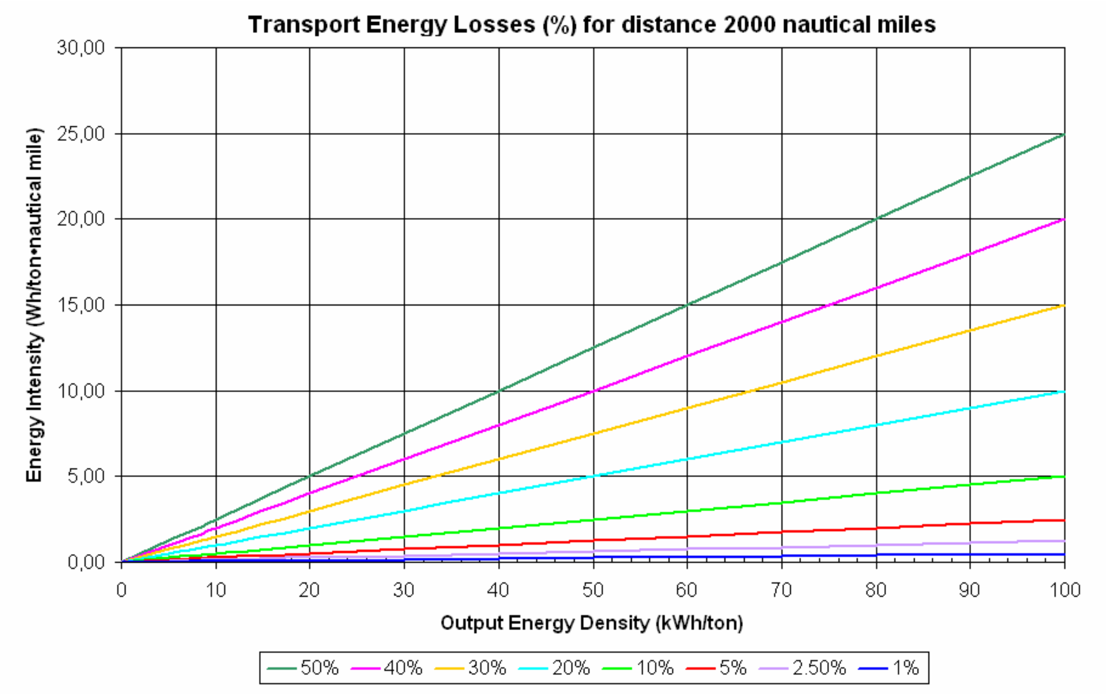

Figure 4.11 The energy intensity in Wh/ton·nautical mile versus the output energy density in kWh/ton with different transport energy losses in % for the travel distance 2000 nautical miles

4.2 Logistical Concepts

The battery ship is more than a cargo ship. The battery ship is a logistical concept or a logistical supply chain, which transports electricity from remotely located power plants across the sea to the grid of electricity consumers. The logistical supply chain may consist of at least one vessel and at least two terminals. For the time being, the assumption is made that the logistical supply chain consists only of one vessel, two terminals and the constant electrical energy supply from the power plants is guaranteed. The vessel transports the electrical energy from one terminal to the other terminal. The terminal is necessary for the transfer of electricity between the sea vessel and the grid. The main requirement for the logistical supply chain is that the electricity transport between the grids is performed against the lowest costs.

4.2.1 The Ship Size and Logistical Concepts

The most important part of the logistical supply chain is the vessel, so consequently the vessel must transport the electricity against the lowest costs. The costs are mainly influenced by the ship size and the vessel speed. The vessel speed depends on different issues such as energy use of the vessel, ship size, energy costs or fuel costs, capital costs and operating costs. Therefore the vessel speed will be the result of the energy use, ship size and total ship costs. The ship size depends mainly on the costs per ton deadweight. The requirement of the lowest costs demands the economy of scale, so the ship size is very large.
The advantages of economy of scale for ships are the following [9][34][50][51]:

- The total resistance per ton deadweight decreases, because mainly the wave resistance per ton deadweight declines with the increase of deadweight.
- The efficiency of the main engine increases, when the main engine size increases.
- The fuel costs per ton deadweight decrease, because the total resistance per ton deadweight decreases and the efficiency of main engine increases.
- The operating costs per ton deadweight decline as the ship size rises, because operating costs such as manning costs and stores and supplies costs do not rise proportionally with the deadweight.
- The capital costs per ton deadweight decrease as the deadweight rises, because the machinery costs and the outfit costs do not rise proportionally with the deadweight.

The economy of scale drives the trend towards bigger ships. Still the economy of scale for ships has a disadvantage. The main disadvantage of economy of scale is that the flexibility of ships becomes more restricted, when the ship size increases [34][52].
Moreover there is a maximum ship size. The maximum ship size is principally determined by limitations of waterway, limitations of terminals facilities and higher risks. The risk consists of the loss of vessel, his cargo and the environmental pollution from the wreck. The higher risks of larger vessels lead to higher insurance costs.
The current operating largest bulk carriers and oil tankers are approximately 300.000 dwt. The ship size around 300.000 dwt seems to be the maximum optimal ship size.
A 300.000 dwt vessel implies a draught of approximately 21 m.
The draught is based on the draughts of bulk carriers and oil tankers, because the largest oil tankers and the largest bulk carriers are the largest ships in the world.

The draught versus the deadweight of oil tankers and bulk carriers is illustrated in figure 4.12 and figure 4.13. In the world there are only a few ports like Rotterdam, which are capable to receive a 300.000 dwt vessel with a draught of 21 m. The port must have enough berth draught and enough terminal storage space to handle the very large vessel. The berth draught and channel depth of some ports in Europe are presented in table 4.4.

Port name	Max. Berth Draught (m)	Min Channel Depth (m)
Liverpool	**12.7**	**8.5**
Thamesport	**13.5**	**11.0**
Le Havre	**13.5**	**15.0**
Zeebrugge	**14.0**	**13.5**
Bremerhaven	**14.0**	**13.0**
Southampton	**15.0**	**12.6**
Hamburg	**15.0**	**12.5**
Antwerp	**15.3**	**14.0**
Felixstowe	**16.0**	**14.5**
Rotterdam	**16.6**	**22.0**

Table 4.4 Berth draught and channel depth of some European ports [10]

As solution for the restricted port access the 300.000 dwt vessels are mainly handled by offshore terminals. The offshore terminals are often located in front of the coast and close to a port. The offshore terminal is connected to an onshore terminal storage space.
There are several offshore terminal configurations, but the most utilized configuration is the Caternary Anchor Leg Mooring (CALM) type buoy [98]. The Single Mooring Buoy CALM type is a simple cheap flexible design. The advantages of the CALM type buoy are that the tanker needs almost no tug assistance and pumping of chemicals can take place in even severe weather circumstances. The buoy is moored with mooring lines to the seabed.
The connection between the ship and the buoy is accomplished with hoses, chains and hawsers. The connection between the buoy and the onshore terminal storage space consists of a short pipeline. An alternative solution for the restricted port access is to change the ship size from 300.000 dwt to 100.000 dwt. The 100.000 dwt ship will have a draught between 13.8 m and 14.5 m. The advantage of this ship is that the ship can enter a large number of important ports in the world. It should be noted that there are still a large number of ports, which the ship cannot enter. Another benefit is that the 100.000 dwt ship requires a smaller terminal and a smaller terminal storage space in the port.

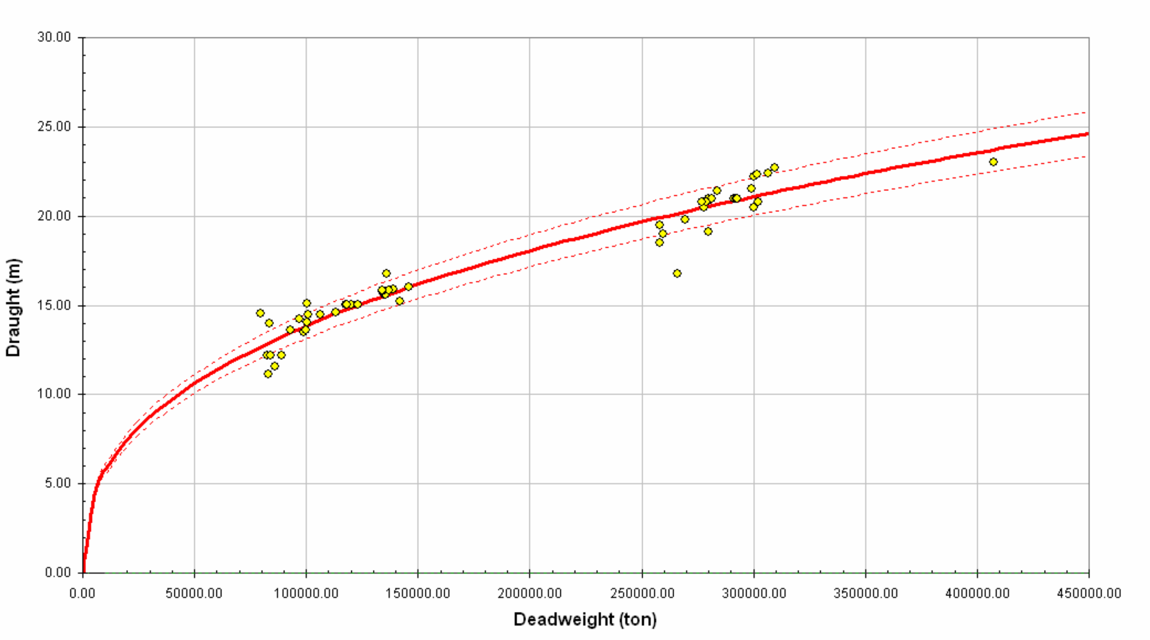

Figure 4.12 The draught of oil tankers versus the total deadweight with function
Draught = 0.168·Deadweight $^{0.383}$ [50]

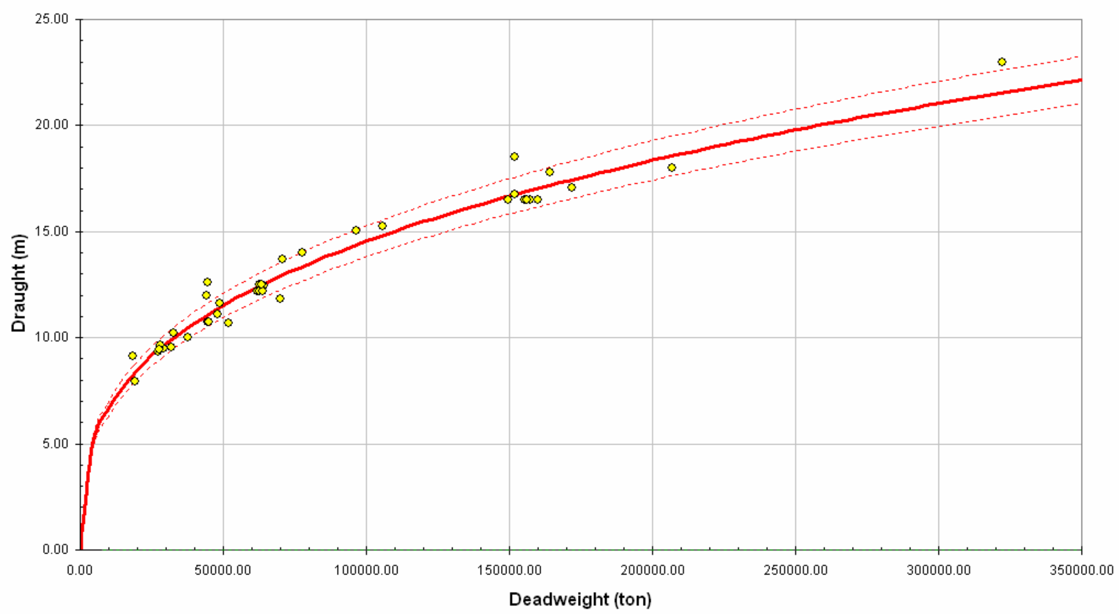

Figure 4.13 The draught of bulk carriers versus the total deadweight with function
Draught = 0.303·Deadweight $^{0.336}$ [50]

As mentioned before the battery ship transports the batteries or a part of the batteries. There are three options to achieve the battery ship. In the first option the transport is carried out with very heavy standard ISO size battery containers. This option is feasible, when the batteries are dry batteries. The battery containers are loaded and unloaded in port container terminals. In the second option the transport is accomplished with a tanker with electrolyte. The transport of electrolyte is comparable with the transport of chemicals or oil over sea.

The electrolyte is a part of the battery. This option is feasible, when the batteries are redox flow batteries. The electrolyte is pumped out and pumped into the tanker in port terminals or offshore terminals. The last option is to install the batteries permanently in the cargo vessel. In the last option the charging and the discharging will take place by means of electrical cables in port terminals or offshore terminals. From the findings in the previous text the following logistical concepts are identified for the battery ship:

- A 100.000 dwt bulk carrier with battery containers
- A 100.000 dwt tanker with battery electrolyte
- A 300.000 dwt tanker with battery electrolyte
- A 100.000 dwt tanker with batteries
- A 300.000 dwt tanker with batteries

Among the five logistical concepts the 300.000 dwt ships have lower operating costs per ton deadweight, lower capital costs per ton deadweight, lower fuel costs per ton deadweight, lower energy intensity coefficients than the 100.000 dwt ships due to the scale of economy. Therefore two logistical concepts with the 300.000 dwt ships will only be investigated in order to get an indication of the costs and the delivered energy. The logistical concepts will be investigated in three case scenarios. The differences between the case scenarios and important parameters are presented in table 4.5.

Parameters	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Energy Density in Wh/kg	**50**	**50**	**100**
DC Efficiency in %	**80**	**80**	**80**
Output Energy Density in Wh/kg	**40**	**40**	**80**
Battery Costs in USD/kWh	**87.5**	**87.5**	**87.5**
Battery Stack Costs in USD/kW	**900**	**900**	**900**
Electrolyte Costs in USD/kWh	**50**	**50**	**50**

Table 4.5 The important parameters of three case scenarios

The chosen values for parameters are based on existing batteries. The cost per MWh at site A in other words the cost per MWh of power plants is 30 USD/MWh [132].
The cost per MWh at site B for terminal equipment is assumed 60 USD/MWh.
In three case scenarios the distance and the energy density are varied in order to determine the implications of those parameters for the battery ship. From the results of the investigation the best logistical concept will be selected. The best logistical concept will have the lowest cost per MWh for energy transport and the lowest energy losses. The two logistical concepts will now be discussed in more details excluding the port times.

4.2.2 The 300.000 dwt Tanker with Electrolyte

The 300.000 dwt tanker with electrolyte transports liquid chemical so called electrolyte. The electrolytes contain the electrical energy. The 300.000 dwt tanker is assumed similar as an oil tanker. At the process plant at site A the electrolyte is charged with electricity.
The process plant is built up from a series of electrochemical cells also known as battery stack or regenerative fuel cell. The battery stack is a part of the redox flow battery.
Through the battery stack, the electrolyte is pumped to charge the electrolyte. The battery stack gets the electrical energy from the power plants. The connection between the process plant and the power plants consists of a high voltage transformer station, AC/DC electricity converter and electrical cables. The transformer station or sub station is connected to an electricity converter by means of electrical cables. The electricity converter is connected to the process plant with electrical cables. After the electrolyte is charged, the electrolyte is stored in storage tanks nearby the process plant in the offshore terminal at site A.
The storage capacity of storage tanks at the terminal must be 588000 ton or 420000 m^3 to store the charged electrolyte and the discharged electrolyte. The density of electrolyte is 1400 kg/m^3 [77]. The storage terminal is comparable with an oil terminal. The 300.000 dwt tanker is too large to enter the ports, so consequently the 300.000 dwt tanker is handled by offshore terminals. The offshore terminal consists of a CALM type buoy, which is connected to onshore storage tanks with a submarine pipeline. The CALM buoy lies in 30 m water depth, 5 km from shore for both terminals. The stored charged electrolyte is pumped into the tanker via the CALM buoy with the terminal pump. The tanker transports the charged electrolyte from the CALM buoy at site A to the CALM buoy at site B. The offshore terminal at site A is shown in figure 4.14.

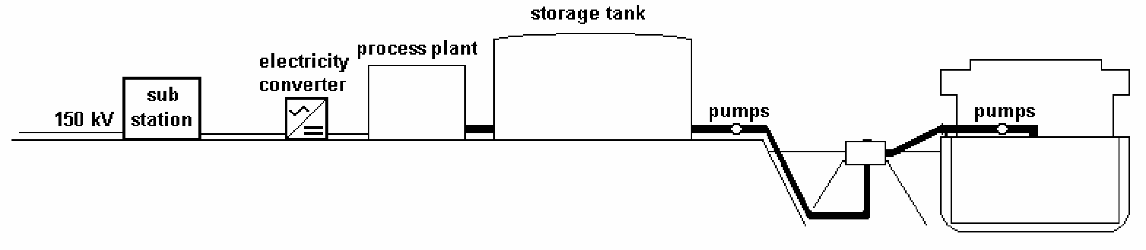

Figure 4.14 The sketch of offshore terminal at site A

At the CALM buoy at site B the charged electrolyte in the tanker is pumped out with the cargo pumps to the storage tanks at site B via a submarine pipeline.
When the charged electrolyte is pumped out, the discharged electrolyte is pumped from the storage tanks at site B into the tanker. The charged electrolyte is stored in the storage tanks till it goes with a pipeline to the nearby battery stack in the power plant. The battery stack converts electrochemical energy in electrical energy. Through the battery stack the charged electrolyte is pumped to generate the electricity. The electricity goes to the grid and the discharged electrolyte goes back to the storage tanks. The battery stack is connected to a DC/AC electricity converter with electrical cables. On his turn the electricity converter is connected to a transformer station with electrical cables. The transformer station distributes the high voltage electrical energy to the electricity consumers. The discharged electrolyte is stored in the storage tanks till the electrolyte is pumped into the tanker with the terminal pump via the CALM buoy. The 300.000 dwt tanker transports the discharged electrolyte back to the storage tanks and the process plant of the offshore terminal at site A. At the offshore terminal of site A the discharged electrolyte is pumped out via the CALM buoy into the storage tanks with cargo pumps.

The offshore terminal at site B is illustrated in figure 4.15. The logistical concept is capable to discharge electricity on demand or to charge electricity on demand. Furthermore the assumption is made that charging and discharging of electricity takes place 24 hours per day.

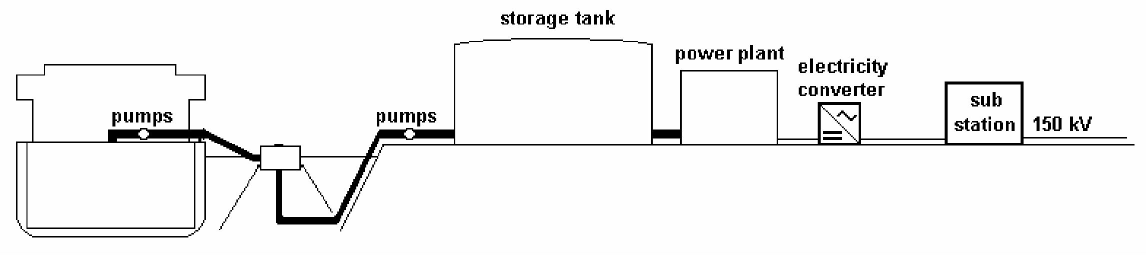

Figure 4.15 The sketch of offshore terminal at site B

4.2.3 The 300.000 dwt Tanker with Batteries

The 300.000 dwt tanker transports batteries. The batteries are permanently installed in the tanker. The batteries may consist of solid or/and liquid materials. The tanker is assumed similar as an oil tanker. The 300.000 dwt tanker is too large to enter the ports, so the 300.000 dwt tanker is handled by offshore terminals. The offshore terminal consists of a modified CALM buoy, which is connected to the AC/DC electricity converter. The CALM buoy lies in 30 m water depth, 5 km from shore for both terminals. The batteries in the tanker are charged with electrical energy from the power plants. The electricity from the grid goes through a high voltage transformer station, electricity converter, a modified CALM buoy by means of electrical cables. The connection between CALM buoy and tanker are flexible electrical cables. At the CALM buoy at site A flexible electrical cables are connected to the tanker. The flexible electrical cables are connected to the sockets on the tanker.
When the batteries are charged, the flexible electrical cables are disconnected.
The offshore terminal at site A is shown in figure 4.16.

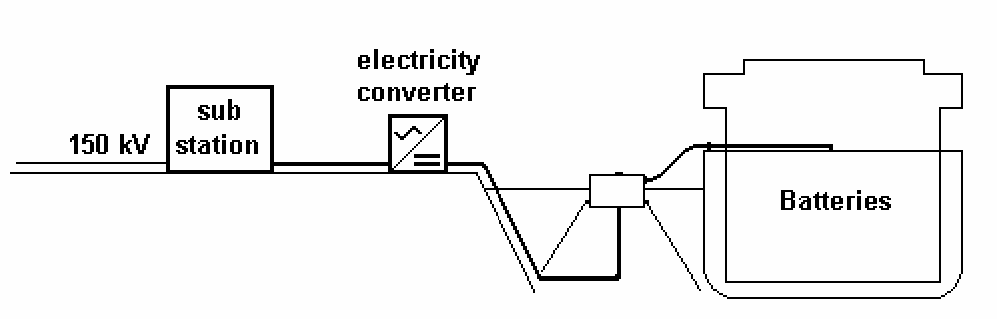

Figure 4.16 The sketch of offshore terminal at site A

The 300.000 dwt tanker transports the electrical energy in the batteries from the CALM buoy at site A to the CALM buoy at site B. At site B flexible electrical cables are connected to the tanker. Hereafter the electrical energy stored in the batteries in tanker is discharged to the electricity consumers. The tanker is connected to a modified CALM type buoy with flexible electrical cables. The electricity goes from the tanker to the electricity consumers via a modified CALM buoy, DC/AC electricity converter and high voltage transformer station. The electricity converter converts the electricity in DC current into AC current. The electrical energy goes from the electricity converter to the high voltage transformer station.
The transformer station distributes the electrical energy to the electricity consumers.

When the electrical storage devices in the tanker have discharged the electrical energy, the flexible cables are disconnected. The 300.000 dwt tanker navigates from the offshore terminal at site B back to the offshore terminal at site A. The offshore terminal at site B is illustrated in figure 4.17. The two converters and two transformers of the offshore terminals in this concept could also be replaced with one converter and one transformer in the tanker. The transformer and the converter should be well protected against seawater and corrosion. For time being, the two ports will have each one converter and one transformer, so the converter and the transformer will not be placed in the tanker. With this logistical concept it is likewise not possible to discharge electricity on demand or to charge electricity on demand.

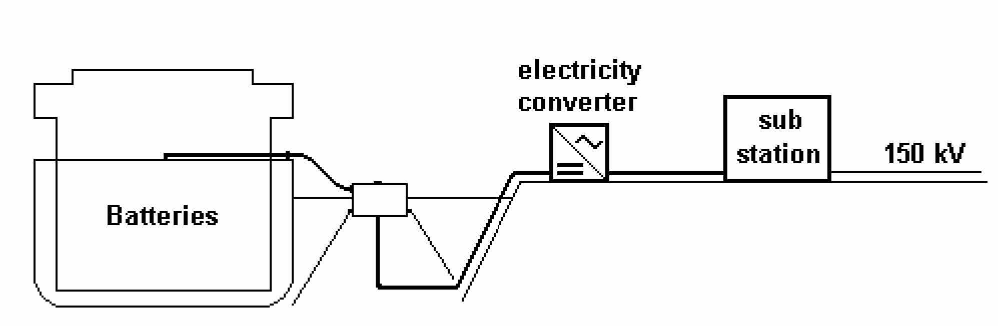

Figure 4.17 The sketch of offshore terminal at site B

4.3 Ship Costs

The shipping costs represent the costs for the transport of the batteries from origin A to destination B and back. The shipping costs are the total ship costs for a certain distance.
The total ship costs are built up from capital costs, operating costs and voyage costs.
The capital costs incur, when acquiring the vessel. The capital expenditures of the vessel are the capital costs. The operating costs incur, when operating the ship. The voyage costs are the cost associated with the voyage such as fuel costs, terminal costs and port charges.
The terminal costs are excluded in the voyage costs. The port charges are also referred as port dues. The operating expenditures are the sum of operating costs and voyage costs.
The total ship costs should be as low as possible due to the requirement to transport electricity against the lowest costs. The main reason behind this requirement is that electricity is a cargo with relative low value. As previously mentioned the requirement of lowest costs demands for economy of scale. According to the economy of scale the largest cargo vessels such as the largest bulk carriers and the largest oil tankers should have the lowest total ship costs.

4.3.1 Capital Costs

A large part of the total ship costs are the capital costs. The capital costs are also referred as capital expenditures. The capital costs are the loan to purchase the vessel.
The vessel could be a secondhand or a newbuilding vessel.
In this case the capital costs will be based on newbuilding vessels, thus the capital costs consist of the newbuilding price and the interest charges of the loan.
The acquisition of the vessel can likewise be financed with different methods such as a mixture of own money and borrowed money.

The newbuilding prices of different cargo vessel types with different ship sizes will be investigated to determine, whether the largest bulk carriers and the largest oil tankers have the lowest newbuilding prices per ton deadweight. The newbuilding prices have influence on the operating costs such as insurance costs and fuel costs. The newbuilding price of cargo vessel is not a fixed price, the price of the vessel depends on the shipyards production costs, material costs, newbuilding demand cycles, shipyards capacities, shipyards utilization rates, freight market cycles, new technologies and other factors. Although the newbuilding price of a cargo vessel type is volatile, the newbuilding price can be estimated by calculating the average newbuilding price. The average newbuilding price is the average of the inflation corrected newbuilding prices over a certain time period. In the investigation the newbuilding prices are corrected by the inflation rate consumer price index of United States of America to the year 2005. The newbuilding prices and inflation corrected newbuilding prices of the following cargo vessel types containerships, general cargoships, bulk carriers, oil tankers, chemical tankers and gas carriers are presented in Appendix B Ship Costs [9][11][12][13][53][99]. The inflation rate consumer price index of United States of America to the year 2005 is presented in Appendix B Ship Costs [99]. The average inflation corrected newbuilding prices of the following cargo vessel types containerships, general cargoships, bulk carriers, oil tankers, chemical tankers and gas carriers are shown in table 4.6.

Cargo Vessel Types	Average Price in million USD
Containership 1.100 TEU	**32.539**
General Cargoship 20.000 dwt	**37.607**
Containership 3.500 TEU	**67.645**
LPG 4.000 cbm	**21.730**
LPG 24.000 cbm	**52.531**
LPG 75.000 cbm	**87.116**
LNG 138.000 cbm	**260.143**
Handysize 27.000 dwt	**23.588**
Handymax 42.500 dwt	**28.086**
Panamax 69.000 dwt	**33.947**
Capesize 150.000 dwt	**54.787**
Chemical Tanker IMO I 8.000 dwt	**22.936**
Chemical Tanker IMO I 14.000 dwt	**32.720**
Chemical Tanker IMO I 24.000 dwt	**69.688**
Chemical Tanker IMO I 32.000 dwt	**95.954**
Products 45.000 dwt	**37.048**
Panamax 68.000 dwt	**48.909**
Aframax 100.000 dwt	**52.900**
Suezmax 150.000 dwt	**67.147**
Vlcc 280.000 dwt	**105.061**

Table 4.6 The average newbuilding prices of different cargo vessel types

In table 4.6 the deadweight of some cargo vessel types are not presented.
Those deadweights of containerships, LNG carriers and LPG carriers are estimated with the following functions [50]:

$$\mathbf{Deadweight = 18.597 \cdot TEU^{0.96}} \tag{4.10}$$

$$\mathbf{Deadweight = 0.517 \cdot (CBM\ LNG)} \tag{4.11}$$

$$\mathbf{Deadweight = 2.193 \cdot (CBM\ LPG)^{0.89}} \tag{4.12}$$

The average newbuilding prices per ton deadweight of the following cargo vessel types containerships, general cargoships, bulk carriers, oil tankers, chemical tankers and gas carriers are presented in table 4.7 with the use of equation 4.10 till 4.12 and the average newbuilding prices in table 4.6. According to table 4.7 the highest average newbuilding prices per ton deadweight have the gas carriers. The containerships, general cargoship and chemical tankers have likewise high average newbuilding prices per ton deadweight. The high average newbuilding prices per ton deadweight of those ships push the ships towards relative higher speeds. The high average newbuilding prices per ton deadweight imply that they are not considered for the battery ship.

Cargo Vessel Types	Average Price/Deadweight in USD/DWT
Containership 1.100 TEU	**2105**
General Cargoship 20.000 dwt	**1880**
Containership 3.500 TEU	**1440**
LPG 4.000 cbm	**6168**
LPG 24.000 cbm	**3027**
LPG 75.000 cbm	**1821**
LNG 138.000 cbm	**3646**
Handysize 27.000 dwt	**874**
Handymax 42.500 dwt	**661**
Panamax 69.000 dwt	**492**
Capesize 150.000 dwt	**365**
Chemical Tanker IMO I 8.000 dwt	**2867**
Chemical Tanker IMO I 14.000 dwt	**2337**
Chemical Tanker IMO I 24.000 dwt	**2904**
Chemical Tanker IMO I 32.000 dwt	**2999**
Products 45.000 dwt	**823**
Panamax 68.000 dwt	**719**
Aframax 100.000 dwt	**529**
Suezmax 150.000 dwt	**448**
Vlcc 280.000 dwt	**375**

Table 4.7 The average newbuilding prices per ton deadweight in USD/DWT of different cargo vessel types

Moreover table 4.7 proves that the largest bulk carriers and the largest oil tankers have the lowest newbuilding prices per ton deadweight, so consequently the largest bulk carriers and the largest oil tankers have the lowest capital costs per ton deadweight.
The newbuilding prices of bulk carriers and oil tankers based on table 4.6 versus deadweight are shown in figure 4.18 and in figure 4.19. The largest bulk carriers have the lowest newbuilding prices per ton deadweight, but the difference with the largest oil tankers is small. The lowest newbuilding prices per ton deadweight make the largest bulk carriers and the largest oil tankers very attractive for the battery ship, but what are the operating costs, running costs and total ship costs of those two cargo ships? In the next paragraphs the operating costs, the running costs and the total ship costs of bulk carriers and oil tankers will be examined. In addition the table 4.6 and the table 4.7 demonstrate that in general the economy of scale implies for the average newbuilding prices of cargo ships, except for the chemical tankers. The economy of scale means that the average newbuilding prices per ton deadweight decrease as the deadweight rises.

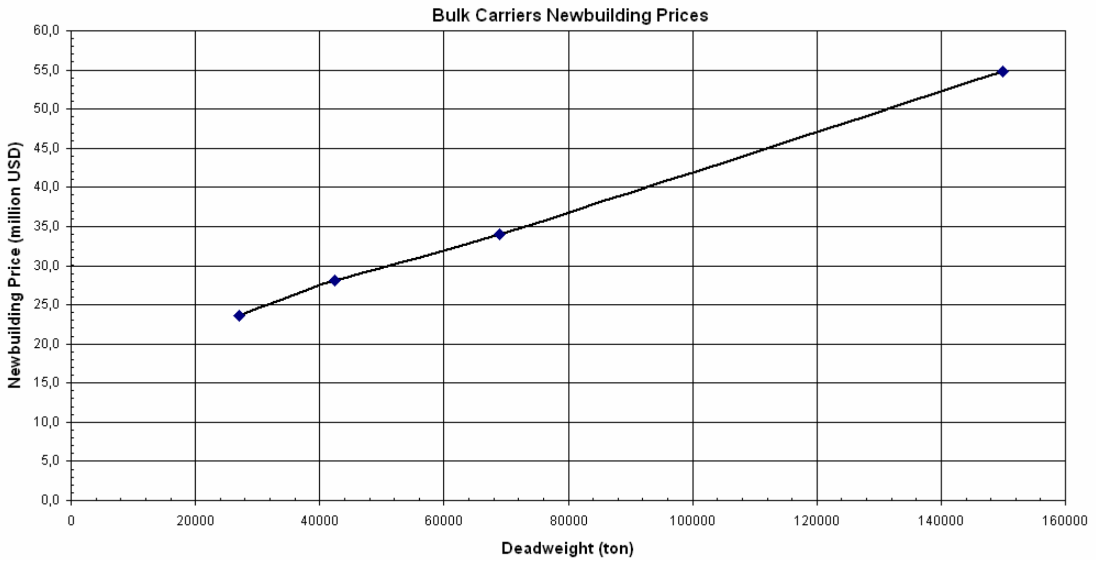

Figure 4.18 The newbuilding prices of bulk carriers versus deadweight approximated by the function **Newbuilding Price = 0.0003·Deadweight + 16.934**

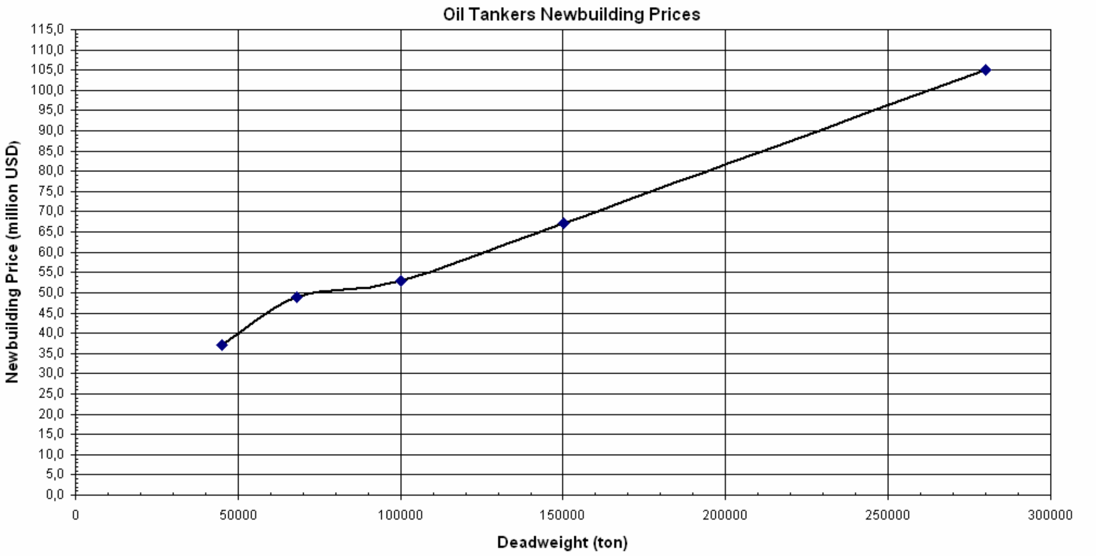

Figure 4.19 The newbuilding prices of oil tankers versus deadweight approximated by the function **Newbuilding Price = 0.0003·Deadweight + 26.173**

4.3.2 Operating Costs

The operating costs are the costs to get the ship operational. The operating costs can be broken down into following costs

- Manning Costs
- H&M Insurance Costs
- P&I Insurance Costs
- Repairs and Maintenance Costs
- Stores and Supplies Costs
- Administration Costs

The manning costs are the wages for seafarers. The wages include the guaranteed/fixed overtime and holidays. The manning costs depend on the rank build-up of the crew and the nationality of the crew. The manning costs are a large part of the operating costs.

The H&M insurance costs are the costs for the insurance for the hull and the machinery. The insurance covers damage or total loss of hull and machinery. The insurance costs depend on assessed hull value of the vessel and the owner's record. The H&M insurance costs are larger than the P&I insurance costs. The P&I insurance costs are the costs for Protection and Indemnity to the assets belonging to third parties such as cargo. The P&I insurance costs depend on cargo vessel type, vessel size and P&I Club. The repairs and maintenance costs are the costs for the inspection, maintenance and repair of the ship and the loss for income. The costs are the result of the regular running repairs and maintenance, the periodic dry docking for special surveys, maintenance and repairs. The repairs and maintenance costs rise, when the age of the ship increases. The repairs and maintenance costs depend on the vessel type, vessel size, vessel age, shipyard, class requirements and shipping market.

The repairs and maintenance costs are a large component of the operating costs.

The stores and supplies costs are the costs for marine and deck stores, engine room stores, steward's stores and spare parts. The marine and deck stores costs are the costs for paints, fresh water supplies, safety equipment, etc. The engine room stores costs are the costs for lubricating oils, chemicals and other items for the engine room. The steward's stores costs are the costs for food, clothing and other stores for the crew. The administration costs are the costs for the administration, overhead and management. The build-up of the operating costs of cargo vessels depends mainly on the vessel type and vessel size.

The build-up of the operating costs of bulk carriers and oil tankers show that the manning costs decrease, when the deadweight of the vessel increases. Some costs such as repairs and maintenance costs will increase, when the age of the vessel increases. The build-up of operating costs of bulk carriers and oil tankers is shown in figure 4.20 and figure 4.21.

The operating costs and the inflation corrected operating costs for the time period 1990-2000 for the bulk carriers and oil tankers are presented in the Appendix B Ship Costs.

The average operating costs of different cargo vessel types are listed in table 4.8 [9][11][12][13][99]. The operating costs are based on the information from Drewry Shipping Consultants. The average operating costs based on table 4.8 versus the deadweight for bulk carriers and oil tankers are shown in figures 4.22 and 4.23.

Cargo Vessel Types	Average Operating Costs in USD/day
Handysize 27.000 dwt	**5184**
Handymax 42.500 dwt	**5439**
Panamax 69.000 dwt	**6063**
Capesize 150.000 dwt	**7213**
Chemical Tanker IMO I 8.000 dwt	**7385**
Chemical Tanker IMO I 14.000 dwt	**8483**
Chemical Tanker IMO I 24.000 dwt	**9529**
Chemical Tanker IMO I 32.000 dwt	**12938**
Products 45.000 dwt	**7385**
Aframax 100.000 dwt	**8483**
Suezmax 150.000 dwt	**9529**
Vlcc 280.000 dwt	**12938**

Table 4.8 The average operating costs in USD/day of different cargo vessel types

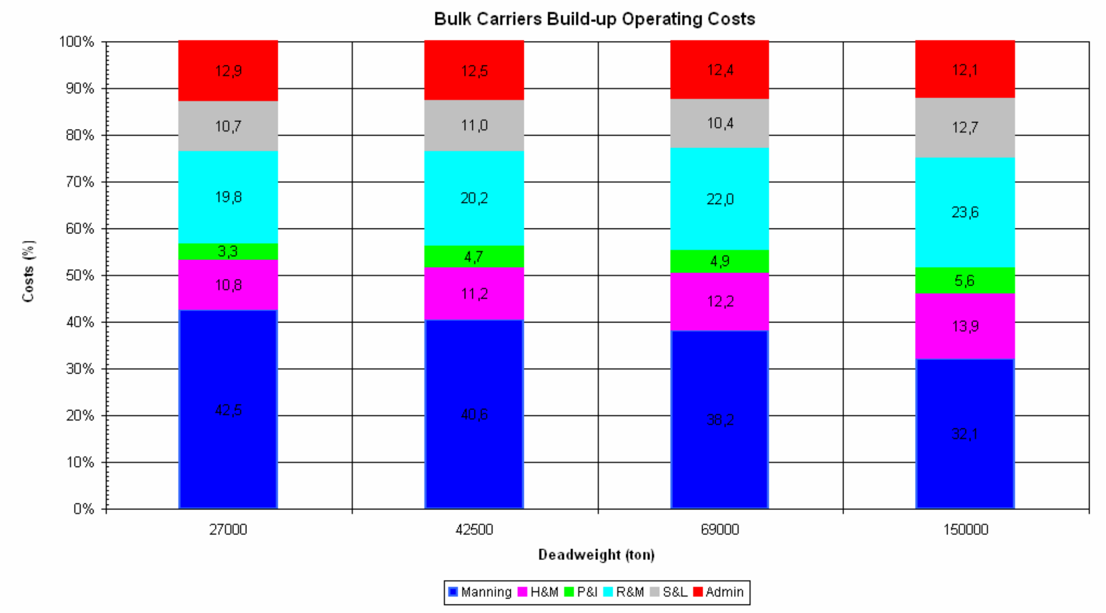

Figure 4.20 The build-up of operating costs of bulk carriers in %

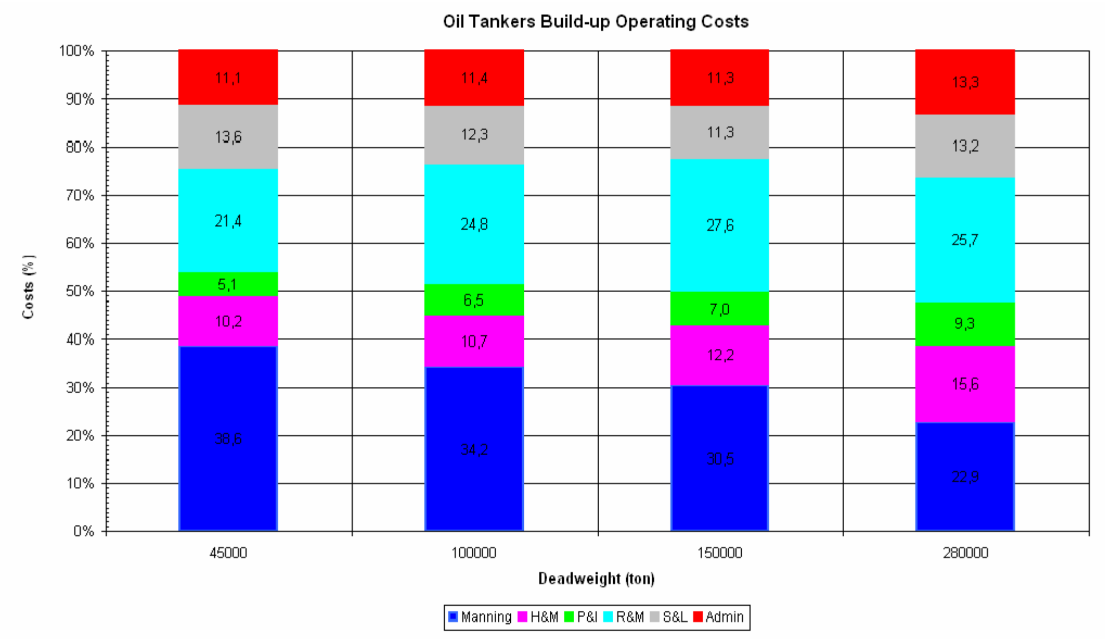

Figure 4.21 The build-up of operating costs of oil tankers in %

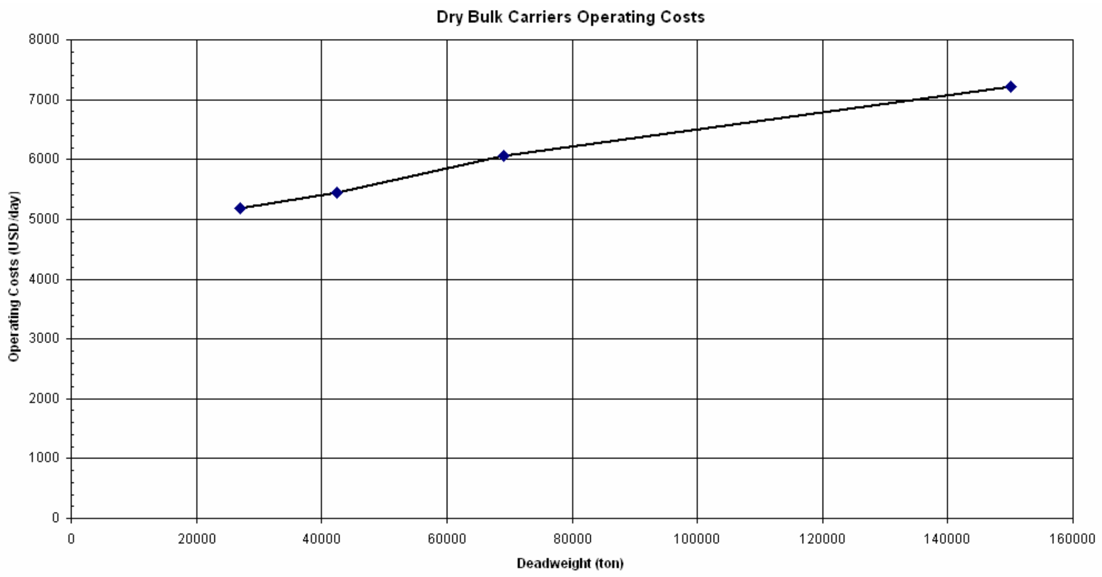

Figure 4.22 The operating costs of bulk carriers in USD/day versus the deadweight approximated by the function

Operating Costs = 0.0164·Deadweight + 4789.3

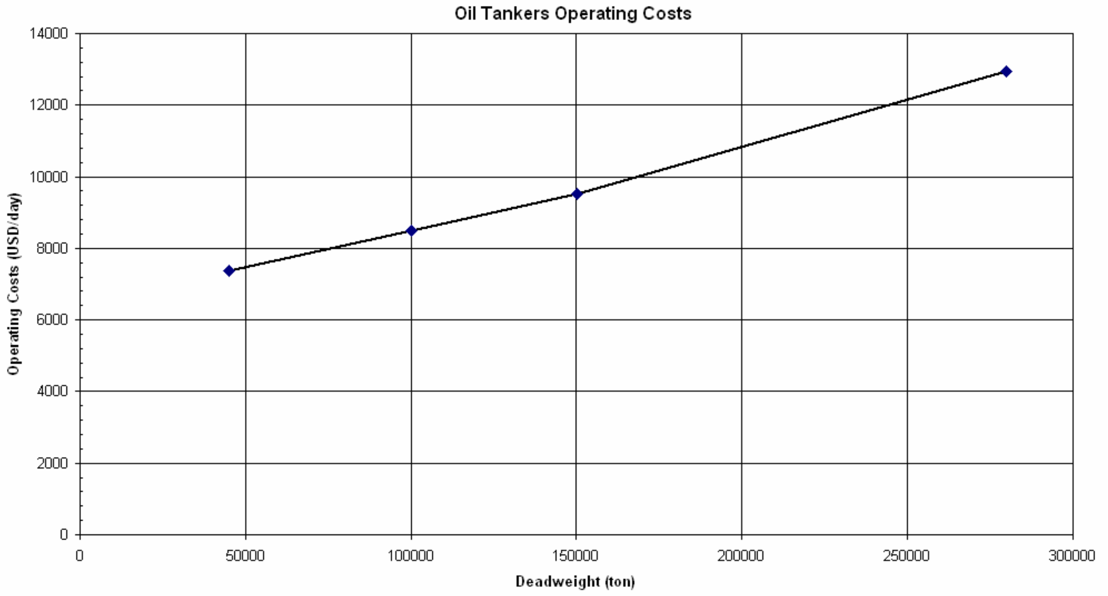

Figure 4.23 The operating costs of oil tankers in USD/day versus the deadweight approximated by the function
Operating Costs = 0.0239·Deadweight + 6155.3

4.3.3 Total Ship Costs

The total ship costs are the sum of capital costs, operating costs and voyage costs.
In this case the voyage costs are the fuel costs. The running costs are the vessel costs during a certain time period, when the vessel is operational and not sailing.
The running costs are the sum of capital costs and operating costs.
The newbuilding price is financed with a loan with an interest rate of 8% for the period of 30 years. The operating lifetime of oil tankers and bulk carriers is assumed 30 years.
The running costs of bulk carriers are illustrated in figure 4.24. The running costs of oil tankers are shown in figure 4.25. The two figures illustrate that the bulk carriers have the lowest running costs per deadweight. Besides the running costs the distance costs are likewise important. The distance costs are here defined as the total ship costs for traveling a certain distance. The total ship costs are the sum of fuel costs and running costs. The fuel costs are the product of energy consumption and energy price. The energy consumption depends on the individual characteristics of the vessel and the propulsion plant. The energy price in USD/MWh is obtained by equation (4.13) with specific fuel rate in ton/MWh of the propulsion plant and fuel price in USD/ton.

$$\textbf{Energy Price} = \textbf{Specific Fuel Rate} \cdot \textbf{Fuel Price} \qquad (4.13)$$

The energy price as function of the fuel price for different specific fuel rates is illustrated in figure 4.26.

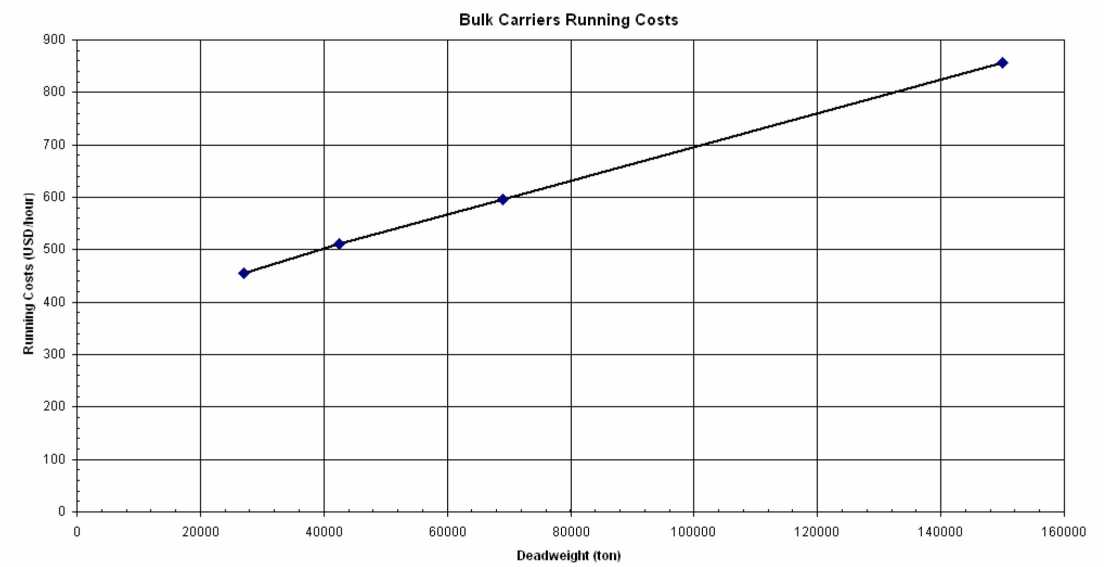

Figure 4.24 The running costs of bulk carriers in USD/hour versus the deadweight in ton

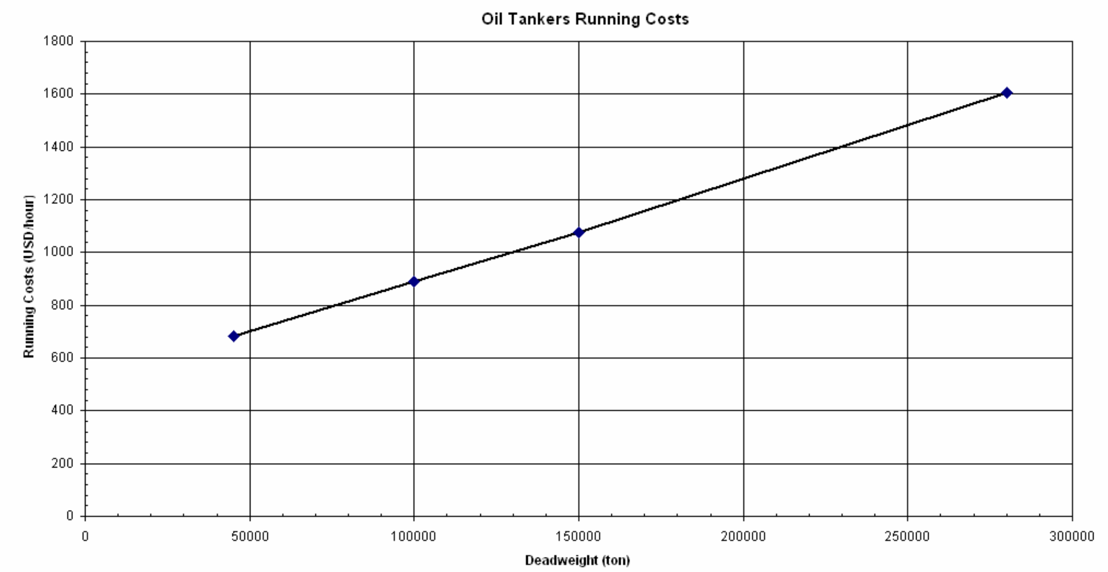

Figure 4.25 The running costs of oil tankers in USD/hour versus the deadweight in ton

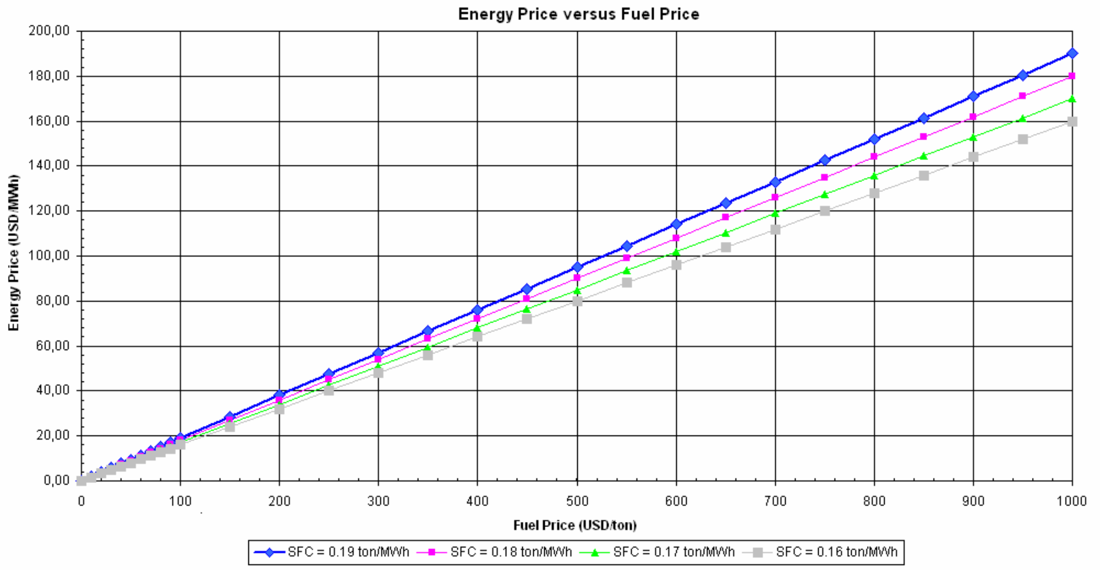

Figure 4.26 The energy price in USD/MWh versus the fuel oil price in USD/ton with different specific fuel rates in ton/MWh

The fuel costs in USD/(ton·nautical mile) are the product of energy price in USD/MWh and the energy intensity in Wh/(ton·nautical mile), which are reflected in equation (4.14).
The energy intensity depends on the vessel speed.

$$\textbf{Fuel Costs} = \textbf{Energy Intensity} \cdot \textbf{Energy Price} \tag{4.14}$$

The distance costs in USD/(ton·nautical mile) are calculated with equation (4.15) with the fuel costs in USD/(ton·nautical mile), the running costs in USD/(ton·hour) and the vessel speed in knots.

$$\textbf{Distance Costs} = \textbf{Fuel Costs} + \frac{\textbf{Running Costs}}{\textbf{Speed}} \tag{4.15}$$

The roundtrip costs in USD/ton are the result of the distance costs in USD/(ton·nautical mile), the distance in nautical miles, the port times in hours and the running costs in USD/(ton·hour). The roundtrip costs are calculated with the equation (4.16).

$$\textbf{Roundtrip Costs} = \textbf{Distance Costs} \cdot \textbf{Distance} + \textbf{Running Costs} \cdot \textbf{Port Times} \tag{4.16}$$

The round trip costs are likewise expressed in USD. The distance versus the speed with the energy price of 60 USD/MWh is shown in figure 4.27 and in figure 4.28.
In addition the figures show the economic speeds of the different ship sizes.
The economic speed is the speed with the minimum distance costs.
The energy price of 60 USD/MWh is based on the fuel price of 350 USD/ton and the specific fuel rate of 0.171 ton/MWh. The distance costs are high at very low speeds, because the distance costs are mainly determined by the running costs.
The distance costs go to a minimum value, when the speed increases.
After the minimum value the distance costs increase, because the fuel costs increase rapidly at relative high speeds. The two figures demonstrate also the economy of scale, because the distance costs decrease with the rise of vessel deadweight.

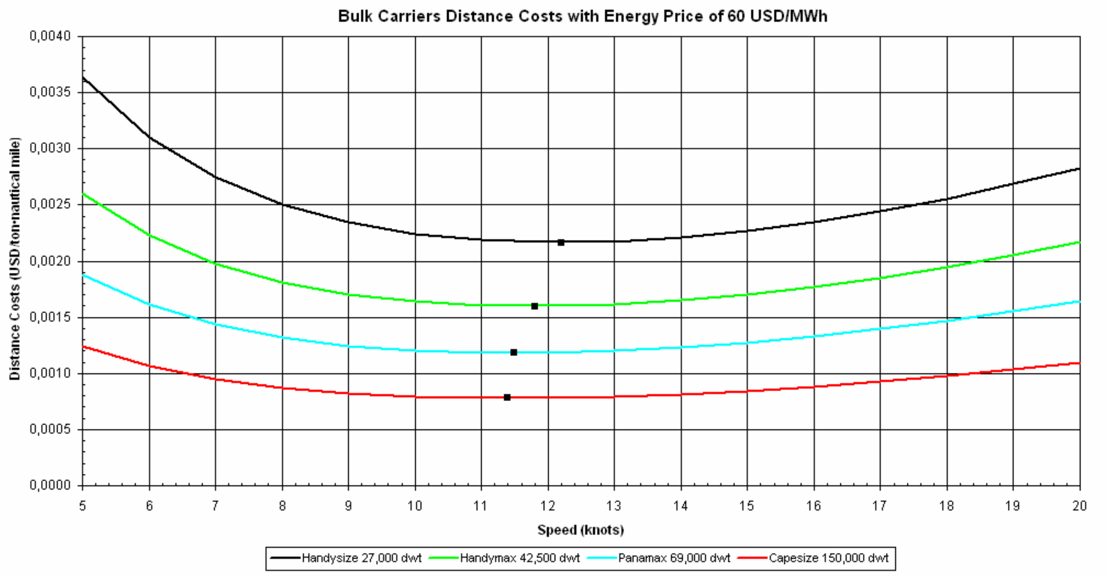

Figure 4.27 The distance costs of bulk carriers at energy price of 60 USD/MWh

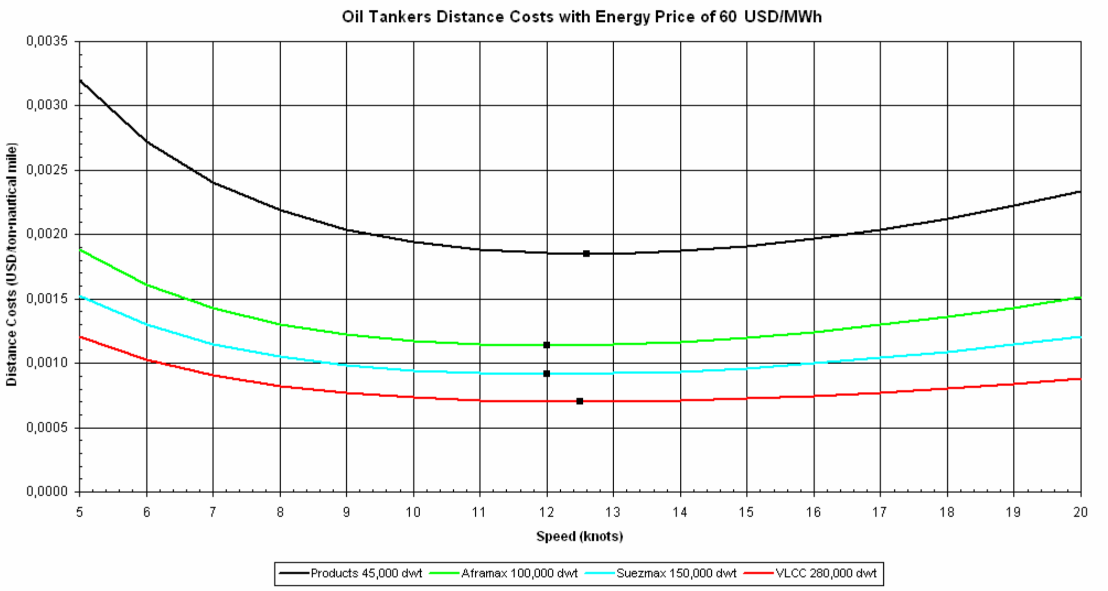

Figure 4.28 The distance costs of oil tankers at energy price of 60 USD/MWh

The 280.000 dwt VLCC oil tanker and the 150.000 dwt Capesize bulk carrier have the lowest energy intensity coefficients, so consequently the large vessels have the lowest fuel costs. Besides that the large vessels have the lowest fuel costs, the large vessels have likewise the lowest running costs. Therefore 280.000 dwt VLCC oil tanker and the 150.000 dwt Capesize bulk carrier have the lowest distance costs. The influence of the energy price on the distance costs of the 280.000 dwt VLCC oil tanker and the 150.000 dwt Capesize bulk carrier is shown in figure 4.29. The figure 4.29 indicates that the economical speeds shift to lower speeds and the distance costs rise, when the energy price increases. Next the total ship costs or break-even freight rates and round trip costs of the two logistic concepts for three case scenarios excluding terminal costs will be determined.

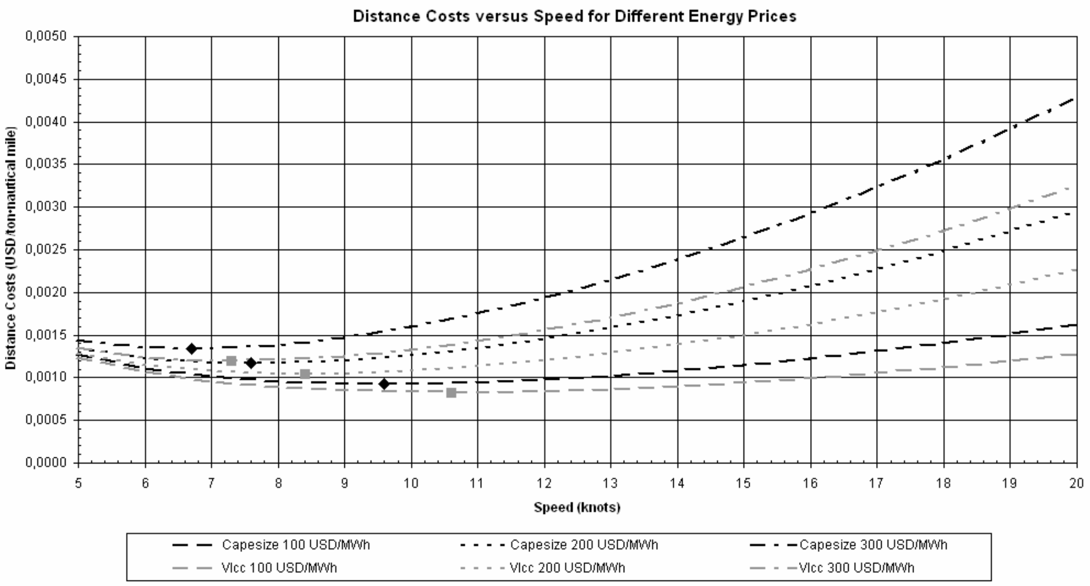

Figure 4.29 The distance costs of oil tanker VLCC and bulk carrier Capesize versus the speed for different energy prices

4.3.4 The 300.000 dwt Tanker with Electrolyte

The 300.000 dwt tanker with electrolyte carries liquid electrolyte in a modified VLCC tanker. The modified VLCC tanker is assumed similar as a VLCC oil tanker.
The ship costs and the characteristics of the VLCC tanker are listed in table 4.9.
The ship costs in table 4.9 are the same for all three case scenarios.
The cargo deadweight of 300.000 dwt tanker is 294000 ton, so the tanker transports 294000 ton electrolyte. The electrolyte in the cargo holds of the tanker contains the electrical energy. The cost of electrolyte is 50 USD/kWh. The electrolyte is pumped in and out at the offshore terminal. The port time in the offshore terminal consists of 24 hours for unloading the electrolyte and 24 hours for loading the electrolyte, so the port time in one offshore terminal is 48 hours. The loading time and unloading time are based on the unloading times of crude oil tankers. The unloading times and the cargo pumps capacity of oil tankers, product tankers and chemical tankers are presented in Appendix C Unloading Times.
The figures in Appendix C Unloading Times show the evidence that the crude oil tankers, chemical tankers and product tankers can be unloaded within 24 hours, if all cargo pumps are used simultaneously. Furthermore it is worth noting that the unloading time depends on the pump capacity and the cargo volume. During one roundtrip 1 hour is added as waiting time.
The distance costs are calculated with the energy price of 60 USD/MWh.
The characteristics of bulk electricity transport with the 300.000 dwt tanker with electrolyte are presented in table 4.10. The energy consumption of the tanker is based on the brake power of the main engine. The characteristics of the roundtrip for the three case scenarios are listed in Appendix D Roundtrip.

Description	Day Costs in USD/day	Year Costs in USD/year	Project Costs in million USD
Newbuilding Price	**10609**	**3872433**	**116.17**
Capital Costs (CAPEX)	**28272**	**10319349**	**309.58**
Operating Costs	**13325**	**4863735**	**145.91**
Running Costs	**41597**	**15183084**	**455.49**
Calculated Economical Speed	**12.7 knots**		
Installed Power	**14306.4 kW**		
Energy Intensity	**3.832 Wh/ton·nautical mile**		
Distance Costs	**0.00069409 USD/ton·nautical mile**		

Table 4.9 The ship costs and the characteristics of the 300.000 dwt VLCC tanker

Parameters	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Electrolyte Weight in ton	**294000**	**294000**	**294000**
Stored Energy in Batteries in GWh	**14.70**	**14.70**	**29.40**
Ship Delivered Energy in GWh	**11.76**	**11.76**	**23.52**
Total Ship Delivered Energy in GWh	**17287.2**	**11642.4**	**23284.8**
Roundtrip Energy Consumption in MWh	**1126.5**	**2253.0**	**2253.0**
Total Energy Consumption in MWh	**1655943**	**2230454**	**2230454**
Running Costs in million USD	**455.49**	**455.49**	**455.49**
Fuel Costs in million USD	**99.36**	**133.83**	**133.83**
Total Ship Costs in million USD	**554.85**	**589.32**	**589.32**

Table 4.10 The characteristics of bulk electricity transport with the 300.000 dwt tanker with electrolyte

The table 4.10 indicates that the fuel costs and the total ship costs rise, when the distance increases. In addition the same table shows that the ship delivered energy increases, when the output energy density increases.

4.3.5 The 300.000 dwt Tanker with Batteries

The 300.000 dwt tanker with batteries transports permanently installed batteries in a modified VLCC tanker. The modified VLCC tanker is assumed similar as a VLCC oil tanker. The permanently installed batteries in the tanker store the electrical energy.
The cargo deadweight of 300.000 dwt tanker is 294000 ton, so the tanker transports 294000 ton batteries. The batteries are charged and discharged in offshore terminals. The ship costs and the characteristics of the VLCC tanker are already listed in table 4.9. The roundtrip costs depend on travel times and port times. The port times in the offshore terminals are determined by the discharge rate and the charge rate of the batteries. The charge time is assumed double the discharge time [101]. Of course, the charge time and the discharge time have implications for the roundtrip costs. The influence of the charge time and the discharge time is determined by calculating the total ship costs for two different charge rate scenarios with chosen charge times and chosen discharges times, so there are six case scenarios. In the first charge rate scenario the chosen charge time is 48 hours and the chosen discharge time is 24 hours. The chosen discharge time is based on the unloading times of crude oil tankers.
The battery costs for the first charge rate scenario is 87.5 USD/kWh. The battery costs are based on figure 4.36.

The characteristics of bulk electricity transport with the 300.000 dwt tanker with batteries for the first charge rate scenario are presented in table 4.11. The characteristics of the roundtrip for the first charge rate scenario are listed in Appendix D Roundtrip.

Parameters	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Battery Weight in ton	**294000**	**294000**	**294000**
Stored Energy in Batteries in GWh	**14.70**	**14.70**	**29.40**
Ship Delivered Energy in GWh	**11.76**	**11.76**	**23.52**
Total Ship Delivered Energy in GWh	**19756.8**	**13053.6**	**26107.2**
Roundtrip Energy Consumption in MWh	**1126.5**	**2253.0**	**2253.0**
Total Energy Consumption in MWh	**1892506**	**2500812**	**2500812**
Running Costs in million USD	**455.49**	**455.49**	**455.49**
Fuel Costs in million USD	**113.55**	**150.05**	**150.05**
Total Ship Costs in million USD	**569.04**	**605.54**	**605.54**

Table 4.11 The characteristics of bulk electricity transport with the 300.000 dwt tanker with batteries for the first charge rate scenario

The charge time and the discharge time in the second charge rate scenario are double the charge time and the discharge time in the first charge rate scenario, so in the second charge rate scenario the chosen charge time is 96 hours and the chosen discharge time is 48 hours. The battery costs in the second charge rate scenario are 68.75 USD/kWh. The battery costs are based on figure 4.36. The characteristics of bulk electricity transport with the 300.000 dwt tanker with batteries for the second charge rate scenario are presented in table 4.12. The characteristics of the roundtrip for the second charge rate scenario are listed in Appendix D Roundtrip.

Parameters	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Battery Weight in ton	**294000**	**294000**	**294000**
Stored Energy in Batteries in GWh	**14.70**	**14.70**	**29.40**
Ship Delivered Energy in GWh	**11.76**	**11.76**	**23.52**
Total Ship Delivered Energy in GWh	**13406.4**	**9878.4**	**19756.8**
Roundtrip Energy Consumption in MWh	**1126.5**	**2253.0**	**2253.0**
Total Energy Consumption in MWh	**1284201**	**1892506**	**1892506**
Running Costs in million USD	**455.49**	**455.49**	**455.49**
Fuel Costs in million USD	**77.05**	**113.55**	**113.55**
Total Ship Costs in million USD	**532.54**	**569.04**	**569.04**

Table 4.12 The characteristics of bulk electricity transport with the 300.000 dwt tanker with batteries for the second charge rate scenario

According to the tables from 4.10 till 4.12 in the first charge rate scenario more energy is delivered than in the second charge rate scenario. Furthermore the total ship costs in the first charge rate scenario are higher than in the second charge rate scenario due to higher frequency.

4.4 Terminal Costs

The terminal is a facility for receiving the vessels and transferring and transforming the cargo. The terminal is located in a harbour or at sea. A terminal situated at sea is an offshore terminal. The location and design of the terminal depends upon several factors such as ship size, characteristics of the cargo, cargo flow, cargo flow direction and the geographical location. The most important factor is the characteristic of the cargo.
Over time different terminals are developed to facilitate the different cargoes such as container terminals for containers, ro-ro berths for trucks, bulk terminals for dry bulk cargoes, oil terminal for oil, etc. In this case the cargo is electricity, so an electricity terminal is necessary for the transfer of electricity between the sea vessel and the grid or power plants. It should be noted that the electricity in the logistical concepts is stored in batteries or in electrolyte. In general the terminal has the following functions:

- Loading/Unloading
- Transferring
- Storage
- Transformation

The functions incorporated in the terminal depend on the design of the terminal, so consequently there will be terminals with not all mentioned functions.
The logistical concept 300.000 dwt tanker with electrolyte has all four functions.
The function loading/unloading consists of pumping the electrolyte in and out the vessel with pumps. The function transferring consists of transporting the electrolyte in the terminal.
The function storage consists of storing electrolyte in storage tanks.
The function storage enables the terminal to discharge electricity on demand and to receive a volatile amount of electricity gradually over time. The last function transformation is the conversion of the electrochemical energy in the electrolyte into electricity.
The logistical concept 300.000 dwt tanker with batteries has only two functions.
The function loading/unloading consists of discharging and charging the batteries with electrical cables. The last function transformation is the conversion of high voltage direct current into high voltage alternating current or vice versa.
It should be noted that before unloading or loading at the terminal can take place, the ship requires to be moored and to be connected to the terminal. After loading or unloading at the terminal, the ship requires to be disconnected and to be unmoored.

4.4.1 Common Equipment

The largest common equipment in the two logistical concepts is the transformer station, the electrical cables and the electricity converter. The three phase transformer station converts low voltage into high voltage or vice versa. The energy losses in the large transformer station are assumed 0.4% of the rated power. The footprint of the transformer station is estimated 1.7 m^2/MW [100]. The cost of the transformer station in million USD is calculated with the following equation [33].

$$\textbf{Transformer Cost} = -0.1580064 + 0.000280308 \cdot \textbf{Rated Power}^{0.4473} \qquad (4.17)$$

The rated power in the equation above is the rated power of transformer station in W.

The cost of the transformer station includes the cost for installing the transformer station in the harbour. The other important common equipment is the electricity converter.
The three level electricity converters are voltage sourced converters (VSC) with insulated gate bipolar transistors (IGBTs). The voltage sourced converters are already discussed in paragraph 3.1. The energy losses in the three level electricity converters are 1.6% [33].
The footprint of electricity converter is 4 m^2/MW [33]. The cost of the electricity converter depends on the rated power through the electricity converter. The cost of the electricity converter is 132 USD/kW for electricity converter below 100 MW [33][35][36]. Between 100 MW and 250 MW the cost of electricity converter is 120 USD/kW [33][35][36].
The typical cost of large electricity converters above 250 MW is 114 USD/kW [33][35][36].
The cost of electricity converter includes AC filters and reactors, protection systems, DC capacitances, control systems, connection transformers, IGBT bridges and the cost for installing the electrical converter in the harbour. The last essential common equipment is the electrical cables. The electrical cables conduct the electrical energy and they connect the different electrical equipment with each other. The AC cables are more expensive than DC cables. In the electricity terminals the AC cable is required for the short distance from electricity converter to transformer station. The distance from the electricity converter to transformer station is 25 meters. The AC cable from the transformer station to the other components of the grid belongs to the grid and it is not a part of the terminal.
The DC cable is required for the cable connection between batteries and electricity converter. A part of the cable connection is the flexible DC cable. For the time being, the flexible DC cable is assumed similar as the normal DC cable connection. The typical DC cable costs below 15 MW are 15 USD/m and the typical cost for AC cable and flexible cable below 15 MW are 20 USD/m [35][36]. The typical electrical cable costs in USD/m above 15 MW are calculated with the rated power in MW through the following equation [33]

$$\textbf{Cable Costs} = -10.9 + 1.8 \cdot \textbf{Rated Power} \qquad \textbf{(4.18)}$$

The cable costs are presumed valid for all type cables. The installation costs of cables depend on canalisation distance, location, ground type and other several practical issues.
The onshore installation costs of cables are estimated 120 USD/m [35][36].
The offshore installation costs of cables are estimated 50 USD/m [33].
Furthermore the electrical power is multiplied with the factor 1.02, so that the electrical equipment is slightly overdimensioned. Besides that the lifetime of all terminal equipment including battery stack is assumed 30 years. The major part of terminal equipment is installed on harbour ground. The harbour ground price is 10 USD/m^2/year, so the harbour ground price for the period 30 years is 300 USD/m^2 [76]. In addition the following issues in the calculation of the terminal costs are neglected:

- the energy losses in the electrical cables are neglected, because the total distance of the cables is very short and the energy losses in the cables is very small.
- the additional costs for the AC cable and flexible cables are neglected, because the cables are used for short distances.
- the maintenance costs of the terminal equipment are neglected, because the maintenance costs is relative small.

4.4.2 The 300.000 dwt Tanker with Electrolyte

The offshore terminal for 300.000 dwt Vlcc tanker with electrolyte is a liquid chemical terminal with battery stacks, electricity converter and transformer station.
The offshore terminal is composed of the following components:

- CALM buoy
- Pipeline
- Terminal pump
- Terminal storage tanks
- Battery stacks
- Electricity converter
- Transformer station

As mentioned before all components are located on shore, except the CALM buoy and a major part of the pipeline. The CALM buoy lies in 30 m waterdepth, 5 km from the shore. The CALM buoy is linked to the terminal storage tanks located on shore with a pipeline. The CALM buoy consists of loading buoy, mooring system and riser system. The mooring system is composed of drag embedded anchors and 6 75 meter 4 inch mooring chains [54]. The riser system is a flexible pipeline, which connects the loading buoy to the pipeline on the seabed. The cost of the loading buoy is 8900000 USD [54]. The cost of mooring system and riser system for the waterdepth of 30 m is 769400 USD. The cost for the CALM buoy is the sum of the cost of mooring system, riser system and loading buoy, so the cost for the CALM buoy is 9669400 USD [54]. The installation of the CALM buoy is accomplished with an AHTS vessel**.** The cost of installation of the CALM buoy is estimated 1000000 USD, therefore the cost for the CALM buoy including installation is 10669400 USD [54]. Furthermore the cost for the internal insulated corrosion resistant pipeline is 2000 USD/m [54]. The pipeline must be corrosion resistant due to the liquid electrolyte. The distance of pipeline in the terminal is assumed 11 km. The pipeline is connected to the loading buoy, terminal storage tanks and the battery stacks. The terminal pump is required to pump the electrolyte into the tanker. For the time being, the terminal pump is assumed similar as cargo pumps concerning the costs and the energy consumption. Therefore the specific energy consumption of unloading the electrolyte is equal to the specific energy consumption of loading the electrolyte. In practice, there will be a small difference between unloading and loading electrolyte, but for the time being the difference is neglected. There are two cargo pump arrangements available. The first arrangement uses hydraulic driven submersible pumps. The second arrangement uses electric deepwell pumps with frequency converters. Both arrangements are capable to pump out the liquid chemical with a density range from 500 kg/m^3 till 2500 kg/m^3. As stated before the density of electrolyte is 1400 kg/m^3.
The specific energy consumption of the electric system is 0.41 kWh/m^3 and the hydraulic system is 0.48 kWh/m^3 for unloading the cargo tanks, so the electric arrangement requires less energy [37]. The specific energy consumption based on weight is illustrated in figure 4.30. According to the figure 4.30 the specific energy consumption based on weight decreases, when the density of chemical increases.
The specific energy consumption based on weight is for the electric arrangement 0.293 kWh/ton and for the hydraulic arrangement 0.343 kWh/ton, so the electric arrangement will be utilized for cargo pumps and terminal pump.

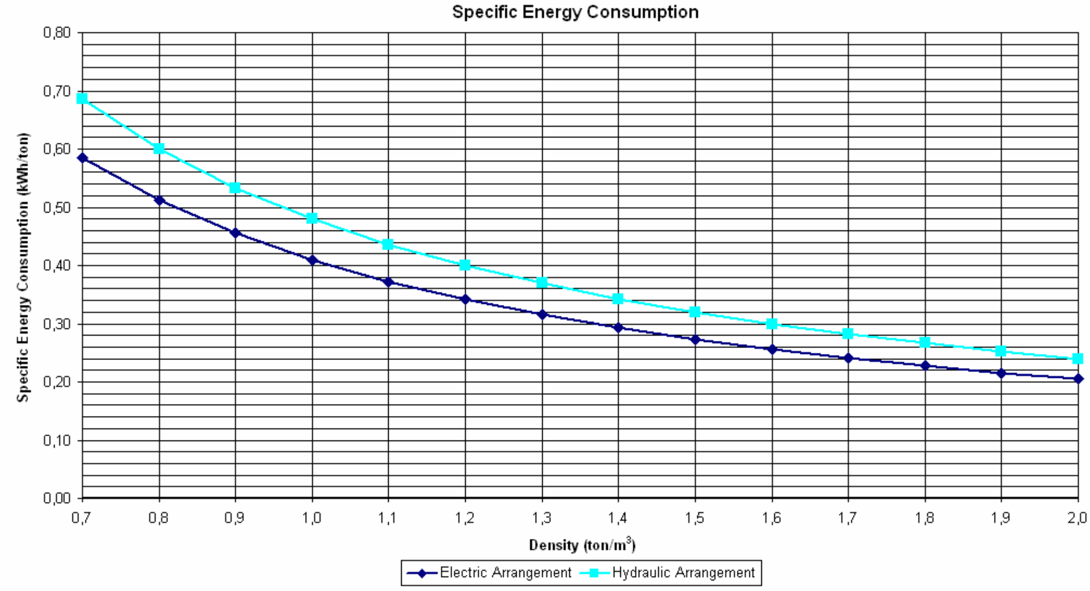

Figure 4.30 The specific energy consumption in kWh/ton versus the density in ton/m^3 for the two pump arrangements.

The specific energy consumption is used for calculating the pump energy costs.
The pump energy costs are obtained with the following equation.

$$\textbf{Pump Energy Costs} = \textbf{Weight} \cdot \textbf{Specific Energy Consumption} \cdot \textbf{Energy Price} \qquad \textbf{(4.19)}$$

The pump energy costs are calculated with weight in ton, specific energy consumption based on weight in kWh/ton and energy price in USD/MWh. The specific energy consumption based on weight is 0.293 kWh/ton. The weight is 294000 ton. The energy price at site A is 30 USD/MWh, because the cost per MWh of power plants at site A (Iceland) is 30 USD/MWh [132]. The energy price at site B is assumed 60 USD/MWh. The pump energy costs at site B are 10337 USD. Furthermore the pump energy costs at site A are 5169 USD.
It should be noted that during one roundtrip the electrolyte must be pumped two times out the tanker and two times into the tanker. The price for pumps is for the hydraulic arrangement around 393 USD/(m^3/h) and for the electric arrangement around 350 USD/(m^3/h) [37].
The electric arrangement is cheaper than the hydraulic arrangement. The required terminal electric pump capacity according to Appendix C is 15000 m^3/h, so the price of the terminal pump is 5250000 USD. The next important terminal equipment is the terminal storage tank.
The terminal storage tanks are used to store the electrolyte. The terminal storage tanks are required, because the battery stacks cannot process the total amount of electrolyte from the tanker during unloading. In addition the storage tanks enable the terminal to deliver continuously electricity. The electrolyte is stored in large size terminal tanks, because the costs per cubic meter of large size terminal tanks are relative lower.
The dimensions of terminal storage tanks for electrolyte are listed in table 4.13.
There are two basic types of terminal storage tanks. The two basic types are floating roof and cone roof [14]. In general the cone roof storage tank is less expensive than the floating roof storage tank. The difference between the cone roof storage tank and the floating roof storage tank is that the floating roof storage tank has an additional internal floating roof.
The floating roof is used in the storage tank structure and it is floating on the stored liquid within the tank. The floating roof falls and rises with the liquid level inside the tank.

The internal floating roof achieves a no vapour zone above the stored liquid, so the safety is improved. The terminal storage tank prices excluding harbour ground are shown in figure 4.31.

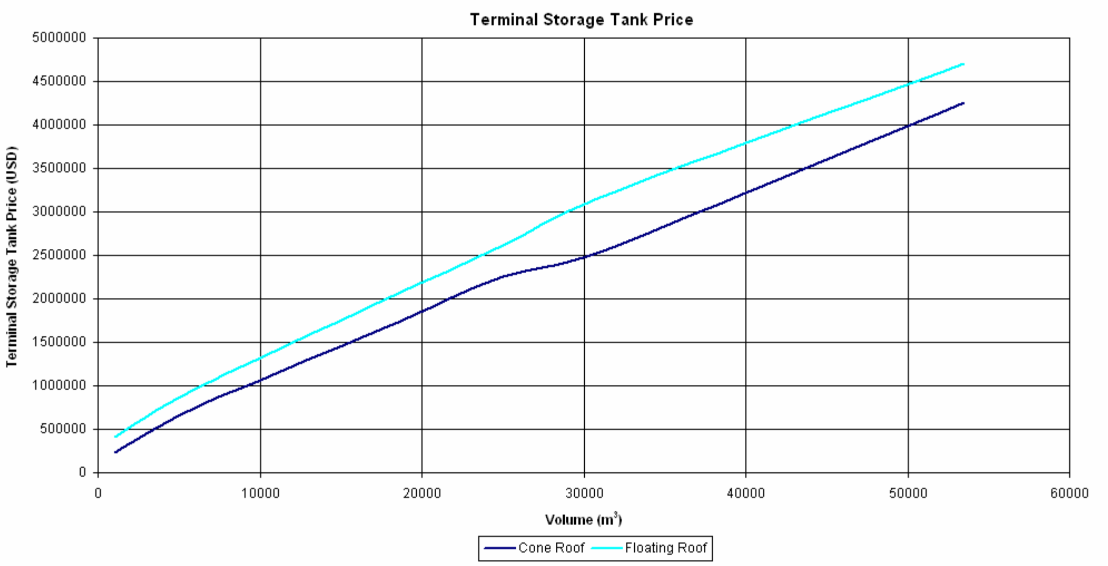

Figure 4.31 The terminal storage tank price in USD versus the volume size in m^3 [14]

The terminal storage tank prices are multiplied with the factor 1.3 to take into account the additional equipment such as stairs, walls, monitoring systems, etc. The storage of electrolyte does not require energy.

Volume in m^3	Height in m	Diameter in m	Harbour Area in m^2	Floating Roof Price in USD	Cone Roof Price in USD
1000	**9.15**	**12.2**	**201.64**	**411840**	**227760**
6000	**12.9**	**24.4**	**696.96**	**965640**	**744120**
17500	**14.7**	**39.1**	**1689.21**	**1968720**	**1653600**
25000	**16.5**	**44.0**	**2116.00**	**2617680**	**2254200**
31000	**16.5**	**48.8**	**2580.64**	**3165240**	**2533440**
53500	**18.3**	**61.3**	**4006.89**	**4700280**	**4252560**

Table 4.13 The dimensions and price of different size storage tanks [14]

The storage capacity of terminal storage tanks must be 588000 ton or 420000 m^3 to store the charged electrolyte and the discharged electrolyte. The storage capacity of the terminal is accomplished by 8 53500 m^3 size floating roof storage tanks.

The charged electrolyte in storage tanks is pumped through the electrochemical cells of the battery stacks with the small pumps. The cells of the battery stack are connected in series. In this case the voltage level of the battery stacks is 100 kV.

The footprint of the battery stack is 25.72 m^2/MW [56]. The battery stack costs are 900 USD/kW. The battery stack costs include the costs for pumps, pipes, valves and housing. The battery stacks are connected to electricity converter with installed DC electrical cables. The distance between the battery stacks and the electricity converter is 25 meters. The electricity converter is connected to the transformer station with installed AC electrical cables.

Furthermore the manning costs for offshore terminal are estimated 300000 USD/year, so the manning costs are 9000000 USD during the project.

The energy losses in the terminal are composed of the transport of electrolyte and the energy losses from the battery stacks, electricity converter, transformer station and electrical cables. The transport of electrolyte consists of transporting the electrolyte from the tanker to the terminal by means of pipeline and vice versa. The transport of electrolyte from the terminal storage tanks to the battery stacks and back are also achieved with small pumps, but the energy losses from the small pumps belong to the redox flow battery. The energy losses associated with the small pumps is small due to the short distance. Therefore the energy losses associated with the transport of electrolyte are the transport from the tanker to the terminal storage tanks and vice versa. Besides the energy losses due to the transport of electrolyte there are also energy losses from the battery stacks, electricity converter, transformer station and electrical cables. The energy losses of the battery stacks are 20%. The energy losses of the electricity converter are 1.6% and the energy losses of the transformer station are 0.4%, so the energy losses of the electrical terminal equipment are 2%. The energy losses in the offshore terminal excluding the battery stacks in % versus the output energy density in kWh/ton are illustrated in figure 4.32. Hence follows that the energy losses in the offshore terminal according to figure 4.32 is 3.20% for the output energy density of 40 kWh/ton and 2.60% for the output energy density of 80 kWh/ton.

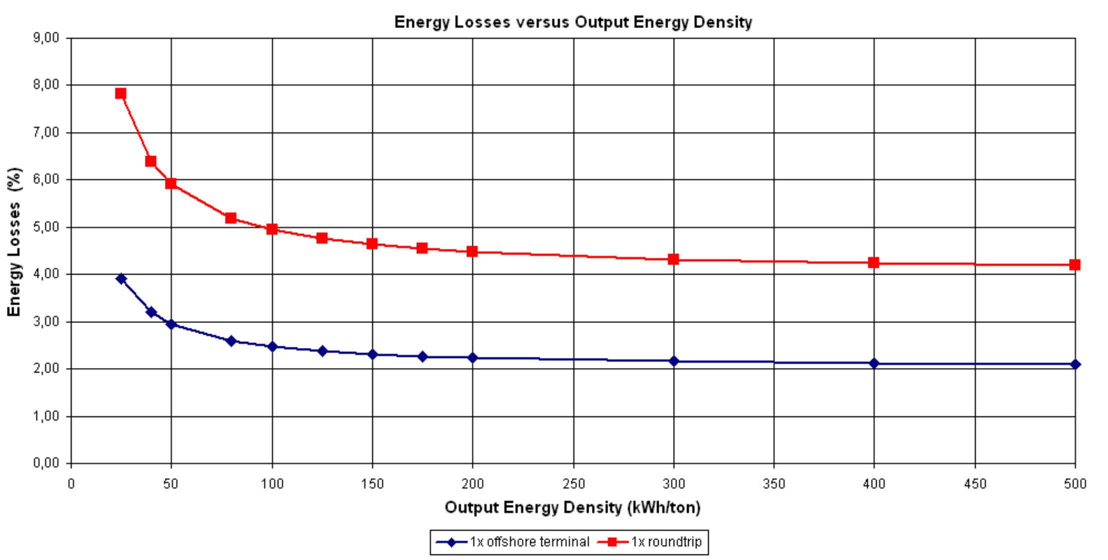

Figure 4.32 The energy losses of offshore terminal excluding battery stacks in % versus the output energy density in kWh/ton

The electrical powers and electrolyte storage times for all three case scenarios for site A and site B are listed in table 4.14. The electrical power is calculated by dividing the ship delivered energy at site B or the energy from power plants at site A by the electrolyte storage time. The terminal costs for all three case scenarios for site A and site B are calculated in Appendix E Terminal Costs. The resulting terminal costs for all three case scenarios are presented in table 4.15.

Parameters	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	50	50	100
Output Energy Density in kWh/ton	40	40	80
Total Frequency (30 years)	1470	990	990
Energy from Power Plants in GWh	15.00	15.00	30.00
Stored Energy in Electrolyte in GWh	14.70	14.70	29.40
Ship Delivered Energy in GWh	11.76	11.76	23.52
Delivered Energy in GWh	11.5248	11.5248	23.0496
Electrolyte Storage Time in hours	126.74	205.48	205.48
Electrical Power in Site A in MW	120.72	74.46	148.92
Electrical Power in Site B in MW	94.64	58.38	116.75

Table 4.14 The electrolyte storage times and the electrical powers for the three case scenarios

Description	Scenario 1	Scenario 2	Scenario 3
Electrical Power Site A in MW	120.72	74.46	148.92
Capital Expenditures in million USD	560.74	435.61	638.41
Operating Expenditures in million USD	678.10	459.62	905.12
Total Terminal Costs in million USD	1238.84	895.23	1543.53
Electrical Power Site B in MW	94.64	58.38	116.75
Capital Expenditures in million USD	491.91	390.72	549.81
Operating Expenditures in million USD	24.20	19.23	19.24
Total Terminal Costs in million USD	516.11	409.95	569.05

Table 4.15 The total terminal costs for all three case scenarios for site A and site B

The table 4.14 and table 4.15 indicate that the electrical power has large implications for the terminal costs. Furthermore the two parameters the distance and the output energy density have influence on the terminal costs. In addition the terminal costs at site A are higher than the terminal costs at site B.

4.4.3 The 300.000 dwt Tanker with Batteries

The terminal for the 300.000 dwt Vlcc tanker with batteries is an offshore terminal, because the 300.000 dwt tanker is too large to enter the ports. The 300.000 dwt tanker transports permanently installed electrical storage devices.
The offshore terminal is composed of the following components:

- Flexible electrical cables
- Modified CALM buoy
- Electrical cables
- Electricity converter
- Transformer station

The flexible electrical cables connect the modified CALM buoy with the batteries of the 300.000 dwt tanker. The flexible electrical cables are connected to sockets on the tanker. The length of the flexible electrical cables is 50 meters. The voltage level of the tanker is 100 kV. The modified CALM buoy lies in 30 m waterdepth, 5 km from the shore. For the time being, the assumption is made that the modified CALM buoy is equal to a normal CALM buoy, except the CALM buoy does not require a riser system.

The CALM buoy consists of loading buoy, mooring system and flexible electrical cables. The mooring system is composed of drag embedded anchors and 6 75 meter 4 inch mooring chains. The cost of the loading buoy is 8900000 USD [54]. The cost of mooring system for the waterdepth of 30 m is 550400 USD [54]. The cost for the modified CALM buoy is the sum of the cost of mooring system and loading buoy. The cost for the CALM buoy is 9450400 USD [54]. The installation of the CALM buoy is performed with an AHTS vessel**.** The cost of installation of the CALM buoy is estimated 1000000 USD [54]. The cost for the CALM buoy including installation is 10450400 USD. The modified CALM buoy is connected with installed DC electrical cables to the electricity converter. The large part of the DC electrical cables lies on the seabed and the other part of the electrical cables lies onshore. The length of installed electrical cables is 5100 meters. The connection between the electricity converter and transformer station is installed AC electrical cables.

The energy losses in offshore terminal consist of energy losses in electricity converter and the energy losses in transformer station. The energy losses in the cables and the required energy for connecting and disconnecting of the flexible cables are neglected.

Thus the energy losses in the offshore terminal are 2%, so the energy losses in the offshore terminal during one roundtrip are 4%. The terminal costs are calculated for two different charge rate scenarios, so the terminal costs are calculated for six case scenarios.

The electrical powers and the electrolyte storage times for all six case scenarios for site A and site B are listed in table 4.16 and in table 4.17. In this case the electrical power depends on the port time in the offshore terminal. The terminal costs for all three case scenarios for site A and site B are calculated in Appendix E Terminal Costs. The resulting terminal costs for all six case scenarios for site A and site B are presented in table 4.18 and in table 4.19.

Parameters	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Total Frequency (30 years)	**1680**	**1110**	**1110**
Energy from Power Plants in GWh	**15.00**	**15.00**	**30.00**
Stored Energy in Batteries in GWh	**14.70**	**14.70**	**29.40**
Ship Delivered Energy in GWh	**11.76**	**11.76**	**23.52**
Delivered Energy in GWh	**11.5248**	**11.5248**	**23.0496**
Port Time Site A in hours	**48**	**48**	**48**
Port Time Site B in hours	**24**	**24**	**24**
Electrical Power Site A in MW	**318.75**	**318.75**	**637.50**
Electrical Power Site B in MW	**499.80**	**499.80**	**999.60**

Table 4.16 The port times and the electrical powers of the first charge rate scenario for the three case scenarios

Parameters	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Total Frequency (30 years)	**1140**	**840**	**840**
Energy from Power Plants in GWh	**15.00**	**15.00**	**30.00**
Stored Energy in Batteries in GWh	**14.70**	**14.70**	**29.40**
Ship Delivered Energy in GWh	**11.76**	**11.76**	**23.52**
Delivered Energy in GWh	**11.5248**	**11.5248**	**23.0496**
Port Time Site A in hours	**96**	**96**	**96**
Port Time Site B in hours	**48**	**48**	**48**
Electrical Power Site A in MW	**159.38**	**159.38**	**318.75**
Electrical Power Site B in MW	**249.90**	**249.90**	**499.80**

Table 4.17 The port times and the electrical powers of the second charge rate scenario for the three case scenarios

Description	Scenario 1	Scenario 2	Scenario 3
Electrical Power Site A in MW	**318.75**	**318.75**	**637.50**
Capital Expenditures in million USD	**139.01**	**139.01**	**247.01**
Operating Expenditures in million USD	**756.00**	**499.50**	**999.00**
Total Terminal Costs in million USD	**895.01**	**638.51**	**1246.01**
Electrical Power Site B in MW	**499.80**	**499.80**	**999.60**
Capital Expenditures in million USD	**200.43**	**200.43**	**369.18**
Operating Expenditures in million USD	**0**	**0**	**0**
Total Terminal Costs in million USD	**200.43**	**200.43**	**369.18**

Table 4.18 The terminal costs of the first charge rate scenario for site A and site B

Description	Scenario 1	Scenario 2	Scenario 3
Electrical Power Site A in MW	**159.38**	**159.38**	**318.75**
Capital Expenditures in million USD	**87.15**	**87.15**	**139.01**
Operating Expenditures in million USD	**513.00**	**378.00**	**756.00**
Total Terminal Costs in million USD	**600.15**	**465.15**	**895.01**
Electrical Power Site B in MW	**249.90**	**249.90**	**499.80**
Capital Expenditures in million USD	**119.56**	**119.56**	**200.43**
Operating Expenditures in million USD	**0**	**0**	**0**
Total Terminal Costs in million USD	**119.56**	**119.56**	**200.43**

Table 4.19 The terminal costs of the second charge rate scenario for site A and site B

According to the table 4.18 and the table 4.19 the terminal costs at site B are more expensive than the terminal costs at site A. Besides that the tables indicate that the terminal costs of the first charge rate scenario are more expensive than the second charge rate scenario.
Moreover the tables demonstrate that the parameter output energy density has influenced on the terminal costs. On the contrary the parameter distance has no influence on the terminal costs. The largest cost components of the offshore terminal are the electricity converter and the modified CALM buoy. The terminal costs could drop, when the terminal is integrated in an offshore wind park. This is feasible under the conditions that the power cables from the offshore wind park to the shore are DC electrical power cables and offshore electrical storage devices are installed and applied to store the electricity from the offshore wind park for the time that the tanker is charging or discharging.

4.5 Total Costs

In the previous paragraphs the terminal costs and the total ship costs of the two logistical concepts are determined. Finally the total costs of the two logistical concepts are determined. The total costs are the costs of the energy supply chain, which transports electricity from the remotely located power plants to the grid of the electricity consumers. The total costs are the sum of the total ship costs, the terminal costs at site A and site B, the battery costs and the energy costs. Moreover the total costs are divided into capital expenditures and operating expenditures. The battery costs or electrolyte costs are not yet determined.
The total costs are required for the calculation of the electricity costs.
The logistical concept with the lowest electricity costs achieves the electrical energy transport against the lowest costs. Besides the costs the energy losses and the energy efficiency in the energy supply chain are important.

4.5.1 The 300.000 dwt Tanker with Electrolyte

The logistical concept 300.000 dwt tanker with electrolyte consists of two offshore terminals and one 300.000 dwt tanker. The Vlcc tanker transports 294000 ton electrolyte.
The entire logistical concept requires 882000 ton electrolyte. The 882000 ton electrolyte enables the logistical concept to deliver continuously electricity to the grid of electricity consumers. The electrolyte costs for the three case scenarios are listed in table 4.20. The total costs of the logistical concept 300.000 dwt tanker with electrolyte are calculated in table 4.21. The electricity costs are listed in table 4.22.

Description	Quantity	Unit Rate	Costs
Electrolyte Costs for Case Scenarios 1 & 2	**882000**	**2500 USD/ton**	**2205000000 USD**
Annuity (8% for 30 years)			**195864491 USD/year**
Capital Expenditures			**5875934719 USD**
Electrolyte Costs for Case Scenarios 3	**882000**	**5000 USD/ton**	**4410000000 USD**
Annuity (8% for 30 years)			**391728981 USD/year**
Capital Expenditures			**11751869437 USD**

Table 4.20 The electrolyte costs for the three case scenarios

Description	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Distance in nautical miles	**500**	**1000**	**1000**
Terminal Costs Site A in million USD	**1238.84**	**895.23**	**1543.53**
Total Ship Costs in million USD	**554.85**	**589.32**	**589.32**
Terminal Costs Site B in million USD	**516.11**	**409.95**	**569.05**
Electrolyte Costs in million USD	**5875.93**	**5875.93**	**11751.87**
Total Costs in million USD	**8185.73**	**7770.43**	**14453.77**
Capital Expenditures in million USD	**7238.16**	**7011.84**	**13249.67**
Operating Expenditures in million USD	**947.57**	**758.59**	**1204.10**

Table 4.21 The total costs for the three case scenarios

Description	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Total Frequency (30 years)	**1470**	**990**	**990**
Delivered Energy in GWh	**11.5248**	**11.5248**	**23.0496**
Total Delivered Energy in GWh	**16941.5**	**11409.6**	**22819.1**
Total Costs in million USD	**8185.73**	**7770.43**	**14453.77**
Cost per MWh of Power Plants in USD/MWh	**30**	**30**	**30**
Cost per MWh for Energy Transport in USD/MWh	**453.2**	**651.0**	**603.4**
Cost per MWh of Delivered Energy in USD/MWh	**483.2**	**681.0**	**633.4**

Table 4.22 The electricity costs for the three case scenarios

The largest cost component of the total costs is the electrolyte costs, so the electrolyte costs are very important. According to table 4.22 the lowest cost per MWh of delivered energy is roughly 16 times more expensive than the cost per MWh of power plants.
Moreover the distance has a large influence on the cost per MWh of delivered energy than the output energy density. The cost per MWh of delivered energy rises sharply, when the distance increases. However the cost per MWh of delivered energy declines, when the output energy density increases.

4.5.2 The 300.000 dwt Tanker with Batteries

The logistic concept 300.000 dwt tanker with batteries consists of two small offshore terminals and one 300.000 dwt tanker. The Vlcc tanker transports 294000 ton permanently installed batteries. The permanently installed batteries are charged and discharged with flexible electrical cables. The logistic concept is examined for two different charge rate scenarios. In the first charge rate scenario the port times are respectively 24 hours and 48 hours and the battery costs are 87.5 USD/kWh. The battery costs for the first charge rate scenario are listed in table 4.23. The total costs of the logistical concept 300.000 dwt tanker with batteries for the first charge rate scenario are calculated in table 4.24.
The electricity costs are listed in table 4.25. In the second charge rate scenario the port times are respectively 48 hours and 96 hours and the battery costs are 68.75 USD/kWh.
The battery costs for the second charge rate scenario are listed in table 4.26. The total costs of the logistical concept 300.000 dwt tanker with batteries for the second charge rate scenario are calculated in table 4.27. The electricity costs are listed in table 4.28.

Description	Quantity	Unit Rate	Costs
Battery Costs for Case Scenarios 1 and 2	**294000**	**4375 USD/ton**	**1286250000 USD**
Annuity (8% for 30 years)			**114254286 USD/year**
Capital Expenditures			**3427628586 USD**
Battery Costs for Case Scenario 3	**294000**	**8750 USD/ton**	**2572500000 USD**
Annuity (8% for 30 years)			**228508572 USD/year**
Capital Expenditures			**6855257172 USD**

Table 4.23 The battery costs for the first charge rate scenario

Description	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Distance in nautical miles	**500**	**1000**	**1000**
Terminal Costs Site A in million USD	**895.01**	**638.51**	**1246.01**
Total Ship Costs in million USD	**569.04**	**605.54**	**605.54**
Terminal Costs Site B in million USD	**200.43**	**200.43**	**369.18**
Battery Costs in million USD	**3427.63**	**3427.63**	**6855.26**
Total Costs in million USD	**5092.11**	**4872.11**	**9075.99**
Capital Expenditures in million USD	**4076.65**	**4076.65**	**7781.03**
Operating Expenditures in million USD	**1015.46**	**795.46**	**1294.96**

Table 4.24 The total costs for the first charge rate scenario

Description	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Total Frequency (30 years)	**1680**	**1110**	**1110**
Delivered Energy in GWh	**11.5248**	**11.5248**	**23.0496**
Total Delivered Energy in GWh	**19361.7**	**12792.5**	**25585.1**
Total Costs in million USD	**5092.11**	**4872.11**	**9075.99**
Cost per MWh of Power Plants in USD/MWh	**30**	**30**	**30**
Cost per MWh for Energy Transport in USD/MWh	**233.0**	**350.9**	**324.7**
Cost per MWh of Delivered Energy in USD/MWh	**263.0**	**380.9**	**354.7**

Table 4.25 The electricity costs for the first charge rate scenario

Description	Quantity	Unit Rate	Costs
Battery Costs for Case Scenarios 1 & 2	**294000**	**3437.5 USD/ton**	**1010625000 USD**
Annuity (8% for 30 years)			**89771225 USD/year**
Capital Expenditures			**2693136746 USD**
Battery Costs for Case Scenario 3	**294000**	**6875 USD/ton**	**2021250000 USD**
Annuity (8% for 30 years)			**179542450 USD/year**
Capital Expenditures			**5386273492 USD**

Table 4.26 The battery costs for the second charge rate scenario

Description	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Distance in nautical miles	**500**	**1000**	**1000**
Terminal Costs Site A in million USD	**600.15**	**465.15**	**895.01**
Total Ship Costs in million USD	**532.54**	**569.04**	**569.04**
Terminal Costs Site B in million USD	**119.56**	**119.56**	**200.43**
Battery Costs in million USD	**2693.14**	**2693.14**	**5386.27**
Total Costs in million USD	**3945.39**	**3846.89**	**7050.75**
Capital Expenditures in million USD	**3209.43**	**3209.43**	**6035.29**
Operating Expenditures in million USD	**735.96**	**637.46**	**1015.46**

Table 4.27 The total costs for the second charge rate scenario

Description	Scenario 1	Scenario 2	Scenario 3
Distance in nautical miles	**500**	**1000**	**1000**
Total Frequency (30 years)	**1140**	**840**	**840**
Delivered Energy in GWh	**11.5248**	**11.5248**	**23.0496**
Total Delivered Energy in GWh	**13138.3**	**9680.8**	**19361.7**
Total Costs in million USD	**3945.39**	**3846.89**	**7050.75**
Cost per MWh of Power Plants in USD/MWh	**30**	**30**	**30**
Cost per MWh for Energy Transport in USD/MWh	**270.3**	**367.4**	**334.2**
Cost per MWh of Delivered Energy in USD/MWh	**300.3**	**397.4**	**364.2**

Table 4.28 The electricity costs for the second charge rate scenario

According to table 4.24 and table 4.27 the largest cost component of the total costs is the battery costs. The battery costs are roughly 70% of the total costs.
The terminal costs are very low compared with the previous logistical concept.
The lowest cost per MWh of delivered energy in the first charge rate scenario according to table 4.25 is almost 9 times more expensive than the cost per MWh of power plants.
The lowest cost per MWh of delivered energy in the second charge rate scenario according to table 4.28 is 10 times more expensive than the cost per MWh of power plants.
Moreover all cost per MWh of delivered energy in the first charge rate scenario are lower than all cost per MWh of delivered energy in the second charge rate scenario, so the port times of the logistical concept will be respectively 24 hours and 48 hours.
In addition the table 4.25 and the table 4.28 indicate that the cost per MWh of delivered energy increases sharply, when the distance increases. As mentioned before, the cost per MWh of delivered energy decreases, when the output energy density increases.

4.5.3 Battery Ship Concept Selection

In the previous text the characteristics of the two logistical concepts are determined.
In order to select the best logistical concept for the battery ship the electricity costs and total costs of the two logistical concepts are compared. The total costs of the two logistical concepts are listed in table 4.29. The delivered energy of the two logistical concepts is presented in table 4.30. The cost per MWh of delivered energy of the two logistical concepts is listed in table 4.31.

Description	Scenario 1	Scenario 2	Scenario 3
Energy Density in kWh/ton	**50**	**50**	**100**
Output Energy Density in kWh/ton	**40**	**40**	**80**
Distance in nautical miles	**500**	**1000**	**1000**
300.000 dwt Tanker with Electrolyte in million USD	**8185.73**	**7770.43**	**14453.77**
300.000 dwt Tanker with Batteries in million USD	**5092.11**	**4872.11**	**9075.99**

Table 4.29 The total costs of the two logistical concepts

Description	Scenario 1	Scenario 2	Scenario 3
300.000 dwt Tanker with Electrolyte in GWh	**16941.5**	**11409.6**	**22819.1**
300.000 dwt Tanker with Batteries in GWh	**19361.7**	**12792.5**	**25585.1**

Table 4.30 The delivered energy in GWh of the two logistical concepts

Description	Scenario 1	Scenario 2	Scenario 3
300.000 dwt Tanker with Electrolyte in USD/MWh	**483.2**	**681.0**	**633.4**
300.000 dwt Tanker with Batteries in USD/MWh	**263.0**	**380.9**	**354.7**

Table 4.31 The cost per MWh of delivered energy of the two logistical concepts

According to tables from 4.29 till 4.31 the 300.000 dwt tanker with batteries is the best logical concept. The 300.000 dwt tanker with batteries has the lowest total costs and the lowest cost per MWh of delivered energy for all three case scenarios.
In addition the 300.000 dwt tanker with batteries has the highest delivered energy.
Besides the costs the energy losses of the two logistical concepts are important.
The main difference between the energy losses of the two logistical concepts is caused by the energy losses in the terminals. The energy losses of batteries and the energy losses of sea transport are the same. The energy losses in terminals are shown in figure 4.33.
The energy losses in terminals of the logistical concept 300.000 dwt tanker with batteries are not influenced by the output energy density according to figure 4.33.
On the other hand the energy losses in terminals of the logistical concept 300.000 dwt tanker with electrolyte are influenced by the output energy density. In addition the energy losses of the logistical concept 300.000 dwt tanker with electrolyte are higher. Above the output energy density of 200 kWh/ton the difference between the two logistical concepts becomes less than 1%, so the difference between the two logistical concepts is negligible from energetic perspective. Summarized the 300.000 dwt tanker with batteries is the most attractive concept of the two logistical concepts. As stated before the 300.000 dwt tanker with batteries has the lowest cost per MWh of delivered energy and the lowest total costs.
In addition the 300.000 dwt tanker with batteries has the highest delivered energy.
Besides that the 300.000 dwt tanker with batteries has the lowest total energy losses.
The main drawback of the 300.000 dwt tanker with batteries is that it does not deliver continuously electricity to the electricity consumers.
Therefore the logistical concept 300.000 dwt tanker with batteries will be elaborated.
Hence follows that a conceptual design of the battery ship will be made.

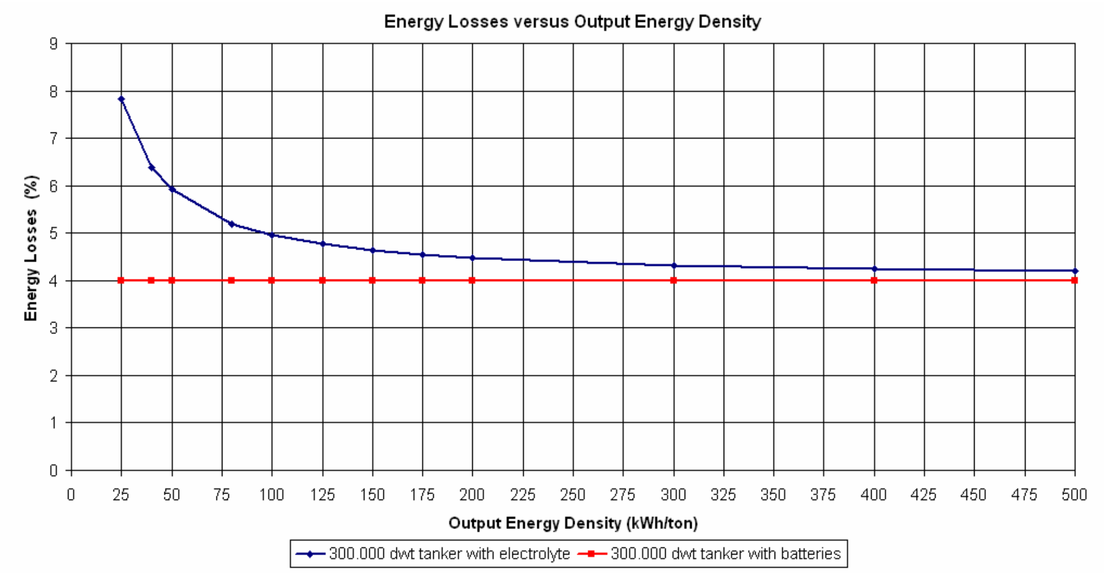

Figure 4.33 The energy losses in terminals of two logistical concepts in % versus the output energy density in kWh/ton

4.5.4 Model

During the investigation about the feasibility of the battery ship a model is built in Microsoft Office Excel. The model calculates the delivered energy and the cost per MWh of delivered energy as function of the input parameters. Moreover the model illustrates in one chart the influence of the speed on the energy intensity.
The input parameters include the deadweight, speed, power, energy price, energy density, port times, type propulsion, etc. The input parameters can be divided in different groups. The groups are the characteristics of the ship, the characteristics of the battery, the loan, the route and the electricity costs. The advantages of the model are that the effect of each parameter is rapidly determined and the economical and technical feasibility of the electrical energy transport is quickly determined.
Besides that the model presents the cost per MWh of delivered energy for two different propulsion concepts. The first propulsion concept uses diesel engine with fuel and the second propulsion concept uses the electrical energy from the batteries for the electric propulsion plant. The main drawback of the model is that the details of terminal costs are not included. The model focuses mainly on the technical and economical performance of the battery ship. The most relevant equations of the model are presented in Appendix F Model. During the variations of the input parameters the following relations are determined:

- The cost per MWh of delivered energy decreases, when the deadweight rises
- The speeds above roughly 16 knots are not attractive due to the high energy losses
- The batteries with low output energy density are applicable on the condition that the battery costs are very low
- The battery costs should be very low

4.6 Battery Ship

From the previous paragraphs the requirements for the conceptual design of the battery ship can be formulated. The function of the battery ship is transporting electricity between offshore terminals for short distances (≈ 2000 nautical miles).
The requirements for conceptual design of the battery ship are presented below:

- Service speed of 12.7 knots
- Electricity storage of 14700 MWh
- The capacity for discharging the electricity within 24 hours
- The capacity for charging the electricity within 48 hours
- Maximum draught of 21 m
- Stability must comply with SOLAS requirements

Furthermore the MARPOL regulations will be used as guidance. During the design of battery ship special attention will be given to the battery system, buoyancy, stability and propulsion plant. The influence of two different propulsion plant configurations will be determined.
The first propulsion plant configuration will have a diesel propulsion plant. The main engine will run on heavy fuel oil. The electricity from the battery system will not be used to propel the battery ship. The second propulsion plant configuration will be fitted out with an electric propulsion plant. The electric propulsion plant will run on electricity from the battery system. The battery ship with electric propulsion will generate significant less pollution. The main dimensions of the battery ship are determined with the assistance of the written program "Batteryship" in Matlab. The program code in Matlab is presented in Appendix G. Before the conceptual design of the battery ship can be made, the appropriate battery system for the battery ship must be selected and dimensioned.

4.6.1 Appropriate Battery Selection

Among the different battery systems on the market and under development one battery system should be chosen for the battery ship. The descriptions of the batteries on the market and under development are presented in Appendix H Batteries.
The battery ship requires large scale batteries or a large amount of batteries in a so called battery energy storage system (BESS). The most appropriate energy storage systems are selected with an approximate comparison. As mentioned before,
the approximate comparison knows only three levels: better (+) or equal (=)
or less (-). The method checks for each specification whether the energy storage system meets the required specification. In this manner the strong points and weak points of each energy storage system for the battery ship will be clarified. For the use in the battery ship the most important specifications are defined as follows:

- DC efficiency: above 75%
- Discharge time: 22 hours
- Self-discharge: below 1%
- Cycle life: above 1000 cycles
- Energy density by mass: above 30 Wh/kg
- Capital costs per energy : below 200 USD/kWh

The defined specific requirements are the most important requirement.
Furthermore it should be mentioned that the energy density by mass of 30 Wh/kg is the lowest allowable value. At the gravimetric energy density of 30 Wh/kg the electricity transport with the battery ship becomes feasible at low sailing speeds and on the condition that the capital costs per energy are also very low. The approximate comparison between different battery systems is presented in table 4.32.
According to the approximate comparison the G2 VRB battery or vanadium bromide battery is identified as most suitable solution. The solution is selected from the current available battery systems. In future new battery systems or improved battery systems could emerge, which might give a different appropriate solution than the current selected solution.

Key Parameters	**DC Efficiency**	**Discharge Time**	**Self-discharge**	**Cycle Life**	**Energy Density By Mass**	**Capital Costs per Energy**	**Score**
Specification	**75%**	**22 hours**	**1%/month**	**1000 cycles**	**30 Wh/kg**	**200 USD/kWh**	
Lead Acid battery	=	-	-	-	=	+	**-2**
Ni-Cd battery	=	-	-	+	+	-	**-1**
NiMH battery	-	-	-	+	+	-	**-2**
NiZn battery	+	-	-	-	+	-	**-2**
NaS battery	+	-	+	+	+	-	**+2**
Na-NiCl$_2$ battery	+	-	+	+	+	-	**+2**
Li ion battery	+	-	=	+	+	-	**+1**
Li polymer battery	+	-	=	=	+	-	**0**
Zinc/Air battery	-	-	-	-	+	+	**-2**
PSB battery	=	+	+	+	-	+	**+3**
VRB battery	+	+	+	+	-	+	**+4**
G2 VRB battery	+	+	+	+	+	=	**+5**
ZBB battery	+	+	+	=	+	-	**+3**
ZnCe battery	-	+	+	+	-	+	**+2**

Table 4.32 The approximate comparison

The second generation vanadium battery or vanadium bromide battery is a new improved vanadium battery, which is developed by V-fuel in Australia.
The battery has an operating temperature between -20 ºC and 50 ºC and a lifetime of almost 20 years. The lifetime of battery depends on the battery stacks. The other redox flow batteries such as PSB battery, VRB battery and ZnCe battery meet also most requirements, but the energy density of those flow batteries is too low.
The ZBB flow battery fulfills most requirements, but the battery is too expensive.

The redox flow batteries seem to be the most interesting batteries for the battery ship. Furthermore it is worth noting that the flow battery is still an immature technology, so the technology is going to improve and become cheaper in the future.
The high temperature batteries like NaS battery and Na-$NiCl_2$ battery are not interesting, because they have large standby losses. The lithium ion battery can also be used in the battery ship, but the immature battery is still far too expensive.
Next the characteristics of vanadium redox battery and vanadium bromide battery from Appendix H are presented in table 4.33 and in table 4.34.

Vanadium Redox Battery

Vanadium redox battery (VRB) is developed by the Japanese Electro-Technical Laboratory (ETL) and Australian University of New South Wales (UNSW) in the 1980s [82].
The vanadium redox battery consists of two electrolytes vanadium redox couples in mild sulfuric acid solutions and hydrogen-ion permeable polymer membrane, which are illustrated in figure 4.34. During a cycle H+ ions are exchanged between the electrolytes. The negative side is V^{2+}/V^{3+} vanadium redox couple and the positive side is VO_2^+/VO^{2+} vanadium redox couple. The reversible electrochemical reactions in vanadium redox battery are [27]:

$$VO_2^+ + 2\,H^+ + V^{2+} \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} VO^{2+} + H_2O + V^{3+}$$

The voltage of the vanadium redox battery is 1.4 V. The advantages of vanadium redox battery are very low costs (for large applications), very fast response to changing loads and large overcharge capacity. The disadvantage of vanadium redox battery is the low energy density, but the energy density of the vanadium redox battery is greater than the polysulfide bromide battery. The second generation of vanadium redox battery will have higher energy densities. The vanadium redox battery is already utilized for several applications such as energy management and power quality applications.

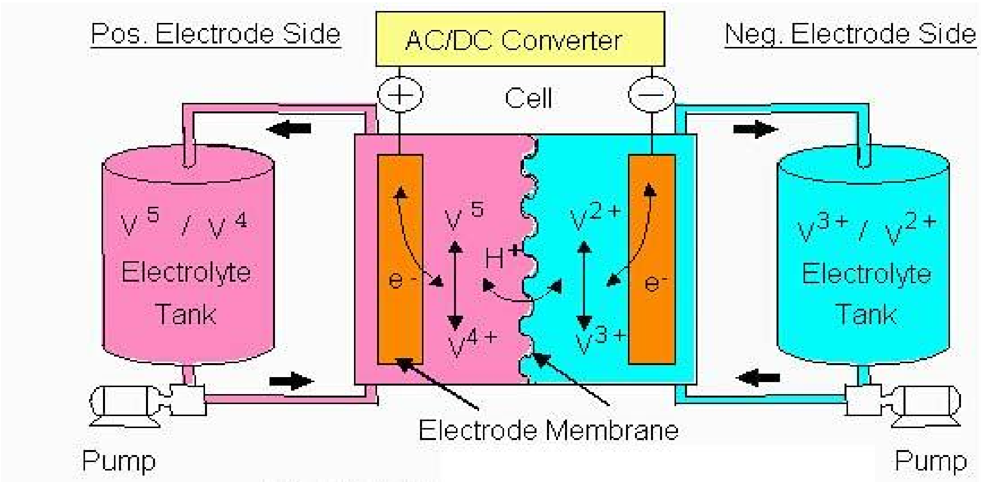

Figure 4.34 The vanadium redox battery [82]

Description	Characteristics
Power	**5 kW -500 kW**
Energy	**1 kWh-5 MWh**
Efficiency	**80-87%**
Discharge Time	**1-8 hours**
Self-discharge	**no**
Cycle Life	**5000-12000**
Lifetime	**6-20 years**
Operating Temperatures	**-10 °C - 40 °C**
Energy Density by Volume	**20 kWh/m^3 – 33 kWh/m^3**
Energy Density by Mass	**15 Wh/kg - 25 Wh/kg**
Power Density	**10 W/kg – 400 W/kg**
Capital Costs per Energy	**180-240 USD/kWh**

Table 4.33 The characteristics of vanadium redox battery [25][27][56][82]

Vanadium Bromide Battery

The vanadium bromide battery or generation 2 vanadium redox batteries (G2 VRB) is introduced by V-fuel in 2005. The vanadium bromide battery is still under development. The vanadium bromide battery has a higher energy density and larger temperature range than the vanadium redox battery. The vanadium bromide battery consists of electrolyte vanadium bromide. The negative side is VBr2/VBr3 redox couple and the positive side is Br/ClBr2 or Cl/BrCl2 redox couple. The first feed solution for the vanadium bromide battery is a mixture of V3 and V4 bromides. The reversible electrochemical reaction in vanadium bromide battery is [107]:

$$V^{3+} + Br_3^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} V^{2+} + 3\ Br^-$$

The voltage of the vanadium bromide battery is 1.4 V. Furthermore the vanadium bromide battery has no problems of cross-contamination. The major benefit of the battery is that the battery can be used in extreme cold climates like Iceland.

Description	Characteristics
Power	**5 kW -500 kW**
Energy	**1 kWh-5 MWh**
Efficiency	**80-87%**
Discharge Time	**1-8 hours**
Self-discharge	**no**
Cycle Life	**5000-12000**
Lifetime	**6-20 years**
Operating Temperatures	**-20 °C - 50 °C**
Energy Density by Volume	**35 kWh/m^3 – 70 kWh/m^3**
Energy Density by Mass	**25 Wh/kg - 50 Wh/kg**
Power Density	**10 W/kg – 400 W/kg**
Capital Costs per Energy	**150-500 USD/kWh**

Table 4.34 The characteristics of vanadium bromide battery [27][77][107]

4.6.2 Battery System

The battery ship will be fitted out with the vanadium bromide battery.
The redox flow battery consists of electrolyte in tanks and battery stacks. In this case the electrolyte is stored in the cargo tanks of the battery ship. In addition the battery ship is fitted out with battery stacks. The liquid electrolyte contains the energy. The benefit of liquid electrolyte is that it can be pumped into or out of the battery ship. According to Maria Skyllas-Kazacos the volumetric energy density of vanadium bromide electrolyte is between 35 Wh/l and 70 Wh/l and the density is 1400 kg/m^3, so the energy density by mass is between 25 Wh/kg and 50 Wh/kg [77]. Therefore the gravimetric energy density is assumed 50 Wh/kg. The density is 1400 kg/m^3. In nearby future new electrolytes could emerge with higher energy densities. The gravimetric energy density versus the volumetric energy density for different densities of electrolyte is illustrated in figure 4.35. The electrolyte density ranges from 1400 kg/m^3 to 1900 kg/m^3.

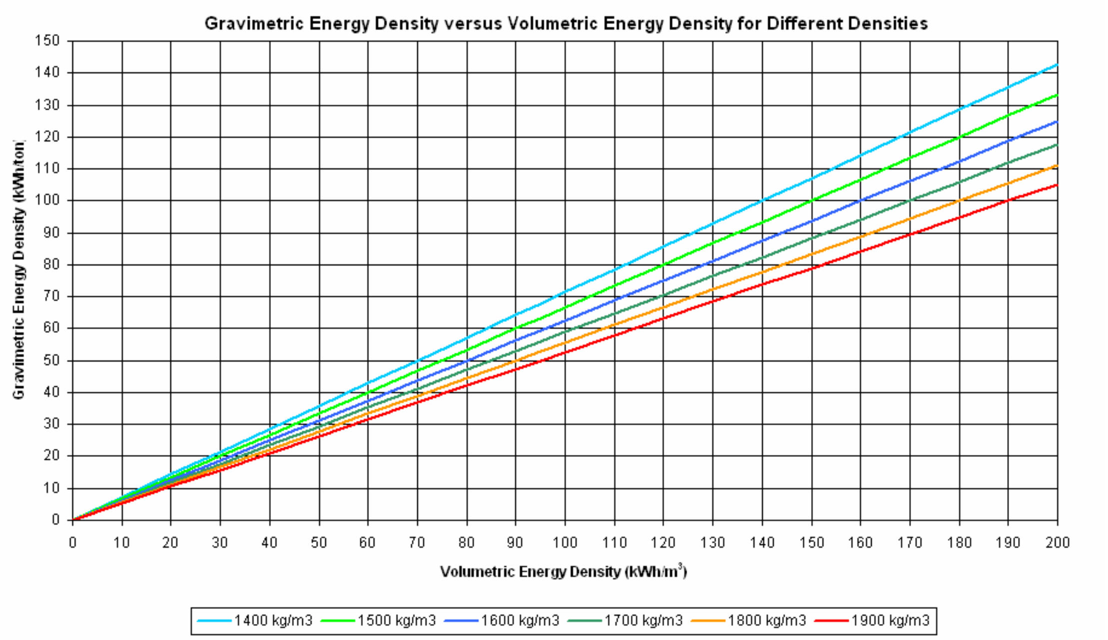

Figure 4.35 The gravimetric energy density in kWh/ton versus the volumetric energy density in kWh/m^3 for different densities of the electrolyte in kg/m^3

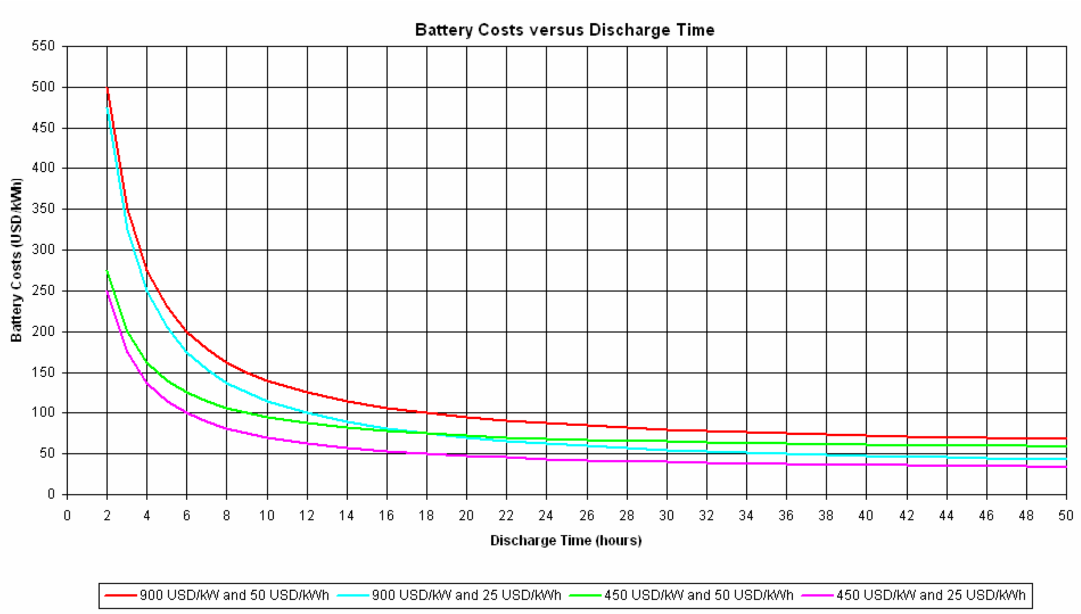

Figure 4.36 The battery costs in USD/kWh versus the discharge time in hours for different electrolyte costs and different battery stack costs

Furthermore the benefit of the redox flow battery is that it is not limited in energy size and power size. In addition the energy size and the power size are independent, so the discharge time depends on the lay-out of the battery. The power size is increased by adding battery stacks. The energy size is increased by increasing the amount of electrolyte.
In addition the power size and the energy size have consequences for the costs of redox flow battery. The commercial electrolyte costs of the vanadium bromide battery are estimated 50 USD/kWh [58][107]. The commercial battery stack costs of the vanadium bromide battery are estimated 900 USD/kWh [58][107]. In the future the battery costs could drop, because the redox flow battery technology is still immature. The battery costs of the redox flow battery versus the discharge time or storage time for different battery stacks and electrolyte costs are shown in figure 4.36. The figure indicates that the battery costs are high for short discharge times. Nevertheless the battery costs drop, when the discharge times increase.
In this case the required discharge time is 24 hours and the battery system stores 14700 MWh. The battery consists of 14805 battery stacks, 210000 m^3 electrolyte and several electrolyte pumps. The battery operates between the temperatures from 0 ºC till 40 ºC.
The sockets for the flexible electrical cables are placed on the deck in the middle of the ship. The cable sockets are connected to the battery stacks by means of electrical cables. The cable sockets are used to connect 5 pairs of flexible electrical cables from the modified CALM buoy to the grid of the battery ship. The connection between modified CALM buoy and battery ship is similar as cold ironing. The general specifications of the battery system are listed in table 4.35. The battery system in the ship is presented in figure 4.37.
In general the electrolyte is toxic and corrosive, so it is dangerous for humans and the environment. However an electrolyte spill is less dangerous than oil, because electrolyte material dissolves quickly in the sea. The electrolyte material such as vanadium pentoxide and bromide, is heavier than water, so the electrolyte sinks to the seabed. In addition the electrolyte material remains in the cargo tanks of the ship during the operating lifetime, so the risk is small for humans and the environment. The electrolyte material leaves only the ship during repairs or emergency situations. Furthermore the steel structure of the electrolyte tanks is protected with a special coating against the corrosive electrolyte liquid.

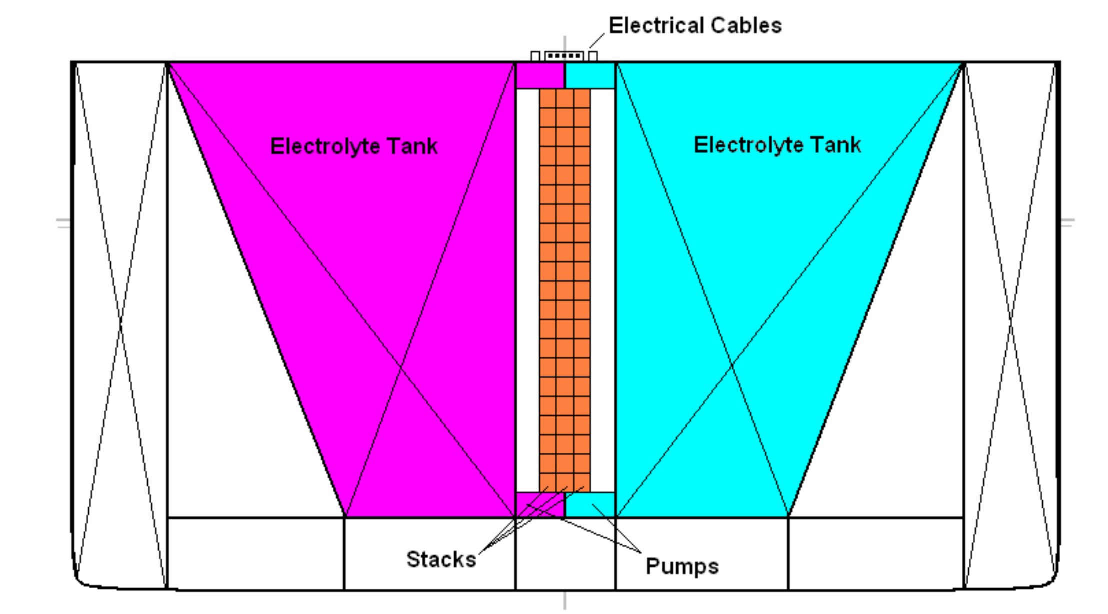

Figure 4.37 The battery system in the ship

Battery System	
Stored Energy	**14700 MWh**
Power	**621.81 MW**
Storage Time	**23.64 hours**
Battery Efficiency	**80%**
Number of Battery Stacks	**14805**
Electrolyte Volume	**210000 m^3**
Pump Losses	**2%**
Battery Stack	
Power	**42 kW**
Dimensions	**1.2L x 0.9W x 1.1H (m)**
Weight	**1400 ton**
Stack Efficiency	**82%**
Electrolyte	
Energy Density	**50 Wh/kg**
Density	**1400 kg/m^3**

Table 4.35 The characteristics of the battery system in the battery ship [56][77][107]

4.6.3 Characteristics of Battery Ship

The design of battery ship is almost similar as a double hull tanker. The superstructure and the engine room are located on the stern. The tank region contains the electrolyte tanks and battery stack rooms. The engine room is composed of a diesel engine with PTO and a diesel alternator or electric motor. The tank region is divided in 5 tank parts. The tank length is 57.06 m. The 5 tank parts are divided by transverse bulkheads. The battery stack rooms are placed in the middle of the ship, so that they are less vulnerable to collision.
The battery stack rooms contain the battery stacks and pumps. The battery stacks are the most expensive part of the battery. The width of the battery stack room is 5.7 m.
The electrolyte tanks are located on both sides of the battery stack. The electrolyte tanks have a leaning bulkhead towards the ballast wing tanks to obtain a higher centre of gravity.

The leaning bulkhead is located 12.35 m from the centreline. The size of one electrolyte tank is 21650 m^3, which is below the MARPOL requirement of 50.000 m^3 [16]. The size of electrolyte tank depends on the hypothetical outflow of electrolyte, sloshing of electrolyte, dynamic loads and hydrostatic loads. The hydrostatic loads in electrolyte tanks are higher than hydrostatic loads in oil tanks due to the higher density of electrolyte, so the structural weight of an electrolyte tank is higher than the structural weight of an oil tank.
The wing tanks of the tank region are the ballast tanks. The width of ballast tanks is larger than the MARPOL requirements, to allow easy access, inspection and maintenance.
The ballast tanks have a width of 8.0 m. The purpose of the ballast tank is to trim the battery ship. Furthermore the battery ship has a double bottom tank.
The height of double bottom clearance is very large, to obtain a higher centre of gravity and to allow easy access and maintenance. The height of the double bottom tank is 4.1 m.
The double bottom tank protects the battery stack rooms and electrolyte tanks against grounding. The general arrangement of the battery ship with diesel propulsion is presented in Appendix I. In addition the general arrangement of the battery ship with electric propulsion using the batteries is likewise presented in Appendix I. The main dimensions and the characteristics of the battery ship with diesel propulsion are listed in table 4.36. The light ship weight estimation is based on the single hull crude oil tankers [17].
The light ship weight includes the weight of the battery stacks. The deadweight is composed of the electrolyte, heavy fuel oil, diesel fuel oil, fresh water and constant.

Main Dimensions	
Length pp	**340.30 m**
Length wl	**347.11 m**
Length oa	**350.48 m**
Breadth	**61.27 m**
Draught	**21.00 m**
Depth	**30.00 m**
Displacement (design)	**389110 ton**
Block Coefficient	**0.85**
Accommodation	**30 persons**
Weights	
Light Ship Weight	**76472 ton**
Battery Stacks Weight	**20727 ton**
Electrolyte	**294000 ton**
Heavy Fuel Oil	**7500 ton**
Diesel Fuel Oil	**400 ton**
Fresh Water	**600 ton**
Constant	**400 ton**
Ballast	**9738 ton**
Volumes	
Electrolyte	**216495 m^3**
Heavy Fuel Oil	**8334 m^3**
Diesel Fuel Oil	**445 m^3**
Fresh Water	**600 m^3**
Constant	**445 m^3**
Ballast	**93489 m^3**

Table 4.36 The characteristics of the battery ship

The initial stability and the centre of gravity are calculated with the assistance of the written software program "Batteryship" in Matlab. The initial stability includes the free surface effects of the electrolyte. The initial stability is listed in table 4.37.
The centre of gravity of the battery ship is estimated in Appendix J.

Initial Stability	
Draught T	**21.00 m**
Transverse metacenteric radius BM	**14.78 m**
Vertical centre of buoyancy KB	**10.80 m**
Distance from baseline to metacentre KM	**25.59 m**
Free surface effect of electrolyte GG	**1.33 m**
Vertical centre of gravity KG	**18.93 m**
Longitudinal centre of gravity LCG	**177.14 m**
Distance from centre of gravity to metacentre GM	**4.76 m**
Longitudinal centre of gravity LCG	**2.99 %**
Longitudinal centre of buoyancy LCB	**3.00%**
Longitudinal centre of flotation LCF	**1.05%**

Table 4.37 The initial stability of the battery ship

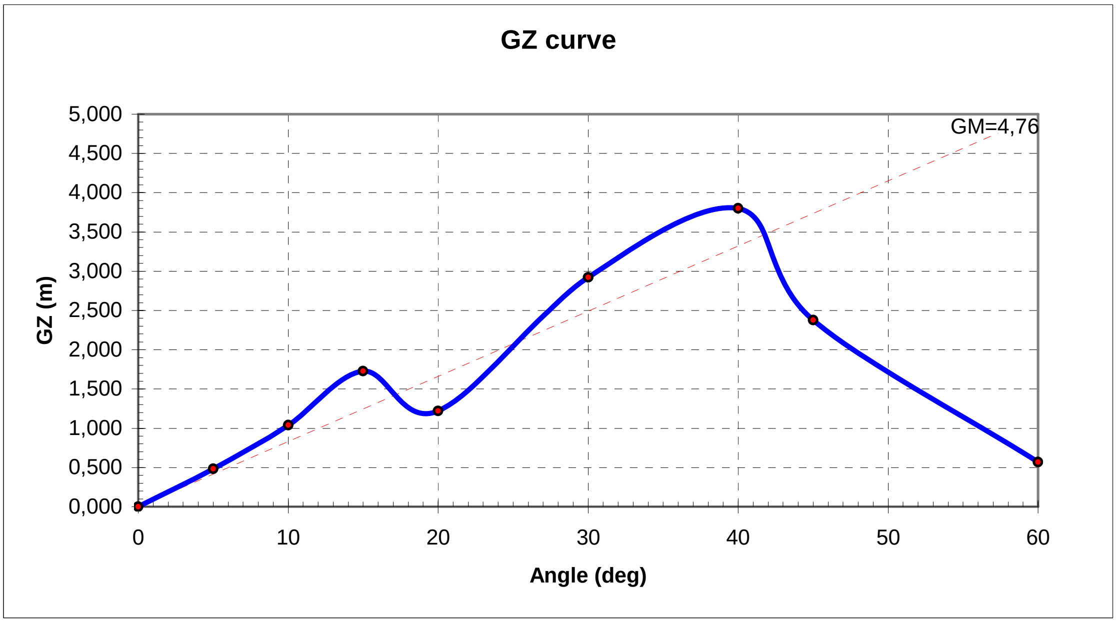

Figure 4.38 The GZ curve of the battery ship

The GZ curve of the battery ship according to Gudenschwager is presented in figure 4.38. The values of GZ curve are likewise presented in Appendix J. The free surface effects are not included in the calculation of the GZ curve. The diesel propulsion plant of the battery ship consists of one contra-rotating propeller (CRP) and one diesel engine. The benefit of contra-rotating propeller is higher efficiency, because the 'swirling flow' energy is recovered. The contra-rotating propeller has 15 % higher propeller efficiency than a normal propeller [50]. Other benefits of contra-rotating propeller are lower loading of propeller, more symmetrical turning circle and lower vibrations. The diameter of the contra-rotating propeller is 9.89 m. The contra-rotating propeller is driven by a diesel main engine. The two propellers are connected to the main engine with a special gearbox. The main engine drives likewise the PTO. The electrical supply is delivered by the PTO and a waste heat recovery plant.
In addition the electrical supply is provided by one auxiliary diesel-driven alternator.

The characteristics of the diesel propulsion plant are listed in table 4.38.
The powering and resistance results of the battery ship are listed in Appendix J.
The resistance and propulsion characteristics of the battery ship are estimated with Holtrop & Mennen method. However the resistance and propulsion characteristic of the battery ship must be validated with the resistance tests and the self-propulsion tests of the ship model in a towing tank.

Characteristics of Diesel Propulsion Plant	
Main Engine Output (MCR)	**17005 kW**
Main Engine Output (NOR)	**14454 kW**
Fuel Consumption	**55.50 tonnes/day**
Number of Revolutions	**74 rpm**
Engine load (% of MCR)	**85%**
Required Electrical Power	**1000 kW**
PTO Power	**400 kW**
Waste Heat Recovery Power	**600 kW**
Diesel-driven Alternator Power	**1000 kW**
Propeller Diameter	**9.89 m**

Table 4.38 The estimated characteristics of diesel propulsion plant

The diesel propulsion plant could be replaced by an electric propulsion plant.
The electric propulsion plant will run on electricity from the battery system.
The advantages of electric propulsion plant are a smaller engine room and significant less pollution. The electric propulsion plant consists of ABB CRP Azipod propulsion [59]. The main diesel engine and special gearbox are replaced by an electric motor. The CRP propeller is replaced by a normal propeller. The conventional rudder will be replaced by a pulling Azipod unit. The pulling propeller of Azipod unit will contra-rotate in relation to the shaft-driven main propeller [59]. The benefit of electric propulsion plant is more space for the battery system or smaller engine room. The electric propulsion plant is smaller. In addition the fuel tanks are no more required. The other advantages of ABB CRP Azipod propulsion are improved maneuvering and higher redundancy. The disadvantages of electric propulsion plant are higher energy price, less delivered energy and significant smaller range of the battery ship. The energy price for the electric propulsion plant is between 120 USD/MWh and 600 USD/MWh. Furthermore the electrical supply is delivered by the battery system. The battery system delivers 1000 kW. The energy price for the electric propulsion plant depends mainly on the number of cycles, battery costs, electricity costs, etc. The energy price for diesel propulsion plant is lower. The energy price for diesel propulsion plant is 56 USD/MWh. The characteristics of the electric propulsion plant are listed in table 4.39.

Characteristics of Electric Propulsion Plant	
Main Engine Output (MCR)	**15616 kW**
Main Engine Output (NOR)	**14054 kW**
Motor Efficiency	**95%**
Main Engine Number of Revolutions	**74 rpm**
Engine load (% of MCR)	**90%**
Required Electrical Power	**1000 kW**
Propeller Diameter	**9.89 m**

Table 4.39 The estimated characteristics of electric propulsion plant

4.6.4 Cost Analysis Battery Ship

The technical characteristics are presented in paragraphs 4.6.2 and 4.6.3.
The building cost of the battery ship is now determined to determine the costs of the bulk electricity transport. The building costs of the battery ship are mainly based on inflation corrected building costs of very large crude oil tankers from Asian shipyards [17].
The cost parameters are based on specific cost per ton or specific cost per kilowatt. The building costs include the costs for the battery system. The newbuilding cost of the battery ship is calculated in table 4.40.

Description	Quantity	Unit	Costs
Hull steel structure	**51287 ton**	**1684 USD/ton**	**86367308 USD**
Outfit	**3204.4 ton**	**9693 USD/ton**	**31060249 USD**
Machinery	**19005 kW**	**522 USD/kW**	**9920610 USD**
Stacks	**621810 kW**	**900 USD/kW**	**559629000 USD**
Electrolyte	**294000 ton**	**2500 USD/ton**	**735000000 USD**
Newbuilding Cost/Investment			**1421977167 USD**
Annuity (8% for 30 years)			**126310582 USD/year**
CAPEX			**3789.32 million USD**

Table 4.40 The build-up of the newbuilding cost of battery ship

The newbuilding cost of battery ship with diesel propulsion is estimated on 1421.98 million USD. The newbuilding cost of battery ship with electric propulsion is estimated on 1420.21 million USD. The major part of the newbuilding cost is the battery system. The cost of the battery system could become cheaper in the future. The cost of the battery stack could drop till 450 USD/kW and the cost of electrolyte could drop till 1250 USD/ton. The newbuilding cost of battery ship would be 774.66 million USD, when the cost of battery stack is 450 USD/kW and the cost of electrolyte is 1250 USD/ton. In the future the energy density of the battery system could likewise increase. The developments could make the bulk electricity transport with the battery ship cheaper. The total ship costs of battery ship for the distances 500 nautical miles and 1000 nautical miles are listed in table 4.41.
The energy consumption of the battery ship in table 4.41 is based on the brake power of the main engine. The characteristics of the roundtrip for the distances 500 nautical miles and 1000 nautical miles are similar as table D2 in Appendix D Roundtrip. The fuel costs are calculated with the fuel price of 350 USD/ton and the specific fuel rate of 0.160 ton/MWh.

Parameters	500 nautical miles	1000 nautical miles
Total Frequency (30 years)	**1680**	**1110**
Roundtrip Time in hours	**151.7**	**230.5**
Total Energy Consumption in MWh	**2034546**	**2607477**
Capital Costs in million USD	**3789.32**	**3789.32**
Operating Costs in million USD	**145.91**	**145.91**
Running Costs in million USD	**3935.23**	**3935.23**
Fuel Costs in million USD	**113.94**	**146.02**
Total Ship Costs in million USD	**4049.17**	**4081.25**

Table 4.41 The total ship costs of the battery ship for 500 and 1000 nautical miles

Besides the costs of battery ship the costs for the offshore terminals are likewise relevant. The offshore terminals are similar as the described offshore terminals in paragraph 4.4.3, except the dimensions of offshore terminals are different.

The resulting terminal costs are presented in table 4.42. The terminal costs for site A and site B are calculated in Appendix E Terminal Costs. The energy costs at site A for the distances 500 nautical miles and 1000 nautical miles are calculated in table 4.43.

Parameters	Terminal at site A	Terminal at site B
Electrical Power in MW	**310.91**	**621.81**
Capital Expenditures in million USD	**136.34**	**241.71**
Operating Expenditures in million USD	**0**	**0**
Total Terminal Costs in million USD	**136.34**	**241.71**

Table 4.42 The costs of offshore terminal for site A and site B

Description	500 nautical miles	1000 nautical miles
Energy from Power Plants in GWh	**15.00**	**15.00**
Stored Energy in Batteries in GWh	**14.70**	**14.70**
Energy Cost in million USD	**0.45**	**0.45**
Total Frequency (30 years)	**1680**	**1110**
Energy Costs in million USD (30 years)	**756.00**	**499.50**

Table 4.43 The energy costs at site A for 500 and 1000 nautical miles

The total costs for distances 500 nautical miles and 1000 nautical miles are calculated in table 4.44. As mentioned before the total costs are the costs of the energy supply chain, which transports bulk electricity from the remotely located power plants to the grid of the electric power consumers. The total costs are divided into capital expenditures and operating expenditures. The electricity costs of the bulk electricity transport with battery ship are listed in table 4.45. As mentioned before the cost per MWh of delivered energy is the total costs divided by delivered energy. The table 4.45 indicates that the costs per MWh of delivered energy are respectively 8.92 times and 12.92 times more expensive than the cost per MWh of power plants. The costs of offshore terminals represent only roughly 7% of the total costs. The cost per MWh could drop in the magnitude of 3.5% by adding a battery ship to the energy supply chain. This measure is only applicable beyond the distance of approximately 500 nautical miles, otherwise the measure would be contra productive. In this case the bulk electricity transport will only consist of two offshore terminals and one battery ship. The energy consumption of bulk electricity transport with battery ship is presented in table 4.46. The energy efficiency of bulk electricity transport with battery ship is calculated in table 4.47. The energy efficiency of bulk electricity transport with battery ship is the ratio between the delivered electrical energy and the energy input. The useful energy output is the delivered energy to the electric power consumers. The energy input consists of the electrical energy from the power plants and the required energy for the bulk electricity transport like the mechanical energy from the ship propulsion plant.

Description	500 nautical miles	1000 nautical miles
Battery Ship Costs in million USD	**4049.16**	**4081.25**
Terminal Costs Site A in million USD	**136.34**	**136.34**
Energy Costs in million USD	**756.00**	**499.50**
Terminal Costs Site B in million USD	**241.71**	**241.71**
Total Costs in million USD	**5183.21**	**4958.80**
CAPEX in million USD	**4167.37**	**4167.37**
OPEX in million USD	**1015.85**	**791.43**

Table 4.44 The terminal costs for the bulk electricity transport with the battery ship

Description	500 nautical miles	1000 nautical miles
Cost per MWh of Power Plants	**30.00 USD/MWh**	**30.00 USD/MWh**
Cost per MWh for Energy Transport	**237.70 USD/MWh**	**357.63 USD/MWh**
Cost per MWh of Delivered Energy	**267.70 USD/MWh**	**387.63 USD/MWh**

Table 4.45 The electricity costs for the bulk electricity transport with the battery ship

Description	500 nautical miles	1000 nautical miles
Production	**25200000 MWh**	**16650000 MWh**
Terminal Operation at site A	**504000 MWh**	**333000 MWh**
Sea Transport	**2034546 MWh**	**2607477 MWh**
Terminal Operation at site B	**5334336 MWh**	**3524472 MWh**
Total	**33072882 MWh**	**23114949 MWh**

Table 4.46 The energy consumption of the bulk electricity transport with battery ship

Description	500 nautical miles	1000 nautical miles
Energy Consumption	**33072882 MWh**	**23114949 MWh**
Delivered Energy	**19361664 MWh**	**12792528 MWh**
Energy Efficiency	**58.54%**	**55.34%**
Energy Losses	**41.46%**	**44.66%**

Table 4.47 The energy efficiency of the bulk electricity transport with battery ship

The influence of the parameters distance and cost per MWh of power plants on the cost per MWh of delivered energy will be more profound examined for two propulsion plant configurations of battery ship. As mentioned before there are two propulsion plant configurations, namely:

- Diesel Propulsion Plant
- Electric Propulsion Plant

The diesel propulsion plant uses heavy fuel oil and diesel fuel oil, which causes harmful emissions such as carbon dioxide emissions. The electric propulsion plant uses the energy in batteries to propel the battery ship. The electric propulsion plant causes no emissions.
The influence of each parameter is determined by varying the parameter. The first parameter that will be investigated is the distance. The distance is varied from 0 nautical miles till 6000 nautical miles. The distance of 6000 nautical miles is the distance between the continents America and Europe. The delivered energy in GWh versus the distance in nautical miles is illustrated in figure 4.39. The energy losses in % versus the distance in nautical miles are shown in figure 4.40.

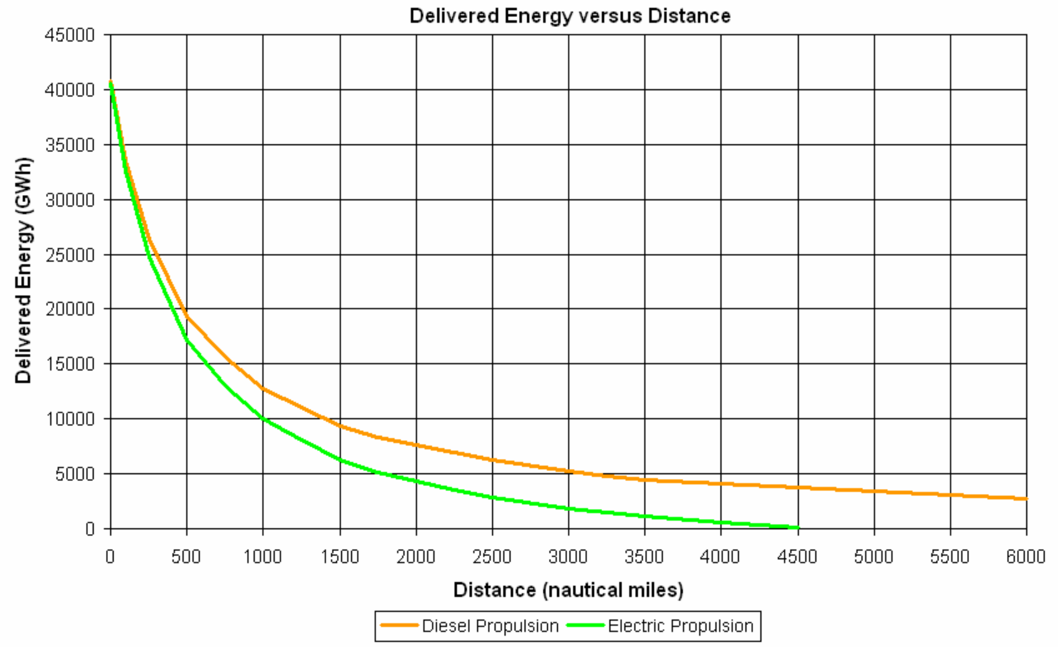

Figure 4.39 The delivered energy in GWh during 30 years versus the distance in nautical miles

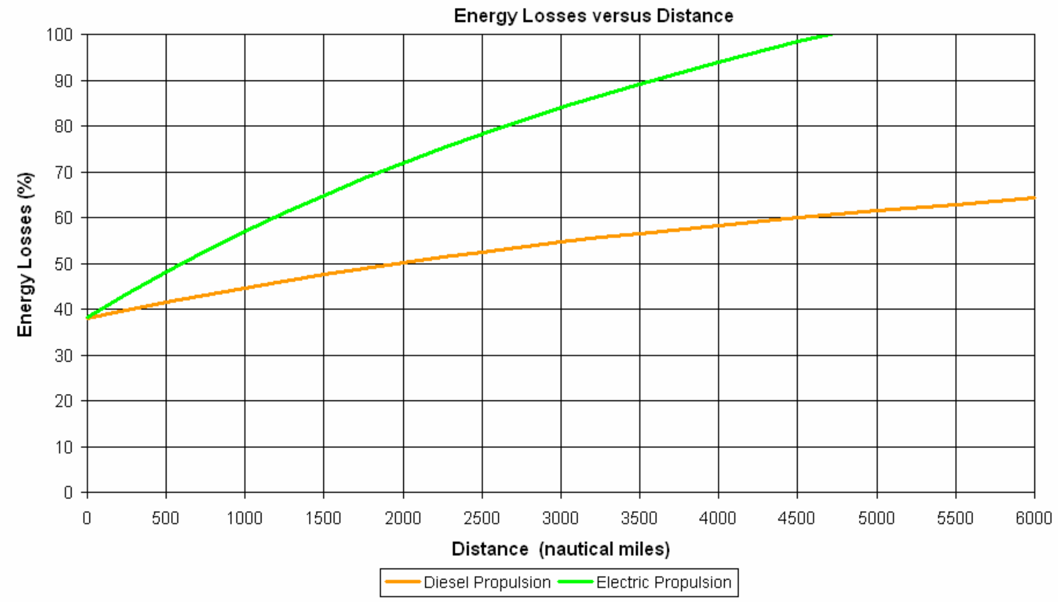

Figure 4.40 The energy losses in % versus the distance in nautical miles

The energy flows of energy transport with the battery ship with diesel propulsion plant are shown in figure 4.41. The energy flows of energy transport with the battery ship using the energy from the batteries are illustrated in figure 4.42.
The two Sankey diagrams show that the largest energy losses occur during sea transport and discharging the redox flow batteries. In addition the energy losses due to sea transport increase, when the distance increases.

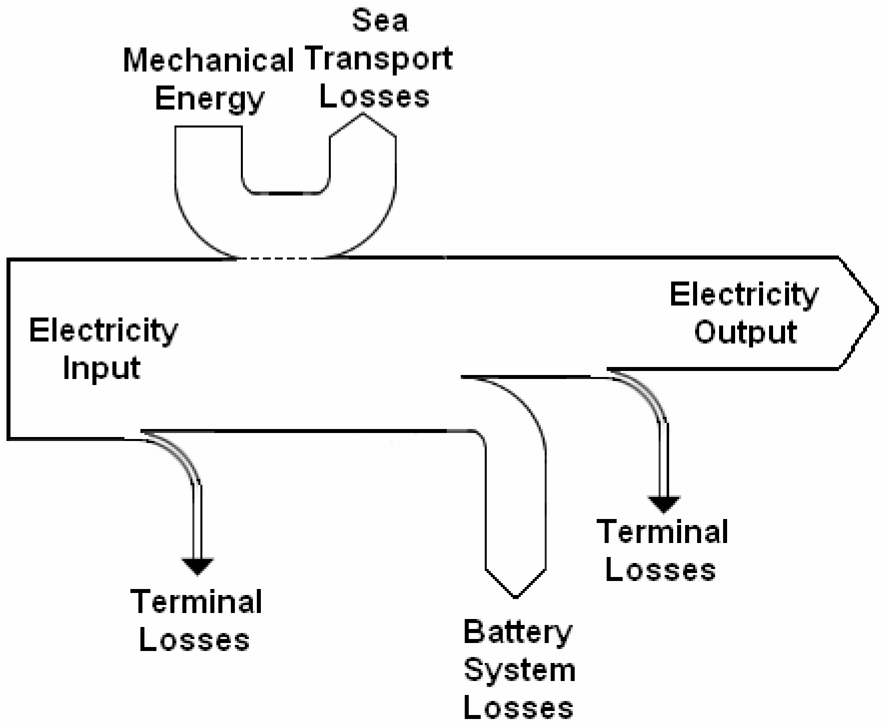

Figure 4.41 The energy flows of energy transport with the battery ship with diesel propulsion

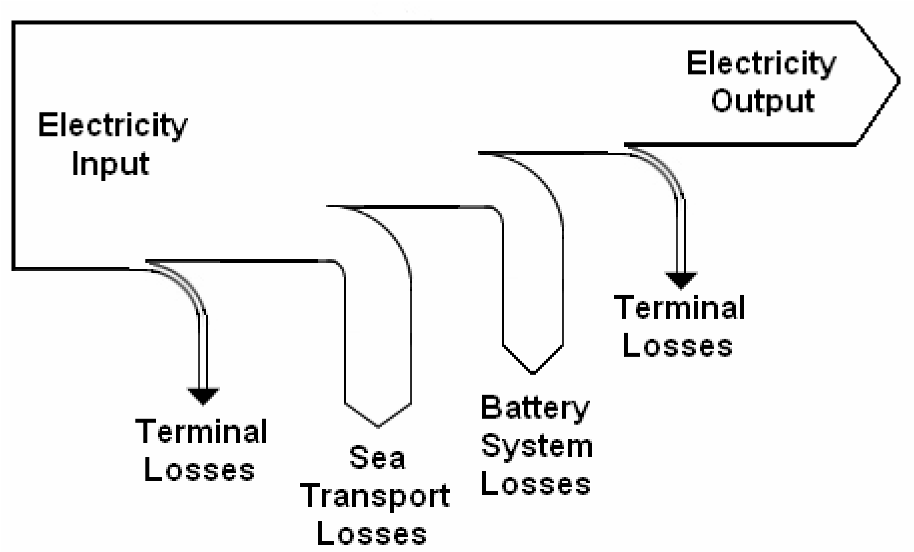

Figure 4.42 The energy flows of energy transport with the battery ship using the energy from the batteries

The cost per MWh of delivered energy in USD/MWh and the cost per MWh for energy transport in USD/MWh versus the distance in nautical miles are illustrated in figure 4.43. During the distance variation the cost per MWh of power plants is 30 USD/MWh. The capital expenditures in million USD versus the distance are shown in figure 4.44.

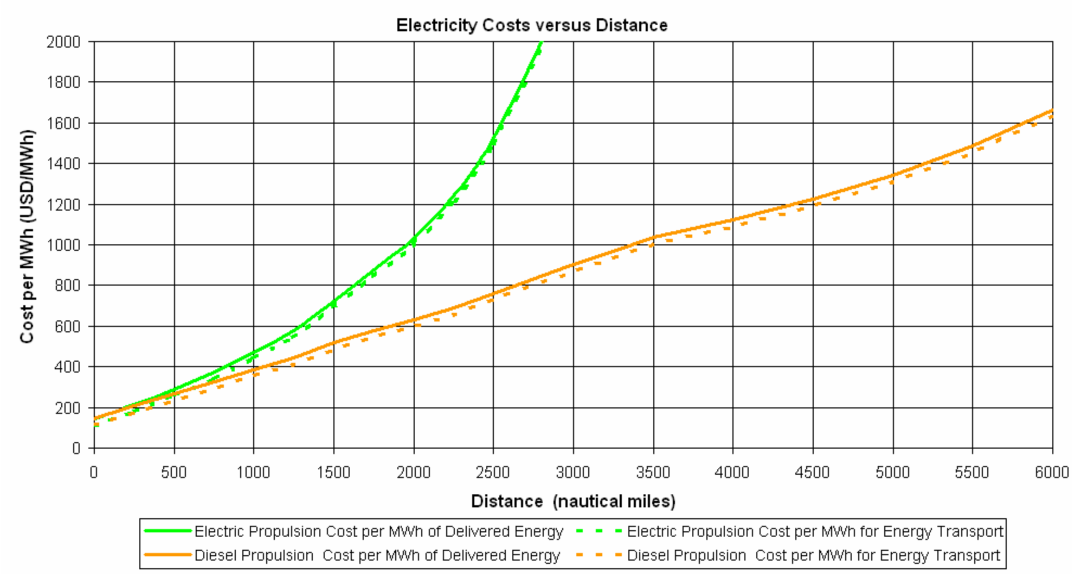

Figure 4.43 The cost per MWh of delivered energy and the cost per MWh for energy transport in USD/MWh versus the distance in nautical miles

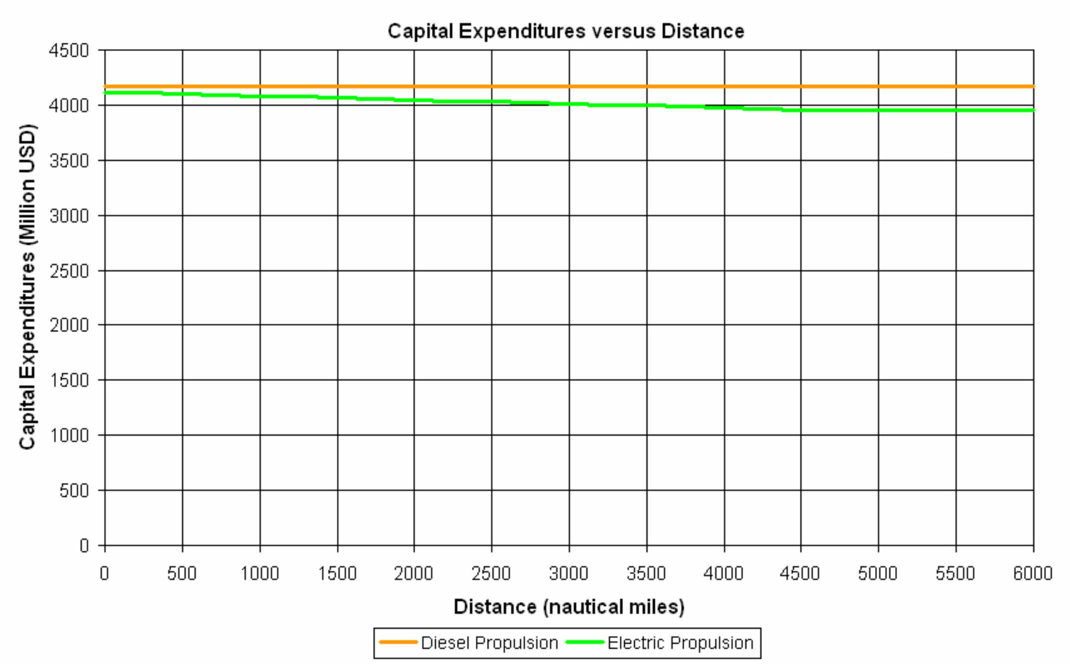

Figure 4.44 The capital expenditures in million USD versus the distance in nautical miles

The figure 4.44 demonstrates that the capital expenditures of the battery ship with diesel propulsion plant are constant for each distance. The capital expenditures of the battery ship with electric propulsion plant become smaller, when the distance increases. The capital expenditures decrease due to a smaller required offshore terminal at site B. However the difference is small. The figure 4.43 indicates that the cost per MWh of delivered energy with the battery ship with electric propulsion plant is higher than the cost per MWh of delivered energy with the battery ship with diesel propulsion plant, so the use of the electric propulsion plant and the energy from the batteries are less attractive from economical perspective. The figure 4.39 and figure 4.40 show the evidence that the battery ship with electric propulsion plant delivers less energy than the battery ship with diesel propulsion plant.

Moreover the battery ship with electric propulsion plant has higher energy losses than the battery ship with diesel propulsion plant. In addition the influence of the distance on the battery ship with electric propulsion plant is larger, so the use of the electric engine and the energy from the batteries are less attractive from energetic perspective. The figures indicate likewise that energy transport beyond approximately 4000 nautical miles is not possible or it is not attractive. Beyond approximately 4000 nautical miles the energy consumption of the battery ship is larger than the delivered energy. Summarized currently the battery ship with diesel propulsion plant is more attractive than the battery ship with electric propulsion plant and the battery ship should not be used beyond approximately 4000 nautical miles. The next parameter that will be investigated is the cost per MWh of power plants. The cost per MWh of power plants is estimated 30 USD/MWh, but the cost per MWh of power plants could be lower or higher than 30 USD/MWh. Therefore the cost per MWh of power plants is varied from 0 USD/MWh to 150 USD/MWh to determine the influence of the parameter cost per MWh of power plants on the cost per MWh of delivered energy. The influence of the cost per MWh of power plants in USD/MWh on the cost per MWh of delivered energy in USD/MWh for the distance 500 nautical miles is illustrated in figure 4.45. The influence of the cost per MWh of power plants in USD/MWh on the cost per MWh of delivered energy in USD/MWh for the distance 1000 nautical miles is shown in figure 4.46.

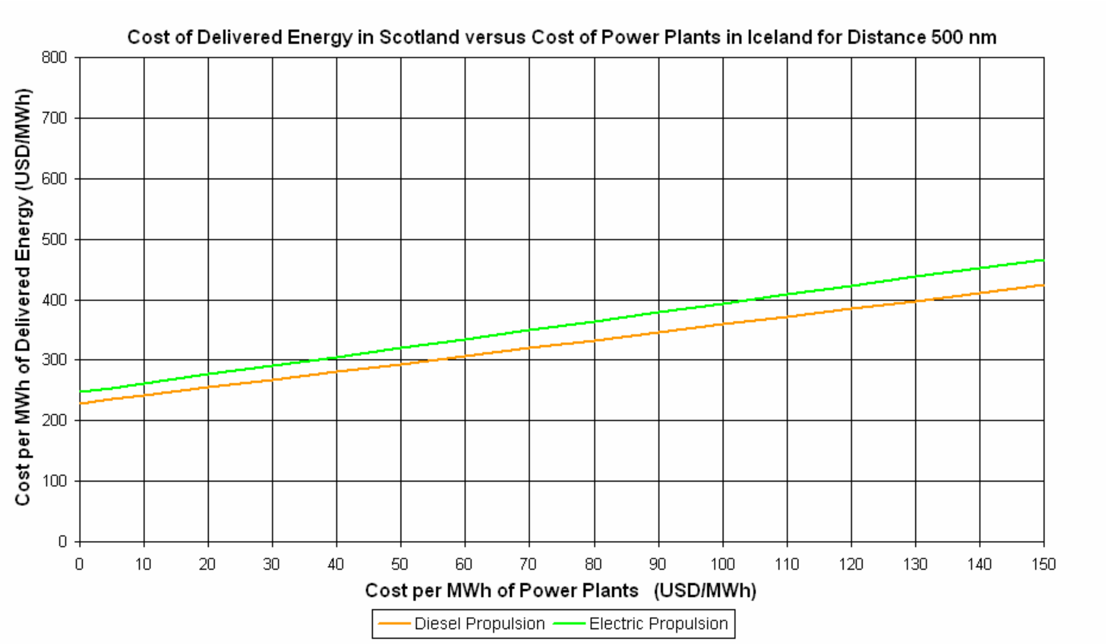

Figure 4.45 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance 500 nautical miles

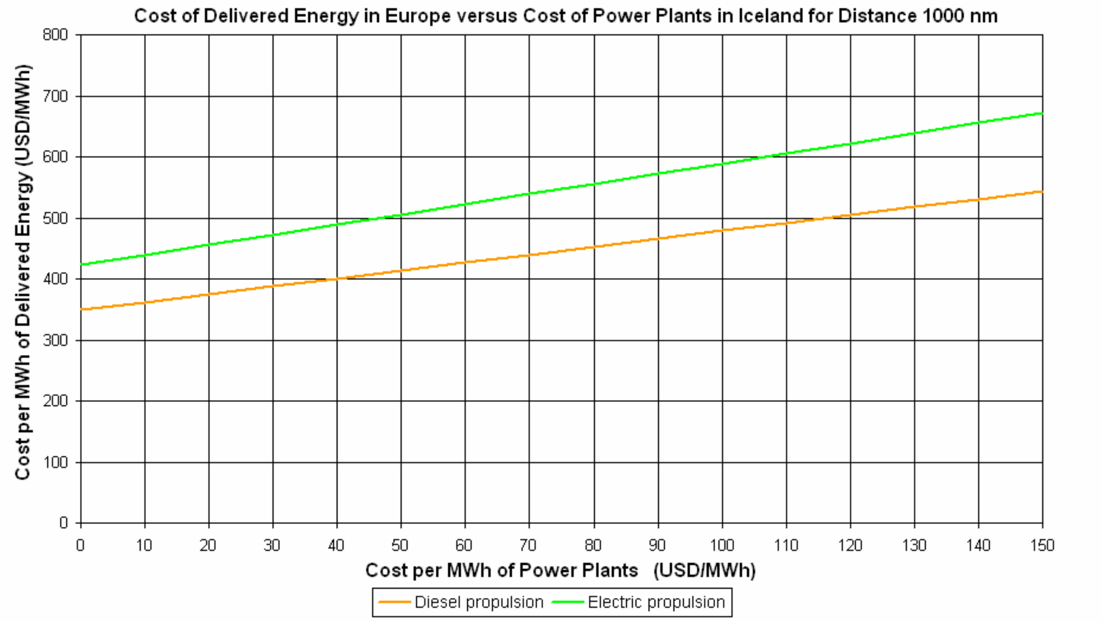

Figure 4.46 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance 1000 nautical miles

5 Synthetic Fuels Investigation

In this chapter the synthetic fuels are investigated and the appropriate synthetic fuels for bulk electricity sea transport are analysed.

5.1 Synthetic Fuels Selection

Synthetic fuel is an industrial manufactured fuel such as diesel, naphtha, hydrogen, methanol, ethanol and paraffin made from chemicals such as natural gas, water, coal, biomass or waste. The synthetic fuels refer to man-made liquids or man-made gaseous fuels. The benefit of gaseous phase and liquid phase is that the synthetic fuel can be moved with pumps or compressors. Furthermore most synthetic fuels have in common that the molecule contains hydrogen atoms. Therefore synthetic fuels can also be referred as hydrogen related fuels.
The synthetic fuels are here divided into two groups of synthetic fuels. The first group synthetic fuels are made from hydrocarbons and biomass. The familiar production processes of the first group synthetic fuels are Gas-To-Liquids (GTL), Biomass-To-Liquids (BTL) and Coal-To-Liquids (CTL). The produced synthetic fuels with thermochemical or photochemical processes belong here to the first group synthetic fuels. The second group synthetic fuels are mainly made from water, CO_2 or other chemicals with the assistance of electricity.
The production of second group synthetic fuels takes place in a chemical reactor or/and electrolyzer. The second group synthetic fuels will be examined for the purpose of bulk electricity transport, so the synthetic fuel is the energy carrier. It should be noted that some synthetic fuels are found in both groups. Furthermore nuclear fuels like uranium are excluded in this report. The synthetic fuels are similar as the other fuels. The most well-known fuels are fossil fuels such as oil, natural gas, coal and biofuels such as wood and biomass.
The mentioned fuels are fuels, which are found in the Earth crust or in nature.
The chemical energy in the fuel is obtained by burning, oxidizing or otherwise modifying the fuel. Most fuels react with oxygen to release the chemical energy. The chemical reaction with oxygen takes usually place in an internal combustion engine or fuel cell. The chemical energy comes free in such a way that the internal combustion engine or fuel cell delivers continuously mechanical energy or electrical energy. After the reaction with oxygen the waste in the form of solids, liquids and gas emissions remains. The waste is released into the atmosphere and the environment or the waste is recycled to produce again synthetic fuel.
The important characteristic of fuel is that the chemical energy is only released, when the energy is needed. The advantages of synthetic fuel compared with batteries or other electrical storage devices are that in general synthetic fuels have a high energy density and no self-discharge. In addition the synthetic fuels are easier storable, easier transportable and the size of production system, storage system and generator system are independent of each other.
The main drawback of synthetic fuel is that the energy efficiency during production and power generation is lower than the batteries. For the use of synthetic fuel the following issues such as energy density, safety, toxicity, storability, transportability, availability of feedstock, operating temperature range, energy efficiency, corrosion, costs, recycling of emissions and pollution of the environment are important. Among the synthetic fuels such as hydrogen, ammonia, methanol, dimethyl ether (DME), sodium borohydride and zinc the two most promising synthetic fuels should be selected for the purpose of bulk electricity sea transport.
The two most promising synthetic fuels will be investigated in more details. The descriptions of synthetic fuels are presented in Appendix K Synthetic Fuels. The two most promising synthetic fuels are selected with an approximate comparison and a comparison of the energy densities of the synthetic fuels.

The energy density of the synthetic fuel is important. The gravimetric and volumetric energy density of the synthetic fuels should naturally be as high as possible due to the benefit during sea transport. The energy densities of synthetic fuels from Appendix K Synthetic Fuels are listed in table 5.1. Furthermore it should be noted that the volumetric energy density is more important than the gravimetric energy density, when the density of synthetic fuel is lower than 0.77 ton/m^3. Below the density of 0.77 ton/m^3 the volumetric energy density is more important, because below the density of 0.77 ton/m^3 the cargo ship design is volume limited. Therefore below the density of 0.77 ton/m^3 the volumetric energy density of the synthetic fuels is only compared. On the other hand the gravimetric energy density is more important than the volumetric energy density, when the density of synthetic fuel is higher than 0.77 ton/m^3. Above the density of 0.77 ton/m^3 the gravimetric energy density is more important, because above the density of 0.77 ton/m^3 the cargo ship design is weight limited. Therefore above the density of 0.77 ton/m^3 the gravimetric energy density of the synthetic fuels is only compared.

Synthetic Fuel	Density in kg/m^3	Gravimetric Energy Density in kWh/kg	Volumetric Energy Density in kWh/m^3
Hydrogen	**0.0899**	**39.7**	**3.568**
Ammonia (gas)	**0.77**	**6.24**	**4.805**
DME (gas)	**1.91**	**8.0**	**15.26**
Hydrogen at 200 bar	**20.028**	**39.7**	**795.1**
Liquid Hydrogen	**72.312**	**39.7**	**2871**
Ammonia (liquid)	**680**	**6.24**	**4243**
DME (liquid)	**668**	**8.0**	**5344**
Methanol	**791**	**6.3**	**4983**
Sodium Borohydride	**1030**	**2.84**	**2925**
Zinc	**7140**	**0.4**	**2865**

Table 5.1 Comparison of density and energy densities of synthetic fuels

The table 5.1 indicates that below the density of 0.77 ton/m^3 the synthetic fuels DME and ammonia have the highest volumetric energy density and above the density of 0.77 ton/m^3 the synthetic fuel methanol has the highest gravimetric energy density. Therefore the result of the comparison in table 5.1 is that the synthetic fuels DME, methanol and ammonia are identified as attractive solutions due to their energy density. Besides the energy densities other issues for the use of synthetic fuels are relevant such as good availability of feedstock, good transportability, etc. Therefore the two most promising synthetic fuels are selected through an approximate comparison. As mentioned before the approximate comparison knows only three levels: better (+) or equal (=) or less (-). The method checks for each specification whether the synthetic fuel meets the required specification. In this way the strong points and weak points for each synthetic fuel for the purpose of bulk electricity sea transport will be clarified.
The important specifications for the synthetic fuels are defined as follows:

- Non-toxic Non-corrosive Fuel
- Good Availability of Feedstock
- Good Transportability
- Only One Ship Type
- No Recycling

Most defined specific requirements are difficult to quantify, but still they are very important to select the two appropriate synthetic fuels. The approximate comparison between different synthetic fuels is presented in table 5.2.

Specifications	Non-corrosive Non-toxic fuel	Good Availability of Feedstock	Good Transportability	Only One Ship Type	No Recycling	Score
Hydrogen (gas)	+	+	-	+	+	+3
Ammonia (gas)	-	+	+	+	+	+3
DME (gas)	+	-	+	+	-	+1
Hydrogen at 200 bar	+	+	-	+	+	+3
Liquid Hydrogen	+	+	-	+	+	+3
Ammonia (liquid)	-	+	+	+	+	+3
DME (liquid)	+	-	+	+	-	+1
Methanol	-	-	+	-	-	-3
Sodium Borohydride	-	-	+	+	-	-1
Zinc	+	-	-	+	-	-1

Table 5.2 Approximate comparison for all synthetic fuels

The result of the approximate comparison is that the synthetic fuels ammonia, hydrogen, and DME are identified as most suitable solutions from the approximate comparison for the purpose of bulk electricity sea transport. Besides that the synthetic fuels are suitable as fuel for vehicles. The most promising synthetic fuel according to the approximate comparison and the comparison of energy densities is anhydrous ammonia. Therefore the bulk electricity sea transport by means of ammonia will be investigated in more details. The main drawback of ammonia according to the approximate comparison is that anhydrous ammonia is a toxic corrosive gas. The second promising synthetic fuel according to the approximate comparison is hydrogen. The main drawback of hydrogen according to the approximate comparison is that hydrogen is not good transportable. In addition hydrogen gas at ambient conditions has a low volumetric energy density according to table 5.1. The volumetric energy density of hydrogen is increased by liquefying or compressing the hydrogen. The most attractive solution to increase the volumetric energy density is compressing hydrogen, because liquefying hydrogen is very energy-intensive and expensive. Therefore the bulk electricity sea transport by means of compressed hydrogen will be investigated in more details. The third synthetic fuel according to the approximate comparison is DME. DME is a non-corrosive non-toxic fuel with very high volumetric energy density according to the table 5.1 and the table 5.2. The main drawbacks of DME are that DME is synthesized from CO_2 and CO_2 recycling is required. Besides that DME is still a promising clean fuel for the future. Notwithstanding the advantages of the bulk electricity sea transport by means of the synthetic fuel DME, the synthetic fuel DME will not be investigated in more details.

5.2 Hydrogen

Hydrogen is a colourless, non-toxic non-metallic, extreme flammable gas. Hydrogen is the simplest, lightest and most abundant element of all elements in the universe. Hydrogen is bound in water and hydrocarbons. The hydrogen does not occur on Earth in high concentrations, but it is found in small concentrations in the atmosphere.
Hydrogen is no greenhouse gas. Hydrogen has the following distinctive characteristics:

- Hydrogen gas is lighter than air
- Hydrogen is the lightest gas
- Hydrogen reacts violently with halogens
- Hydrogen is non-corrosive
- Hydrogen is non-toxic
- Hydrogen is tasteless
- Hydrogen is liquefied under extreme cold temperatures
- Hydrogen burns with a colourless flame and it has no harmful soot
- Hydrogen is extreme flammable and it has a low ignition energy

Hydrogen is extreme flammable, because hydrogen has a wide range of flammable concentrations in air and it has low ignition energy.
Hydrogen is not very explosive in open area, because hydrogen rises and disperses quickly. Hydrogen in confined space is more dangerous, because hydrogen is difficult to detect. Even burning hydrogen is difficult to detect, because the flame radiates less heat than other fuels and the flame is invisible. Another problem with hydrogen is hydrogen embrittlement. Hydrogen embrittlement is the process by which metal becomes brittle due to the exposure to hydrogen. The embrittlement of metal will result in leaks, cracks and failures.
For the time being, the assumption is made that hydrogen embrittlement poses no problem. The risks associated with hydrogen are acceptable, when the proper safety measures are taken.

Chemical formula	H_2
Molecular weight	2.016
Appearance	Colourless gas
Odour	tasteless
Chemical composition (%)	
Hydrogen	100
Melting point	-259.3 ºC
Boiling point	-252.9 ºC
Density of gas	0.0899 kg/m^3 (1 bar)
Density of liquid	72.312 kg/m^3
Vapor pressure	-
Energy content	39.7 kWh/kg
Autoignition temperature	565-581 ºC
Minimum ignition energy	0.02 MJ
Flammability limits in air	4%-75%

Table 5.3 The characteristics of hydrogen [6][18][60][147]

5.2.1 Hydrogen Production

Hydrogen is mainly found bound in different molecules. Hydrogen is abundant in nature. The most common molecule with hydrogen is water. The production of hydrogen from water requires energy. Today most hydrogen is produced through the reforming of hydrocarbons or through the electrolysis using electricity. The different methods of producing hydrogen are:

- Reforming natural gas
- Reforming coal
- Reforming oil
- Reforming biomass and waste feed stocks
- Electrolysis of water
- Photo-electrolysis (photolysis)
- Photo-biological hydrogen production (biophotolysis)
- Thermal dissociation

The most utilized method for producing hydrogen is steam reforming of natural gas, but the most sustainable method for producing hydrogen is electrolysis of water using electricity from the renewable power plants. The electrolysis of water using electricity is the most appropriate method for the bulk electricity sea transport. As stated before water electrolysis splits water into hydrogen gas and oxygen gas. The hydrogen and oxygen are created through a direct current, which goes through water. The electrical energy required for water splitting decreases, when the water temperature increases. The splitting of water takes place in the electrolyzer. Today water electrolysis is performed with the following electrolyzers:

- Alkaline electrolyzer
- Polymer electrolyte membrane (PEM) electrolyzer
- High-temperature electrolyzer

The most mature cheapest electrolyzer with the highest efficiency is the alkaline electrolyzer. The drawback of alkaline electrolyzer is that it is not so capable to cope with variations in electricity supply. The PEM electrolyzer is better capable to cope with variations in electricity supply. The disadvantages of PEM electrolyzer are low capacity, high costs, poor efficiency and short lifetime. The immature PEM electrolyzer should be improved, if the PEM electrolyzer wants to compete with the alkaline electrolyzer. For the time being, the alkaline electrolyzer is the most favourable electrolyzer. The alkaline electrolyzer consists of two electrodes cathode and anode and an alkaline electrolyte such as sodium or potassium hydroxide. In the electrolyzer the following reaction takes place [6][18]:

$$\mathbf{2\,H_2O\,(l) + electricity \rightarrow 2\,H_2\,(g) + O_2\,(g) \qquad \Delta H = 572\ kJ\ or\ 286\ kJ/mol}$$

The alkaline electrolyzers are the most important part of the hydrogen production plant. The hydrogen production plant consists of the following parts:

- 138 alkaline electrolyzer Norsk Atmospheric Type No 5040 (4000 Amp DC)
- 136 three stage metal diaphragm compressors (1 bar to 200 bar)
- 1 electricity converter
- 1 transformer station

The parts of the hydrogen production plant are presented in Appendix L Hydrogen Production Plant. The material input of the hydrogen production plant consists of purified water, which is supplied from the municipal water system. The hydrogen production plant consumes 431845 m^3 water yearly. The material output of the hydrogen production plant consists of oxygen and hydrogen. The oxygen could be released into the atmosphere or the oxygen could be stored in pressure vessels. After that the stored pure oxygen is sold to the chemical industry. In this case the oxygen is released into the atmosphere. The production rate of the hydrogen production plant is 4263.93 kg/hr. The annual hydrogen production of the hydrogen production plant is 36098412 kg, so the hydrogen production plant produces 1082952360 kg hydrogen during 30 years. The costs and the energy consumption of the hydrogen production plant are calculated in Appendix N Cost Calculations. The resulting costs of the hydrogen production plant during 30 years are presented in table 5.4.

Description	Costs
Capital Expenditures in million USD	**461.68**
Operating Expenditures in million USD	**1765.99**
Total Costs in million USD	**2227.67**

Table 5.4 The costs of hydrogen production plant

The hydrogen price from hydrogen production plant is 2.06 USD/kg. Furthermore the energy consumption for producing 1 kg hydrogen is 50,109 kWh and the energy consumption of hydrogen production plant during 30 years is 54265660 MWh. The hydrogen production plant is placed in the terminal at site A. The terminal consists of the following parts:

- 1 hydrogen production plant
- 27 hydrogen storage tanks
- 27 three stage metal diaphragm hydrogen compressors
- hydrogen pipelines

The parts of the terminal at site A are presented in Appendix M Hydrogen Terminal.
The storage capacity of the terminal is 707812 kg hydrogen. The hydrogen compressors of the terminal are capable to compress 707812 kg hydrogen from the hydrogen storage tanks into the hydrogen CNG ship within 24 hours. The costs of the terminal at site A are calculated in Appendix N Cost Calculations. Furthermore the port dues for site A and site B are neglected. The energy consumption of the terminal at site A is 356291 MWh during 30 years.
The resulting costs of the terminal at site A during 30 years are presented in table 5.5.

Description	Costs
Capital Expenditures in million USD	**949.00**
Operating Expenditures in million USD	**1776.69**
Total Costs in million USD	**2725.69**

Table 5.5 The costs of terminal at site A

5.2.2 Hydrogen Transport

The sea transport of hydrogen is no common practice. Hydrogen could be transported with compressed hydrogen containers or in a gas tanker. The hydrogen transport with gas tanker is more attractive, because a gas tanker is more flexible. The gas tanker is capable to visit both offshore terminals and port terminals. The containerships are restricted to port terminals.
In addition the gas tanker is an optimal design for the carriage of gases. The gas tanker fleet is divided into LPG tankers and natural gas tankers. The LPG tankers carry gas with the densities of 0.60 ton/m^3 up to 0.97 ton/m^3. In principal the LPG tankers are capable to carry hydrogen gas at atmospheric pressures, but the density of hydrogen is far too low for a LPG tanker. The natural gas tankers carry the fossil fuel natural gas. The natural gas could be transported as liquefied natural gas or as compressed natural gas. The density of liquefied natural gas is approximately 0.42 ton/m^3 and the density of compressed natural gas is roughly 0.21 ton/m^3 [72][79]. The low density of natural gas makes transport and storage difficult. Today most natural gas is transported as liquefied natural gas, because liquefied natural gas is safer and it has a higher energy density. In addition the technology for compressed natural gas is just recently developed. Still the first compressed natural gas (CNG) ship is not yet constructed. The hydrogen has a lower density than natural gas. The density of hydrogen corresponds almost with helium. The difference between helium and hydrogen is that hydrogen is extreme flammable. Similar as natural gas hydrogen could be transported as liquefied hydrogen, but as stated before it is very energy intensive and very expensive. Therefore liquefied hydrogen is not a viable option. The hydrogen should be transported as compressed hydrogen, so consequently hydrogen is transported with a CNG ship. The first CNG concepts have emerged in the 1960's [138]. Among CNG concepts the Coselle CNG ship has only received approval for construction by the classification society American Bureau of Shipping (ABS). The Coselle CNG ship is developed by Sea NG Corporation. Thus the Coselle CNG ship will be used for the transport of compressed hydrogen.
The cargo containment system of the Coselle CNG ship consists of several Coselles.
The containment system is easy sizeable.
The Coselle is a large coil of high-strength X70 pipe wound into a carousel [116].
The Coselle has the shape of a cylindrical container. The diameter of the Coselle is 15.24 m and the height of Coselle is 3.43 m.
The diameter of the coiled pipe is 168 mm.
The length of coiled pipe is 18.3 km.
The weight of Coselle is 450 ton.
The volume of a Coselle is 392 m^3.

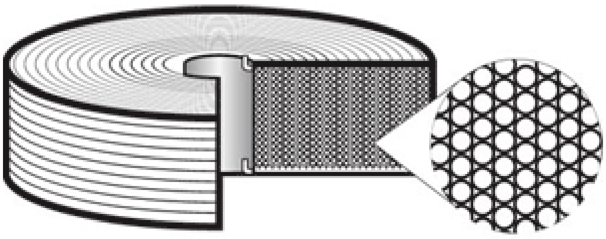

Figure 5.1. The Coselle [116]

The pressure in the Coselle ranges from 1 bar to 220 bar. The Coselle CNG ship transports hydrogen at the pressure of 200 bar. The Coselle CNG tanker consists of 108 Coselles.
The weight of 108 Coselles excluding hydrogen is 48600 ton. The volume capacity of Coselle CNG tanker is 42336 m^3, so the CNG tanker transports 42336 m^3 hydrogen at the pressure of 200 bar. The 42336 m^3 hydrogen at the pressure of 200 bar is equal to 707812 kg hydrogen.
The Coselle CNG ship transports 36098412 kg hydrogen yearly.
The 108 Coselles are installed in the cargo holds of a double-hulled Panamax bulk carrier.
The deadweight of a Panama bulk carrier is 69000 dwt. The Coselle CNG ship is shown in figure 5.2. The newbuilding price for the Coselle CNG ship is 156.463 million USD [42].
The newbuilding price of the 69000 dwt Panamax bulk carrier is 33.947 million USD, so the newbuilding price of 108 Coselles is 122.516 million USD [12].

The operating costs of the CNG tanker according figure 4.23 are estimated 7804.4 USD/day. The energy intensity coefficient of the CNG ship is similar as the energy intensity coefficient of bulk carriers.

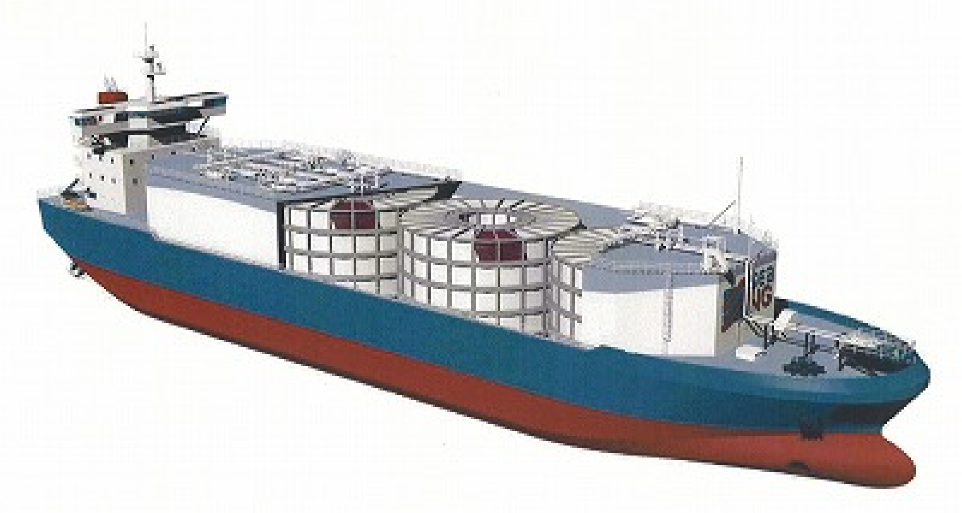

Figure 5.2 The Coselle CNG Ship [116]

The hazards of transporting hydrogen are comparable with the transport of natural gas, but hydrogen gas is extreme flammable. In contract to natural gas hydrogen disperses and rises rapidly into the atmosphere, so an explosion of hydrogen is less likely. Nevertheless hydrogen is not a safer fuel than natural gas, because hydrogen leaks are difficult to detect and hydrogen embrittlement poses also a safety risk. Still the transport of hydrogen or natural gas in a CNG ship is more dangerous than the transport of natural gas in a LNG carrier, because high pressure gas fires are more difficult to extinguish. The safety risks are minimized by inspections, safety procedures and good design of the gas containment system. The CNG ship transports the hydrogen over the distance of 1000 nautical miles. The Coselle CNG ship is likewise small enough to enter and to leave several ports. During one roundtrip the hydrogen is loaded into the CNG tanker at the terminal of site A. After the sea transport the compressed hydrogen is discharged at the terminal of site B. Furthermore the assumption is made that the loading and discharging of CNG tanker is accomplished within 24 hours. The assumption is based on the figures in Appendix C Unloading Times. The vessel sails roughly 360 days per year. The CNG ship runs on heavy fuel oil and diesel fuel oil, which have the energy price of 60 USD/MWh. The ship costs and the characteristics of the Coselle CNG tanker are calculated in Appendix N Cost Calculations. The energy consumption of hydrogen CNG tanker is 2886026 MWh during 30 years. The energy consumption of the tanker is based on the brake power of the main engine. The resulting costs of the Coselle CNG tanker during 30 years are presented in table 5.6.

Description	Costs
Capital Expenditures in million USD	**416.95**
Operating Expenditures in million USD	**258.62**
Total Costs in million USD	**675.57**

Table 5.6 The costs of hydrogen Coselle CNG tanker

5.2.3 Power Generation with Hydrogen

The hydrogen is an environmental benign fuel. The hydrogen is good compatible in several energy devices due to it is widely flammability range. Hydrogen is applicable in internal combustion engines and fuel cells. The efficiency of internal combustion engine is 45% [61]. The efficiency of fuel cell is 60% [18]. During the use in engines and fuel cells hydrogen produces no soot and it produces no carbon dioxide or other greenhouse gases.
In the internal combustion engine or fuel cell the following reaction takes place [6]:

$$\mathbf{2\ H_2\,(g) + O_2\,(g) \rightarrow 2\ H_2O\,(l) \qquad \Delta H = -572\ kJ\ or\ -286\ kJ/mol}$$

In the energy devices hydrogen reacts with oxygen to produce energy and potable water. The fuel hydrogen does not produce harmful emissions, when it reacts with oxygen. The pure water could be used for human consumption or the water could be transported back to the terminal at site A. In this case the pure water is sold for human consumption. The water price for human consumption is 0.5 USD/m^3 [115]. The chemical energy is converted into heat and mechanical energy or heat and electrical energy. On his turn mechanical energy is converted to electrical energy. The released chemical energy during burning of one kg hydrogen is 39.72 kWh or 143 MJ [6]. The power generation with hydrogen is accomplished with fuel cells or engine-driven generator sets. The main difference between the two energy devices is the efficiency and the capital costs. In addition the fuel cells require an electricity converter. The power generation with both energy devices will be now examined. The power generation with fuel cells is first examined. The fuel hydrogen is compatible in most fuel cells such as AFC, PEMFC, PAFC, MCFC, SOFC and URFC [27]. The important requirement for power generation with fuel cells is high energy efficiency. The power generation with fuel cells is sure enough very expensive. Currently the SOFC is the most attractive fuel cell for stationary application, because the fuel cell has high lifetime expectancy and high energy efficiency. Therefore the SOFC is selected for power generation. The solid oxide fuel cell is a mature fuel cell technology. The operating temperatures of SOFC range from 750 ºC to 1050 ºC. The electrical efficiency of SOFC is roughly 60% [81]. The SOFC fuel cell is developed by Siemens Westinghouse and Sulzer. Typical cost of SOFC is 3000 USD/kW [81]. The footprint of the solid oxide fuel cell is 12 m^2/MW [81]. The power plant with solid oxide fuel cells consumes 4264 kg hydrogen per hour. Therefore the size of power plant is 101.62 MW. The power plant is composed of solid oxide fuel cells, electricity converter, transformer station and electrical cables. Furthermore the annual operation and maintenance costs of the power plant such as insurance, salaries, maintenance and repairs are 1.5% of the investment. The energy losses in the power plant with solid oxide fuel cells are 42%. Besides 1 kg hydrogen furbishes 8.9365 kg pure water, so the power plant produces 38.10 m^3 pure water per hour. The costs of the 101.618 MW power plant are calculated in Appendix N Cost Calculations.

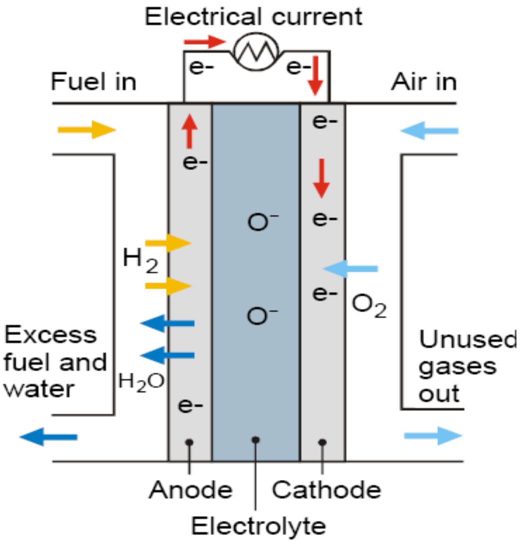

Figure 5.3. Hydrogen fuel cell [81]

The power plant with solid oxide fuel cells delivers 24948623 MWh electricity during 30 years. The resulting costs of the 101.618 MW power plant during 30 years are presented in table 5.7.

Description	Costs
Capital Expenditures in million USD	**851.05**
Operating Expenditures in million USD	**138.87**
Total Costs in million USD	**989.92**

Table 5.7 The costs of power plant with fuel cells

The power generation with hydrogen could likewise be accomplished with generator sets. For that reason the power generation with generator sets is now examined. The engine-driven generator set consists of an internal combustion engine and an alternator. The hydrogen burns in an internal combustion engine with some modifications. The efficiency of internal combustion engine is 45% [61]. The typical cost of internal combustion engine with alternator is assumed similar as the cost of natural gas engine with alternator. The cost of the internal combustion engine with alternator is 600 USD/kW [80]. The footprint of generator sets is 4.5 m^2/MW [117]. The energy losses in the power plant with generator sets are 56.5%. The annual operation and maintenance costs of the power plant are 1.5% of the investment. The power plant is composed of generator sets, transformer station and electrical cables. The costs of the 76.213 MW power plant are calculated in Appendix N Cost Calculations. The power plant with generator sets delivers 18711467 MWh electricity during 30 years. The resulting costs of the 76.213 MW power plant during 30 years are presented in table 5.8.

Description	Costs
Capital Expenditures in million USD	**121.16**
Operating Expenditures in million USD	**15.62**
Total Costs in million USD	**136.78**

Table 5.8 The costs of power plant with generator sets

The terminal at site B is similar as the terminal at site A, except the hydrogen production plant is replaced by a power plant. The terminal consists of the following parts:

- 1 power plant
- 27 hydrogen storage tanks
- 27 three stage metal diaphragm hydrogen compressors
- hydrogen pipelines

The storage capacity of the terminal is 707812 kg hydrogen. The hydrogen compressors and hydrogen storage tanks are identical as hydrogen compressors and hydrogen storage tanks deployed in the terminal at site A. The cost per MWh for hydrogen compressors is assumed 60 USD/MWh. The hydrogen compressors enable the unloading of 707812 kg hydrogen from the hydrogen CNG ship into the hydrogen storage tanks within 24 hours. The hydrogen compressors compress hydrogen from the pressure of 100 bar back to the pressure 200 bar. The pressure in hydrogen CNG tanker will drop to 100 bar, when the hydrogen CNG ship is connected to the hydrogen storage tanks by means of pipelines [21]. The pressure drop is caused by the doubling of the hydrogen storage volume. The hydrogen storage tanks store the hydrogen at the pressure of 200 bar till the hydrogen goes to the power plant. The hydrogen transport from the hydrogen storage tanks to the power plant is accomplished by the decompression of the compressed hydrogen in the hydrogen storage tanks. The pressure of hydrogen will drop from 200 bar to 1 bar. The power plant consumes the hydrogen.

The product of the power plant is energy and pure water. The pure water is transported away with a water pipeline. The water pumps and water pipeline for the water transport are excluded in the cost calculations. The terminal costs at site B with fuel cells and the terminal costs at site B with generator sets are calculated in Appendix N Cost Calculations. The resulting costs of the terminal at site B with fuel cells during 30 years are presented in table 5.9. The resulting costs of the terminal at site B with generator sets during 30 years are presented in table 5.10. Furthermore the energy consumption of hydrogen compressors on the terminal is 356291 MWh.

Description	Costs
Capital Expenditures in million USD	**1309.59**
Operating Expenditures in million USD	**160.26**
Total Costs in million USD	**1469.85**

Table 5.9 The terminal costs with fuel cells

Description	Costs
Capital Expenditures in million USD	**579.70**
Operating Expenditures in million USD	**37.00**
Total Costs in million USD	**616.70**

Table 5.10 The terminal costs with generator sets

5.2.4 Total Costs

In the previous paragraphs the different parts of the bulk electricity sea transport by means of the synthetic fuel hydrogen over the distance of 1000 nautical miles are determined.
As stated before, the total costs are the sum of the total ship costs, the terminal costs at site A and the terminal costs at site B. The total costs for the bulk electricity transport with the assistance of fuel cells and the bulk electricity transport with the assistance of generator sets are calculated in table 5.11. Moreover the total costs are divided into capital expenditures and operating expenditures. The electricity costs of the electricity transport by means of hydrogen are listed in table 5.12. Besides the costs, the energy consumption, energy efficiency and energy losses are important. The energy consumption of the bulk electricity transport by means of hydrogen is presented in table 5.13. The energy efficiency and the energy losses of the bulk electricity sea transport by means of hydrogen are presented in table 5.14.
The energy efficiency is the ratio between the delivered electrical energy and the energy input. The energy input consists of the total energy consumption from table 5.13.

Description	Fuel Cells	Generator Sets
Terminal Costs Site A in million USD	**2725,69**	**2725,69**
Total Ship Costs in million USD	**675,57**	**675,57**
Terminal Costs Site B in million USD	**1469,85**	**616,70**
Total Costs in million USD	**4871,11**	**4017,95**
CAPEX in million USD	**2675,54**	**1945,65**
OPEX in million USD	**2195,57**	**2072,30**

Table 5.11 The total costs of the electricity transport by means of hydrogen

Description	Fuel Cells	Generator Sets
Cost per MWh of Power Plants	**30.00 USD/MWh**	**30.00 USD/MWh**
Cost per MWh for Energy Transport	**165.25 USD/MWh**	**184.73 USD/MWh**
Cost per MWh of Delivered Energy	**195.25 USD/MWh**	**214.73 USD/MWh**

Table 5.12 The electricity costs of the electricity transport by means of hydrogen

Description	Fuel Cells	Generator Sets
Production	**54265660 MWh**	**54265660 MWh**
Terminal Operation at site A	**356291 MWh**	**356291 MWh**
Sea Transport	**2886026 MWh**	**2886026 MWh**
Terminal Operation at site B	**356291 MWh**	**356291 MWh**
Total	**57864268 MWh**	**57864268 MWh**

Table 5.13 The energy consumption of the electricity transport by means of hydrogen

Description	Fuel Cells	Generator Sets
Energy Consumption	**57864268 MWh**	**57864268 MWh**
Delivered Energy	**24948623 MWh**	**18711467 MWh**
Energy Efficiency	**43.12%**	**32.34%**
Energy Losses	**56.88%**	**67.66%**

Table 5.14 The energy efficiency of electricity transport by means of hydrogen

The table 5.12 demonstrates that the costs per MWh of delivered energy are respectively 6.51 times and 7.16 times more expensive than the cost per MWh of power plants. Thus the bulk electricity transport with the assistance of generator sets is more expensive than the bulk electricity transport with the assistance of fuel cells, despite the fuel cells are more expensive than the generator sets. Furthermore it is worth noting that bulk electricity transport by means of hydrogen is not only bulk electricity transport, but it is also water transport.

5.3 Ammonia

Ammonia is a colourless, highly irritating, toxic gas with a pungent odour. Ammonia gas is also known under the name anhydrous ammonia. Ammonia is a molecule, which is composed of one nitrogen atom and three hydrogen atoms. Hydrogen constitutes 17.65% of the mass of ammonia [39]. The nitrogen constitutes approximately 78% of the atmosphere air and hydrogen is bound in water and hydrocarbons. The ammonia does not occur on Earth in high concentrations, but it is found in small concentrations in the atmosphere. Ammonia is not a greenhouse gas. Ammonia has the following distinctive characteristics:

- Ammonia gas is lighter than air
- Ammonia dissolves easily in water. Ammonia dissolved in water is referred as aqueous ammonia or as ammonium hydroxide
- Ammonia is low flammable and it has a high ignition energy
- Ammonia burns with a yellow flame and it has no harmful soot
- Ammonia is corrosive and it corrodes copper- and zinc-containing alloys
- Ammonia is liquefied under mild pressure and mild cold temperature
- Ammonia is a weak base
- Ammonia is toxic

The ammonia in low concentrations irritates eyes and skin and it damages the respiratory tract. The inhalation in large concentrations can cause severe lung damage or death.
In addition ammonia causes burns on skin. The odour of ammonia is detectable at the concentration of 0.5 ppm [139]. Ammonia has the short-term exposure limit (STEL) of 35 ppm and the Immediately Dangerous to Life and Health (IDLH) concentrations of ammonia is 300 ppm.[110].

Chemical formula	NH_3
Molecular weight	17.03
Appearance	Colourless gas
Odour	distinctive very pungent
Chemical composition (%)	
Nitrogen	25
Hydrogen	75
Melting point	-77.7 °C
Boiling point	-33.4 °C
Density of gas at 20 °C	0.77 kg/m^3
Density of liquid at 20 °C	680 kg/m^3
Vapor pressure at 20 °C	11.9 bar
Energy content	6.24 kWh/kg
Autoignition temperature	651 °C
Minimum ignition energy	680 MJ
Flammability limits in air	15%-28%

Table 5.15 The properties of anhydrous ammonia [39][110][139][148]

5.3.1 Ammonia Production

Ammonia is one of the most common produced chemical in the world. Ammonia was first synthesized by Joseph Priestley in 1774 and the molecular composition is established by Claude-Louis Berthollet in 1785. The ammonia synthesis from nitrogen and hydrogen or Haber-Bosch process is developed by Fritz Haber in 1909. Carl Bosch scaled the process up to an industrial process. Today ammonia is used in the production of explosives, plastics and fertilizers. The ammonia could be produced from the following different feedstocks:

- Coal
- Water
- Oil
- Natural Gas
- Biomass
- Human and Animal Waste

Presently most ammonia is produced from natural gas, because natural gas is a cheap feedstock. The hydrogen for the Haber-Bosch process is produced with steam reforming of natural gas.
After that ammonia is synthesized from hydrogen and nitrogen with the Haber-Bosch process. The mature technologies for manufacturing ammonia are mainly licensed by the companies Haldor Topsoe, Uhde, ICI, Brown & Root and M.W. Kellogg. Over time the ammonia plants have become more energy efficient. Besides that the ammonia plants have become large due to the economy of scale.

Figure 5.4 Ammonia Plant [73]

The main drawbacks of natural gas as feedstock are that natural gas produces carbon dioxide emissions and natural gas is not everywhere available.

Therefore the most appropriate feedstock for the bulk electricity sea transport is water, because the substance water is everywhere available on Earth. The production process of ammonia from water consists of electrolysis and Haber-Bosch synthesis. Another production process of ammonia from water is solid state ammonia synthesis [68]. This production process is still under development. The ammonia production from water with by means of electrolysis and Haber-Bosch synthesis consists of the following three important processes:

- Separating nitrogen from air
- Electrolysis of water
- Ammonia synthesis

The process scheme of the ammonia plant is illustrated in figure 5.5. The most important reactions for the ammonia production take place in the electrolyzer and ammonia synthesis loop. During electrolysis water is split into hydrogen gas and oxygen gas using direct current electricity. In the electrolyzer the following reaction takes place [6]:

$2\ H_2O\ (l) + \text{electricity} \rightarrow 2\ H_2\ (g) + O_2\ (g)$ $\qquad \Delta H = 572$ kJ or 286 kJ/mol

The ammonia plant consists of 705 atmospheric bipolar alkaline electrolyzers Norsk Atmospheric Type No 5040 (4000 Amp DC). The production capacity of Norsk Atmospheric Type No 5040 is 9048 Nm^3 hydrogen per day or 756.4 kg hydrogen per day [40][112]. The other characteristics of the electrolyzer are described in Appendix L Hydrogen Production Plant.

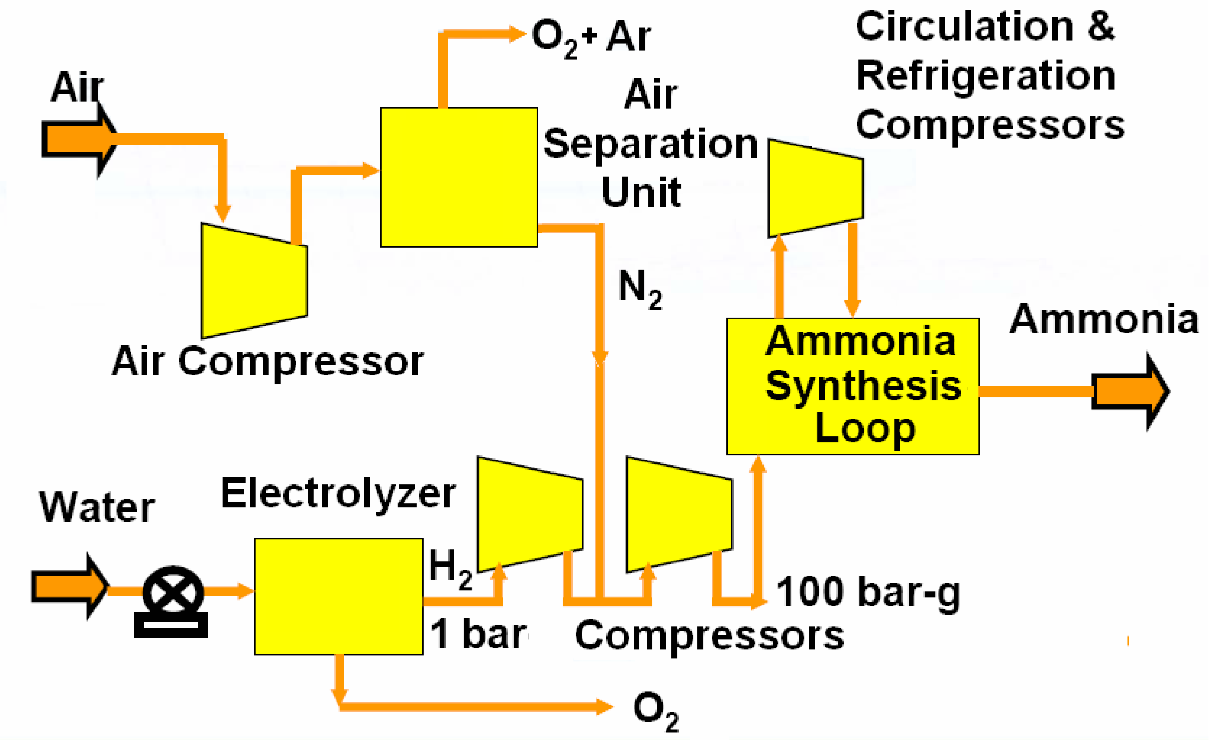

Figure 5.5 The process scheme for producing ammonia from water [73]

In the ammonia synthesis loop takes place the Haber-Bosch process. The exothermic reaction in the Haber-Bosch process is carried out over iron catalysts at pressures ranging from 90 bar to 175 bar and at temperatures between 400°C and 500 °C [6][39]:

$3\ H_2\ (g) + N_2\ (g) \rightarrow 2\ NH_3\ (g)$ $\qquad \Delta H = -92.4$ kJ or -46.2 kJ/mol

In the ammonia synthesis loop hydrogen and nitrogen are circulated through the catalyst filled pressure vessel and ammonia is formed and removed by means of refrigeration compressors. The remaining hydrogen and nitrogen are recirculated to form ammonia.
The process scheme shows that the material input of the ammonia plant consists of purified water and air. The purified water is supplied from the municipal water system. The cost of water is 0.5 USD/m^3 [115]. The production of one metric ton ammonia requires 178 kg hydrogen. The 178 kg hydrogen is produced from 1587.2 kg water.
The material output of the ammonia plant consists of oxygen, argon and liquid ammonia. The gases oxygen and argon could be released into the atmosphere or the gases oxygen and argon could be stored in pressure vessels. After that the stored oxygen and argon are sold to the chemical industry. In this case the oxygen and the expensive noble gas argon are released into the atmosphere. The ammonia from water and electricity is produced in a 3000 tpd ammonia plant. The production capacity of the 3000 tpd ammonia plant is 3000 metric ton per day. The 3000 tpd ammonia plant operates 360 days per year. The annual operation and maintenance costs of the ammonia plant are 1.5% of the investment and the cost per MWh of power plants is 30 USD/MWh [132]. The costs and the energy consumption of the 3000 tpd ammonia production plant are calculated in Appendix N Cost Calculations. The resulting costs of the 3000 tpd ammonia production plant during 30 years are presented in table 5.16.

Description	Costs
Capital Expenditures in million USD	**2884.34**
Operating Expenditures in million USD	**8887.32**
Total Costs in million USD	**11771.66**

Table 5.16 The costs of ammonia production plant

The ammonia price from the ammonia plant is 363.32 USD/ton.
In addition the energy consumption for producing one metric ton ammonia is 8330 kWh and the energy consumption of ammonia plant during 30 years is 269892 GWh. Furthermore it should be noted that in certain circumstances the power plant and the ammonia production plant could be integrated into one plant such as nuclear powered ammonia plant or geothermal powered ammonia plant [150]. The ammonia terminal at site A is a chemical port terminal with 1 3000 tpd ammonia plants and 1 liquid ammonia storage tank. The liquid ammonia from the ammonia plant is transported to the liquid ammonia storage tank by means of 184 m^3/h electric pump and ammonia pipeline. The energy consumption of the ammonia pump is 0.603 kWh/ton. The acquisition cost of the 184 m^3/h terminal pump is 64400 USD [37].
The capacity of the cone roof liquid ammonia storage tank is 88350 m^3, so the ammonia storage tank could store 60000 ton liquid ammonia at atmospheric pressure. The diameter of the ammonia storage tank is 72 m. The height of the ammonia storage tank is 22 m.
The footprint of the ammonia storage tank is 5476 m^2. The cost of ammonia storage tank including refrigeration system is 25 million USD [71]. The boil-off of ammonia in the liquid ammonia storage tank is less than 0.04%, so the boil-off of ammonia is neglected [149].
The liquid ammonia in the storage tank is transported to the ammonia/LPG carrier within 24 hours by means of a 3125 m^3/h electric terminal pump, ammonia pipeline and vapour return. The energy consumption of the ammonia pump is likewise 0.603 kWh/ton. The acquisition cost of the 3125 m^3/h terminal pump is 1093750 USD [37]. Besides the port dues for site A and site B are neglected. The costs of the terminal at site A are calculated in Appendix N Cost Calculations. The energy consumption of ammonia pumps is 39074 MWh during 30 years. The resulting costs of the terminal at site A during 30 years are presented in table 5.17.

Description	Costs
Capital Expenditures in million USD	**2966.42**
Operating Expenditures in million USD	**8888.49**
Total Costs in million USD	**11854.91**

Table 5.17 The costs of terminal at site A

5.3.2 Ammonia Transport


Figure 5.6 The LPG/gas tanker [118]

The sea transport of ammonia is performed with a LPG/gas tanker. The LPG/gas tanker fleet is divided into pressurized liquefied gas carrier, pressurized and refrigerated liquefied gas carrier and refrigerated gas carrier. The gas/LPG tanker is composed of several cylindrical horizontal or bi-lobe tanks. The tanks are constructed from stainless steel. The stainless is used to prevent corrosion. The cylindrical horizontal or bi-lobe tanks are placed in the hull of the tanker. The design of tanks allows a pressure ranging from 1 bar to 6 bar or higher. Each tank in the gas tanker is equipped with a cargo pump for unloading the cargo. The LPG/gas tanker is capable to carry a large variety of chemical gases such as LPG, ethane, chlorine, etc. The LPG tanker is suitable to carry gas with the densities from 0.60 ton/m^3 to 0.97 ton/m^3 [22][50]. The liquefied ammonia is carried in a 41800 m^3 refrigerated LPG tanker. The toxicity of ammonia poses no large safety risk in relation with sea transport. The deadweight of 41800 m^3 ammonia/LPG tanker is 28424 ton with the cargo density of 0.68 ton/m^3. The average newbuilding price for the 41800 m^3 ammonia/LPG tanker is 65.516 million USD. The operating costs of the 41800 m^3 ammonia/LPG tanker according figure 4.23 is estimated 6835 USD/day. The 41800 m^3 ammonia/LPG tanker transports the liquefied ammonia over the distance of 1000 nautical miles. During one roundtrip the liquefied ammonia is loaded into the LPG tanker at the terminal of site A. After the sea transport the liquefied ammonia is discharged at the terminal of site B. The loading and discharging of the LPG tanker is accomplished within 24 hours. The evidence of loading and discharging within 24 hours is presented in the figures in Appendix C Unloading Times.
The LPG tanker sails 353 days per year. The LPG tanker runs on heavy fuel oil and diesel fuel oil, which have the energy price of 60 USD/MWh. The ship costs and the characteristics of the 41800 m^3 ammonia/LPG tanker are calculated in Appendix N Cost Calculations.
The energy consumption of the ammonia/LPG tanker is 884708 MWh during 30 years.
The energy consumption of the tanker is based on the brake power of the main engine.
The resulting costs of the 41800 m^3 ammonia/LPG tanker during 30 years are presented in table 5.18.

Description	Costs
Capital Expenditures in million USD	**174.59**
Operating Expenditures in million USD	**127.92**
Total Costs in million USD	**302.51**

Table 5.18 The costs of 41800 m^3 ammonia/LPG tanker

5.3.3 Power Generation with Ammonia

The anhydrous ammonia is an environmental friendly fuel. The main drawback of ammonia is the low flame speed, so consequently pure ammonia is not applicable for high speed internal combustion engines. Still pure anhydrous ammonia is applicable in other applications such as low-speed internal combustion engines and fuel cells. The efficiency of low-speed internal combustion engine is 45% [70]. Furthermore the efficiency of fuel cell is 60% [62].
During the use in internal combustion engines ammonia produces no soot and it produces no carbon dioxide. However ammonia can be blended with other fuels, so that ammonia is likewise suitable as fuel in high speed internal combustion engines. In addition ammonia could be decomposed (cracked) into hydrogen and nitrogen. The decomposition (cracking) of ammonia takes place at high temperatures and the decomposition requires energy [39].
The hydrogen from cracking ammonia could be used in high speed internal combustion engines. During power generation the following reaction takes place [6]:

$$\mathbf{4\,NH_3\,(g) + 3\,O_2\,(g) \rightarrow 2\,N_2\,(g) + 6\,H_2O\,(l) \qquad \Delta H = -1531.2\ kJ\ or\ -382.8\ kJ/mol}$$

In the energy devices anhydrous ammonia reacts with oxygen to produce energy, water and nitrogen. The fuel ammonia does not produce harmful emissions, when it reacts with oxygen. The nitrogen could be released into the atmosphere or the nitrogen could be stored in pressure vessels. After that the nitrogen in pressure vessels is sold to the chemical industry.
In this case the nitrogen is released into the atmosphere. The water could be used for agriculture consumption or the water could be transported back to the ammonia terminal at site A. In this case the water is sold for agriculture consumption, because the water could contain very small concentrations ammonia. The water price for agriculture consumption is 0.01 USD/m^3 [115]. The chemical energy of ammonia is converted into heat and mechanical energy or heat and electrical energy. On his turn mechanical energy is converted to electrical energy. The released chemical energy during burning of one kg ammonia is 6.243 kWh or 22.47 MJ. The power generation with ammonia is accomplished with direct ammonia fuel cells or low-speed generator sets. The power generation with both energy devices will be now examined. The power generation with direct ammonia fuel cells is first examined. The fuel anhydrous ammonia is only suitable for solid oxide fuel cells (SOFC) and protonic ceramic fuel cells (PCFC). The two fuel cells are high temperature fuel cells.
The SOFC is a mature technology, but PCFC is under development. Therefore SOFC is selected for the power generation. There are two methods to use ammonia in fuel cells. The first method is that ammonia is directly reacted with oxygen in the fuel cell. The second method is that ammonia is cracked to hydrogen and hydrogen reacts in the fuel cell.
In this case the ammonia is not cracked. The power plant with solid oxide fuel cells consumes 12860.2 ton liquefied ammonia per hour. Thus the size of power plant is 481.718 MW. The power plant is composed of solid oxide fuel cells, electricity converter, transformer station and electrical cables. Furthermore the annual operation and maintenance costs of the power plant such as insurance, salaries, maintenance and repairs are 1.5% of the investment.

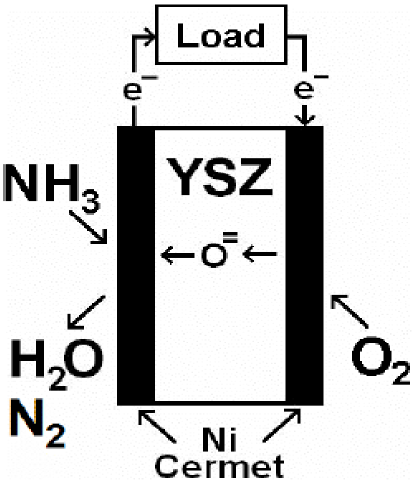

Figure 5.7. Ammonia fuel cell [74]

The energy losses in the power plant with solid oxide fuel cells are 42%. Besides 1 ton liquefied ammonia furbishes 1.5872 ton pure water. The costs of the 481.718 MW power plant with solid oxide fuel cells are calculated in Appendix N Cost Calculations. The 481.718 MW power plant with solid oxide fuel cells delivers 117318456 MWh electricity during 30 years. The resulting costs of the 481.718 MW power plant with solid oxide fuel cells during 30 years are presented in table 5.19.

Description	Costs
Capital Expenditures in million USD	**4020.40**
Operating Expenditures in million USD	**678.40**
Total Costs in million USD	**4698.80**

Table 5.19 The costs of power plant with fuel cells

The power generation is likewise feasible with generator sets. The generator set consists of a low-speed internal combustion engine and an alternator. The ammonia burns in a low-speed internal combustion engine with little modifications. The internal combustion engine fuelled by ammonia is developed by Hydrogen Engine Center Inc and US Army. The cost of the internal combustion engine with alternator is assumed similar as the cost of natural gas engine with alternator. Therefore the typical cost of generator set is 600 USD/kW [80]. The footprint of generator set is 4.5 m^2/MW [117]. The energy losses in the power plant with generator sets are 56.5%. The power plant is composed of generator sets, transformer station and electrical cables. Furthermore the annual operation and maintenance costs of the power plant are 1.5% of the investment. The costs of the 401.431 MW power plant with generator sets are calculated in Appendix N Cost Calculations. The power plant with generator sets delivers 87988842 MWh electricity during 30 years. The resulting costs of the 401.431 MW power plant with generator sets during 30 years are presented in table 5.20.

Description	Costs
Capital Expenditures in million USD	**652.29**
Operating Expenditures in million USD	**109.64**
Total Costs in million USD	**761.93**

Table 5.20 The costs of power plant with generator sets

The terminal at site B is similar as the terminal at site A, except the ammonia production plant is replaced by a power plant. The terminal at site B is likewise a chemical terminal with 1 power plant and 1 liquid ammonia storage tank. The storage capacity of the terminal is 60000 ton liquid ammonia at atmospheric pressure. The electric pumps and liquid ammonia storage tank are identical as electric pumps and liquid ammonia storage tank deployed in the terminal at site A. Furthermore the cost per MWh for pumps is 60 USD/MWh. The liquid ammonia from the ammonia/LPG carrier is transported to the liquid ammonia storage tank by means of cargo pumps of the ammonia/LPG tanker, ammonia pipeline and vapour return within 24 hours. The liquid ammonia stays in the liquid ammonia storage tank till it goes directly to the power plant by means of 184 m^3/h electric pump and ammonia pipeline. The power plant consumes the liquid anhydrous ammonia. The product of the power plant is energy, nitrogen gas and water. The nitrogen could be released into the atmosphere or the nitrogen could be stored in pressure vessels. In this case the nitrogen is released into the atmosphere. The water for agriculture consumption is transported away with a pipeline. The power plant produces 1714176 m^3 water yearly. The water pumps and water pipeline for the water transport are excluded in the cost calculation. The terminal costs at site B with fuel cells and the terminal costs at site B with generator sets are calculated in Appendix N Cost Calculations.

The resulting costs of the terminal at site B with fuel cells during 30 years are presented in table 5.21. The resulting costs of the terminal at site B with generator sets during 30 years are presented in table 5.22. Furthermore the energy consumption of ammonia pumps is 39074 MWh during 30 years.

Description	Costs
Capital Expenditures in million USD	**4099.57**
Operating Expenditures in million USD	**680.74**
Total Costs in million USD	**4780.31**

Table 5.21 The terminal costs with fuel cells

Description	Costs
Capital Expenditures in million USD	**731.46**
Operating Expenditures in million USD	**111.98**
Total Costs in million USD	**843.44**

Table 5.22 The terminal costs with generator sets

5.3.4 Total Costs

In the previous paragraphs the different parts of the bulk electricity sea transport by means of the synthetic fuel ammonia over the distance of 1000 nautical miles are determined.
The total costs for the bulk electricity transport with the assistance of fuel cells and the bulk electricity transport with the assistance of generator sets are calculated in table 5.23. Moreover the total costs are divided into capital expenditures and operating expenditures. The electricity costs of the electricity transport by means of ammonia are listed in table 5.24. Besides the costs, the energy consumption, energy efficiency and energy losses are important. The energy consumption of the bulk electricity transport by means of ammonia is presented in table 5.25. The energy efficiency and energy losses of the bulk electricity sea transport by means of ammonia are presented in table 5.26. The energy efficiency is the ratio between the delivered electrical energy and the energy input. The energy input consists of the total energy consumption from table 5.25.

Description	Fuel Cells	Generator Sets
Terminal Costs Site A in USD	**11854.91**	**11854.91**
Total Ship Costs in USD	**302.51**	**302.51**
Terminal Costs Site B in USD	**4780.31**	**843.44**
Total Costs in USD	**16937.73**	**13000.86**
CAPEX in USD	**7240.58**	**3872.47**
OPEX in USD	**9697.15**	**9128.39**

Table 5.23 The total costs of electricity transport by means of ammonia

Description	Fuel Cells	Generator Sets
Cost per MWh of Power Plants	**30.00 USD/MWh**	**30.00 USD/MWh**
Cost per MWh for Energy Transport	**114.37 USD/MWh**	**117.76 USD/MWh**
Cost per MWh of Delivered Energy	**144.37 USD/MWh**	**147.76 USD/MWh**

Table 5.24 The electricity costs of electricity transport by means of ammonia

Description	Fuel Cells	Generator Sets
Production	**269892000 MWh**	**269892000 MWh**
Terminal Operation at site A	**39074 MWh**	**39074 MWh**
Sea Transport	**884708 MWh**	**884708 MWh**
Terminal Operation at site B	**39074 MWh**	**39074 MWh**
Total	**270854857 MWh**	**270854857 MWh**

Table 5.25 The energy consumption of electricity transport by means of ammonia

Description	Fuel Cells	Generator Sets
Energy Consumption	**270854857 MWh**	**270854857 MWh**
Delivered Energy	**117318456 MWh**	**87988842 MWh**
Energy Efficiency	**43.31%**	**32.49%**
Energy Losses	**56.69%**	**67.51%**

Table 5.26 The energy efficiency of electricity transport by means of ammonia

The table 5.24 indicates that the costs per MWh of delivered energy are respectively 4.81 times and 4.93 times more expensive than the cost per MWh of power plants.
Thus the bulk electricity transport with the assistance of generator sets is more expensive than the bulk electricity transport with the assistance of fuel cells, despite fuel cells are more expensive than generator sets. In addition it is worth noting that bulk electricity transport by means of ammonia is not only bulk electricity transport, but it is likewise water transport for agriculture consumption.

5.4 Final Synthetic Fuel Selection

In the previous paragraphs the bulk electricity sea transport by means of the synthetic fuels hydrogen and ammonia are investigated. The costs and the energy use of the bulk electricity sea transport by means of both synthetic fuels are determined. Among the two synthetic fuels the most energy efficient and the most cost efficient synthetic fuel for bulk electricity sea transport should be selected. In addition the synthetic fuel should be a relative safe fuel.
The most energy efficient synthetic fuel is obtained by comparing the energy efficiency of bulk electricity sea transport of both synthetic fuels. Moreover the most cost efficient synthetic fuel is obtained by comparing the electricity costs of bulk electricity sea transport of both synthetic fuels. The bulk electricity transport with the assistance of fuel cells of both synthetic fuels is first compared. It should be noted that the fuel cells have an efficiency of 60%. The energy efficiency of bulk electricity transport with the assistance of fuel cells of both synthetic fuels is presented in table 5.27. The electricity costs of bulk electricity transport with the assistance of fuel cells of both synthetic fuels are listed in table 5.28.

Description	Hydrogen	Ammonia
Energy Efficiency	**43.12%**	**43.31%**
Energy Losses	**56.88%**	**56.69%**

Table 5.27 The energy efficiency of electricity transport with the assistance of fuel cells

Description	Hydrogen	Ammonia
Cost per MWh of Power Plants	**30.00 USD/MWh**	**30.00 USD/MWh**
Cost per MWh for Energy Transport	**165.25 USD/MWh**	**114.37 USD/MWh**
Cost per MWh of Delivered Energy	**195.25 USD/MWh**	**144.37 USD/MWh**

Table 5.28 The electricity costs of electricity transport with the assistance of fuel cells

The bulk electricity transport with the assistance of generator sets of both synthetic fuels is now compared. It should be noted that the generator sets have an efficiency of 43.5%.
The energy efficiency of bulk electricity transport with the assistance of generator sets of both synthetic fuels is listed in table 5.29. The electricity costs of bulk electricity transport with the assistance of generator sets of both synthetic fuels are presented in table 5.30.

Description	Hydrogen	Ammonia
Energy Efficiency	**32.34%**	**32.49%**
Energy Losses	**67.66%**	**67.51%**

Table 5.29 The energy efficiency of electricity transport with the assistance of generator sets

Description	Hydrogen	Ammonia
Cost per MWh of Power Plants	**30.00 USD/MWh**	**30.00 USD/MWh**
Cost per MWh for Energy Transport	**184.73 USD/MWh**	**117.76 USD/MWh**
Cost per MWh of Delivered Energy	**214.73 USD/MWh**	**147.76 USD/MWh**

Table 5.30 The electricity costs of electricity transport with the assistance of generator sets

The tables demonstrate that the power generation method has influence on the efficiency and the electricity costs. Furthermore the table 5.27 and table 5.29 illustrate that the synthetic fuel ammonia is the most energy efficient synthetic fuel of the two synthetic fuels. However the difference in energy efficiency is small. The energy transport with synthetic fuel hydrogen is less energy efficient, because the compressing of hydrogen requires a lot of energy and the volumetric energy density of hydrogen is lower than the volumetric energy density of ammonia. Nevertheless the hydrogen has a higher gravimetric energy density than ammonia. In this case the volumetric energy density is more crucial, because the synthetic fuels are transported in volume limited ships. In addition the synthetic fuel ammonia is the most cost efficient synthetic fuel. The difference between the synthetic fuels is significant according to table 5.28 and table 5.30. The bulk electricity sea transport by means of hydrogen is more expensive due to the hydrogen storage. The hydrogen storage is expensive and difficult due to the very low density of hydrogen and hydrogen embrittlement. The hydrogen embrittlement is related to the other important issue safety. Both synthetic fuels are dangerous chemicals.
The synthetic fuel hydrogen is characterized as difficult detectable extreme flammable explosive fuel. Hydrogen is mainly dangerous, because it is very difficult to detect.
The hazards with hydrogen are fires and explosions. The human exposure to hydrogen causes no adverse effects on the health. On the contrary the synthetic fuel ammonia is characterized as detectable toxic flammable fuel. The hazards with anhydrous ammonia are fires, health loss and poisoning. Ammonia is mainly dangerous, because ammonia is poisonous.
The human exposure to ammonia causes adverse effects on the health. The benefit of ammonia is that the ammonia is easily detected. Ammonia is detected at very low concentrations. Therefore the release of ammonia in the environment has no larger consequences than the release of hydrogen in the environment. Summarized the synthetic fuels ammonia and hydrogen are dangerous chemicals, but hydrogen is not safer than ammonia. The other benefit of bulk electricity sea transport by means of ammonia is that during ammonia production the chemicals oxygen and argon could be recovered for the chemical industry at site A and during power generation the chemicals nitrogen and water could be recovered for the chemical industry and agriculture at site B. The recovery of the chemicals makes the bulk electricity sea transport more profitable. On the contrary during the bulk electricity sea transport by means of hydrogen the chemical oxygen could be recovered for the chemical industry at site A and pure water could be recovered at site B.
Thus the bulk electricity sea transport by means of ammonia furbishes more chemicals.

The other benefit of the bulk electricity sea transport by means of ammonia is that the ammonia supply chain is already in place. The sea transport of ammonia is common practice. The ammonia production from water and the power generation with ammonia is not yet common practice, but the technology for ammonia production from hydrogen exist already. The bulk electricity sea transport by means of ammonia could be deployed immediately as energy supply chain. In summary the ammonia is most energy efficient and cost efficient synthetic fuel of both synthetic fuels for the purpose of bulk electricity sea transport. Hence follows that the bulk electricity sea transport by means of ammonia will be further investigated in the next paragraph.

5.5 Cost Analysis Synthetic Fuel

The influence of the parameters distance and cost per MWh of power plants on the cost per MWh of delivered energy will be more profound examined for two propulsion plant configurations of the ammonia/LPG carrier. The two propulsion plant configurations of the ammonia/LPG carrier are presented below:

- Diesel Propulsion Plant
- Ammonia Propulsion Plant

The diesel propulsion plant uses heavy fuel oil and diesel fuel oil in diesel engines to propel the ammonia/LPG carrier. The utilization of fossil fuels causes harmful emissions.
As stated before, the energy price of diesel fuel oil and heavy fuel price is 60 USD/MWh. The ammonia propulsion plant uses anhydrous ammonia from the cargo tanks in internal combustion engines to propel the ammonia/LPG carrier. The utilization of ammonia fuel causes no harmful emissions. The efficiency of the internal combustion engines fuelled by ammonia is 45%. Furthermore the assumption is made that the cost of the two different propulsion plant configurations is the same. Besides that among the two power generation methods the most cost efficient power generation method should be chosen. The two power generation methods are power generation with fuel cells and power generation with generator sets. The cost efficient power generation method is selected through investigating the influence of the parameter cost per MWh of power plants on the cost per MWh of delivered energy for the distances 500 nautical miles and 1000 nautical miles. During the investigation the size of ammonia production and the size of the power generation with ammonia fuel will not change. The sea transport of ammonia is accomplished with 75000 m^3 ammonia/LPG tankers. The 41800 m^3 ammonia/LPG tanker is replaced by 75000 m^3 ammonia/LPG tanker due to the advantages of the economy of scale for long distances. The ship costs and the characteristics of the 75000 m^3 ammonia/LPG tanker are listed in Appendix N Cost Calculations. The number of 75000 m^3 ammonia/LPG tankers for the bulk electricity sea transport depends on the distance between site A and site B. The influence of the cost per MWh of power plants in USD/MWh on the cost per MWh of delivered energy in USD/MWh for the distance 500 nautical miles is illustrated in figure 5.8. The influence of the cost per MWh of power plants in USD/MWh on the cost per MWh of delivered energy in USD/MWh for the distance 1000 nautical miles is presented in figure 5.9.

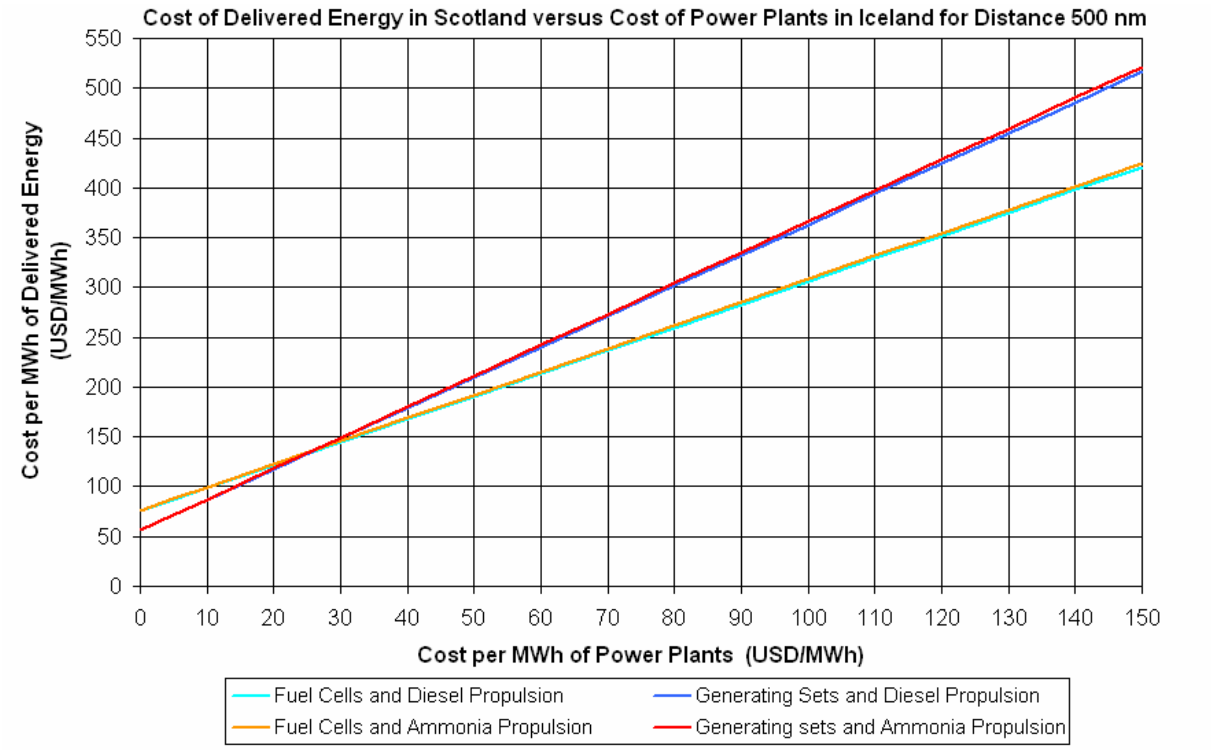

Figure 5.8 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance 500 nautical miles

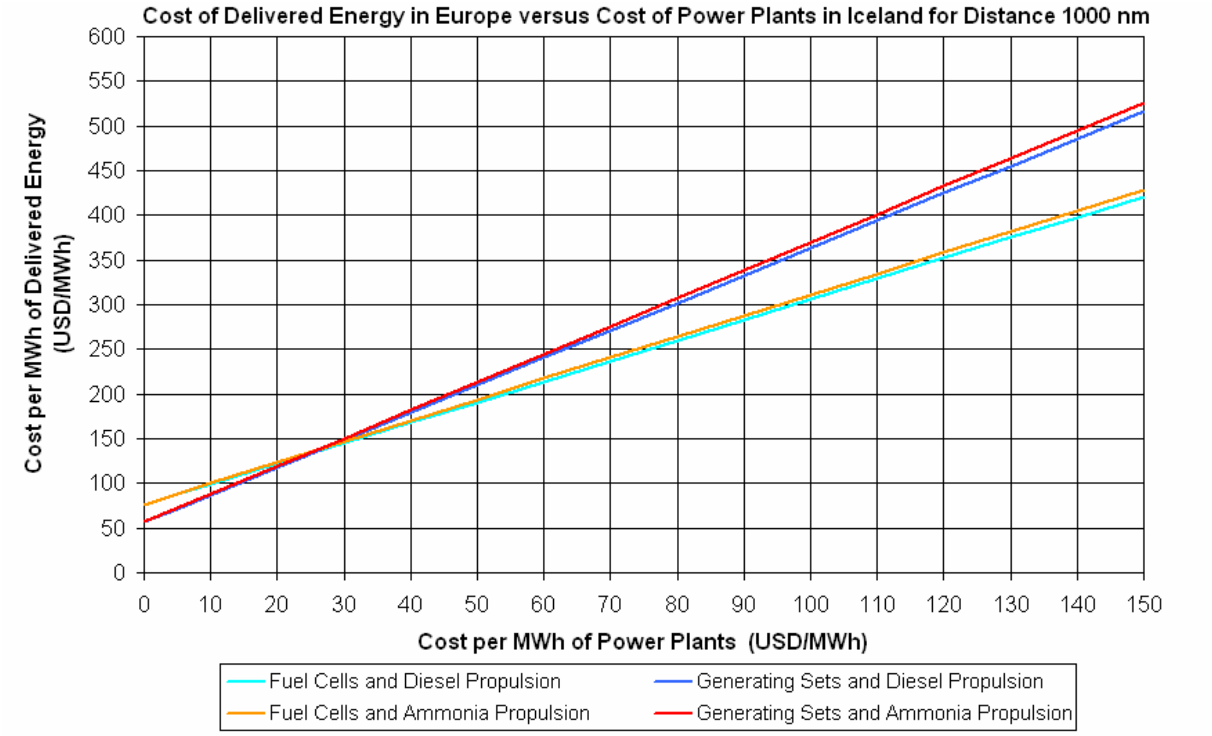

Figure 5.9 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance 1000 nautical miles

The figure 5.8 and figure 5.9 demonstrate that the power generation with generator sets is cheaper than the power generation with fuel cells, when the cost per MWh of power plants is lower than 25 USD/MWh. The power generation with fuel cells is cheaper than the power generation with generator sets, when the cost per MWh of power plants is higher than 25 USD/MWh. The high efficiency of fuel cells has a large influence on the cost per MWh of delivered energy, when the cost per MWh of power plants is high. In this case the cost per MWh of power plants is 30 USD/MWh, so the power generation with fuel cells is the cost efficient power generation method. Thus the bulk electricity sea transport by means of ammonia will only be done with solid oxide fuel cells. The next parameter that will be investigated is the distance. The distance is varied from 0 nautical miles till 6000 nautical miles. The cost per MWh of delivered energy in USD/MWh and the cost per MWh for energy transport in USD/MWh versus the distance in nautical miles are illustrated in figure 5.10. During the distance variation the cost per MWh of power plants is 30 USD/MWh.
The capital expenditures in million USD versus the distance are presented in figure 5.11. The delivered energy versus the distance is illustrated in figure 5.12. The energy losses versus the distance are shown in figure 5.13. The energy flows of bulk electricity sea transport with the ammonia/LPG carrier with diesel propulsion plant are shown in figure 5.14.
The energy flows of bulk electricity sea transport with the ammonia/LPG carrier with ammonia propulsion plant are illustrated in figure 5.15. The two Sankey diagrams show that the largest energy losses are the energy losses associated with the conversion of electricity into ammonia and ammonia into electricity. These energy losses are quit high. The energy losses associated with sea transport is very small. Nevertheless the energy losses due to sea transport increase, when the distance increases. Still the effect of the distance on the energy losses is very small according to figure 5.13, so a small part of cargo ammonia is used to propel the ammonia/LPG carrier. Therefore the bulk electricity sea transport by means of ammonia is attractive for electricity transport over long distances such as 6000 nautical miles or more.

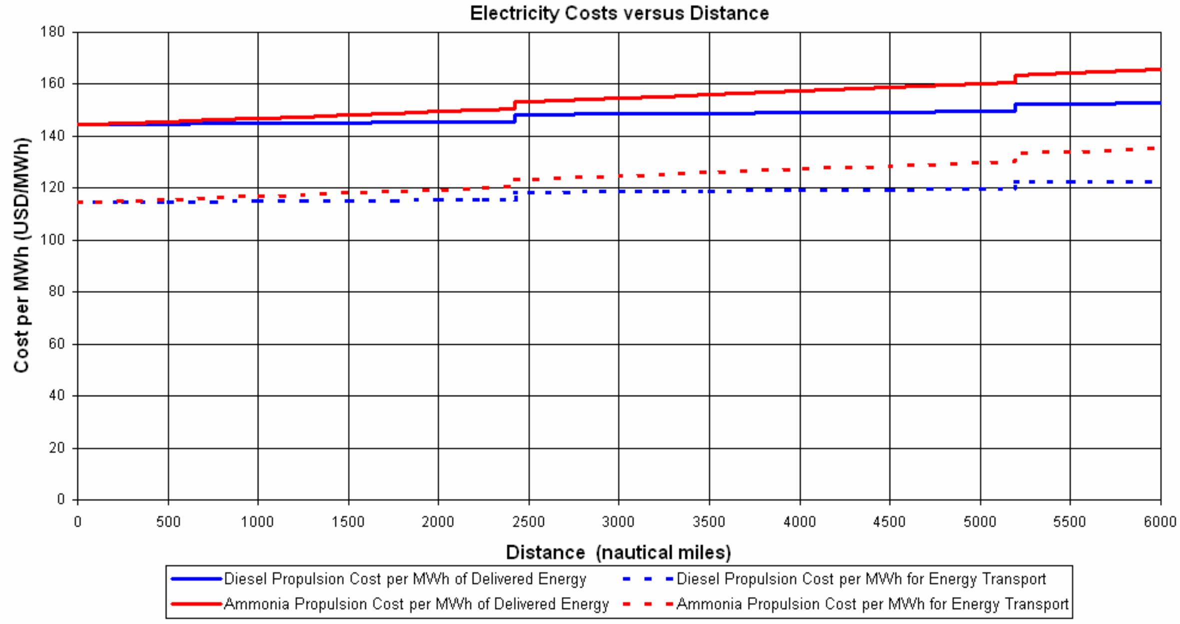

Figure 5.10 The cost per MWh of delivered energy and the cost per MWh for energy transport in USD/MWh versus the distance in nautical miles

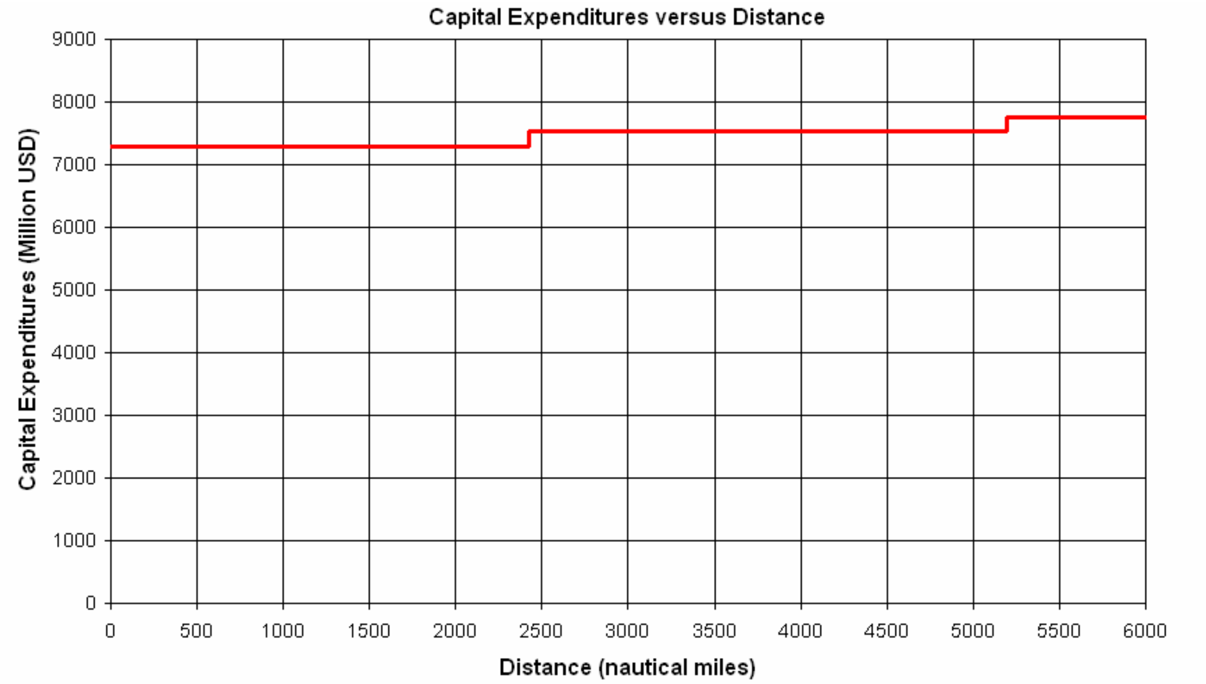

Figure 5.11 The capital expenditures in million USD versus the distance in nautical miles

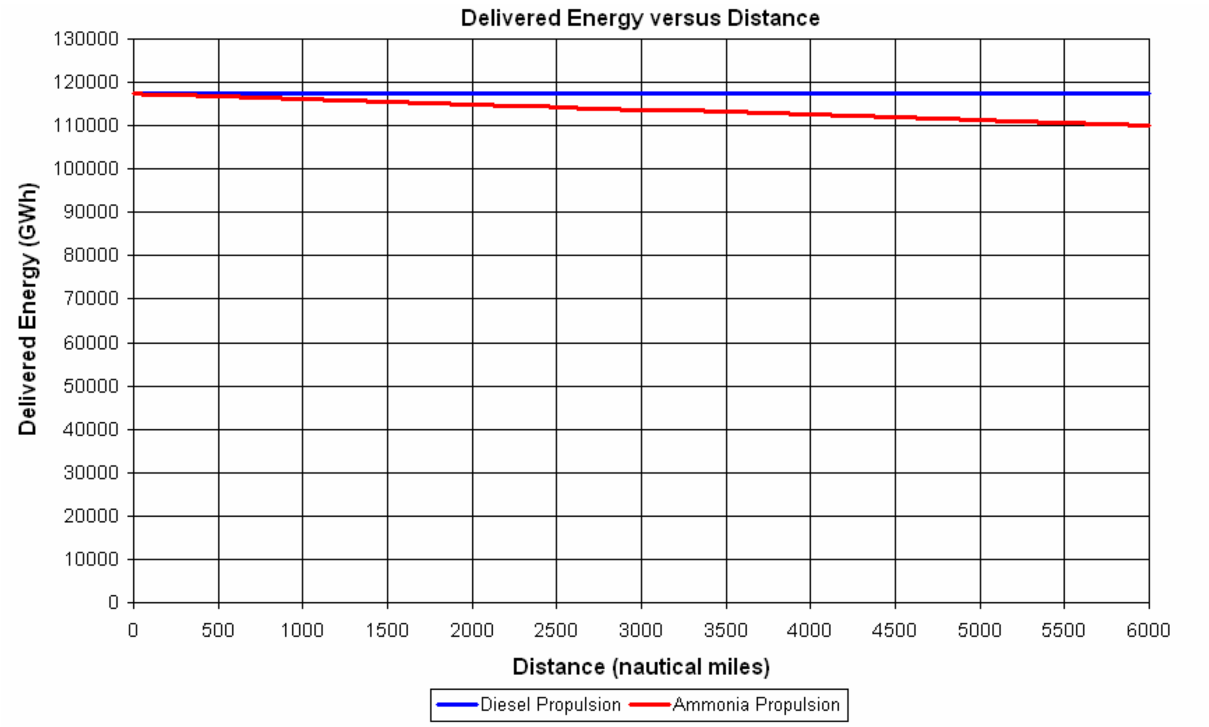

Figure 5.12 The delivered energy in GWh during 30 years versus the distance in nautical miles

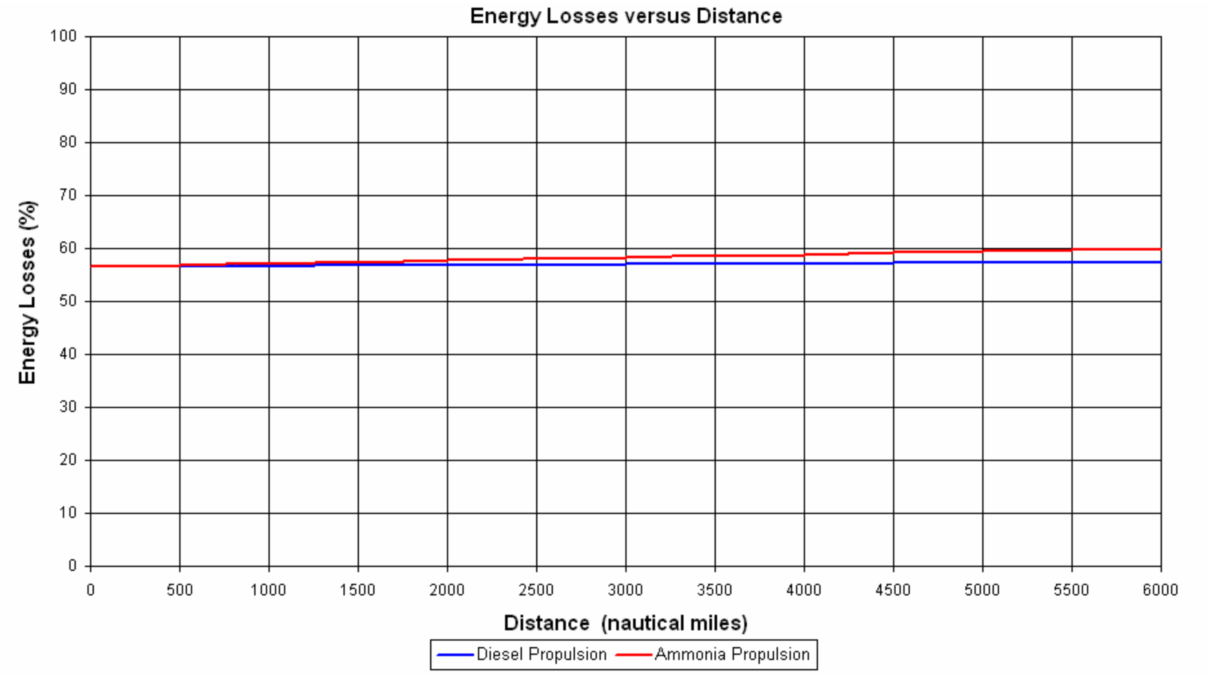

Figure 5.13 The energy losses in % versus the distance in nautical miles

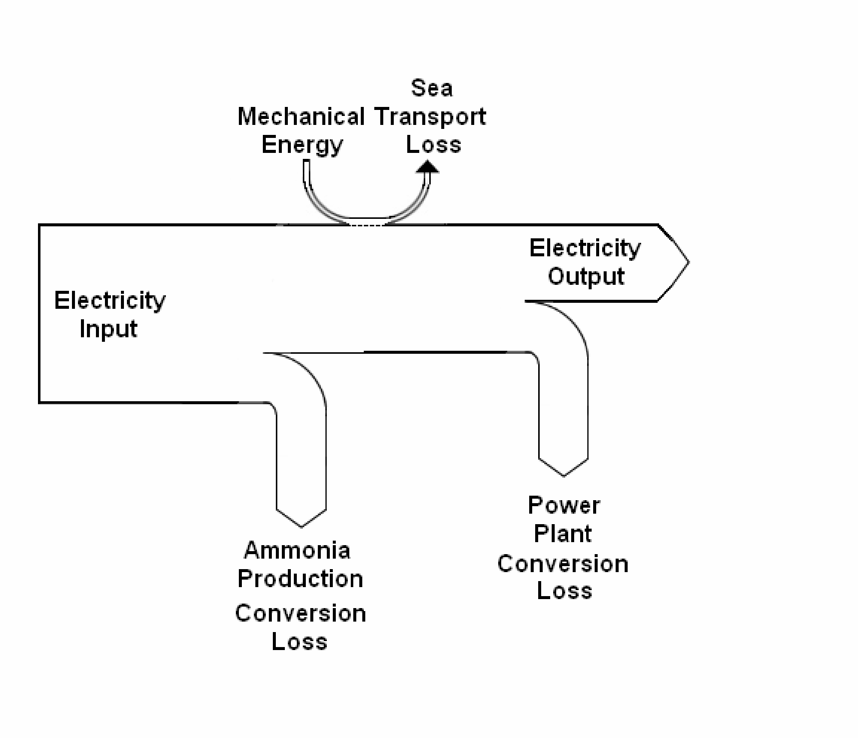

Figure 5.14 The energy flows of energy transport with synthetic fuel ammonia with diesel propulsion

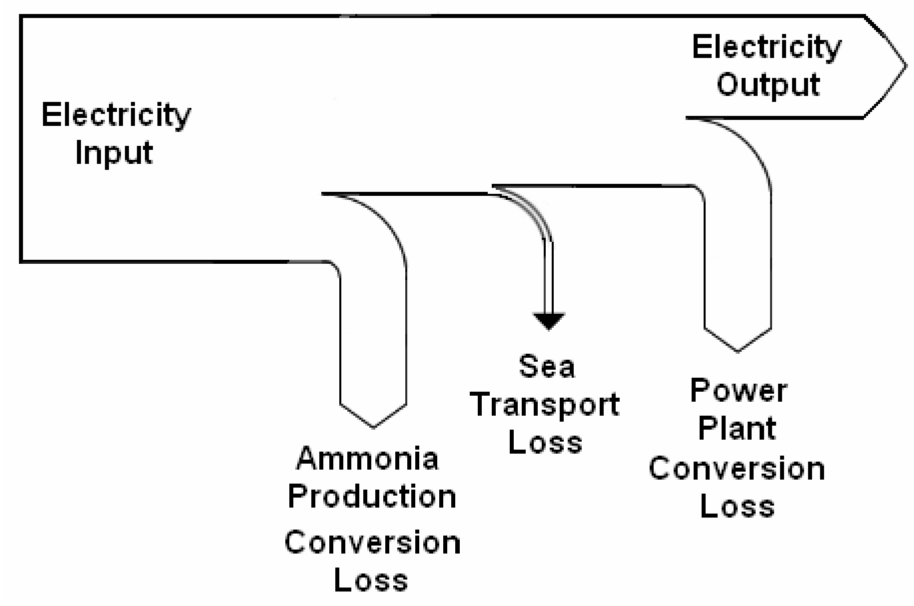

Figure 5.15 The energy flows of energy transport with synthetic fuel ammonia with ammonia propulsion

The jumps in figure 5.10 and figure 5.11 are caused by adding 75000 m^3 ammonia/LPG carriers. The bulk electricity sea transport over the distance of 6000 nautical miles consists of three 75000 m^3 ammonia/LPG carriers. Moreover the capital expenditures of the bulk electricity sea transport in figure 5.11 are the same for both propulsion plants. Furthermore the ammonia/LPG carriers with ammonia propulsion is currently less attractive than ammonia/LPG carriers with diesel propulsion according to figures 5.8 till 5.10, figure 5.12 and figure 5.13 due to less delivered energy and higher energy price for the ammonia/LPG carriers. Nevertheless the difference between the two propulsion plant configurations is not significant.

6 Electricity Transport Concepts Comparison

In this chapter electricity transport concepts are compared and evaluated.

6.1 Electricity Transport Concepts

In the previous chapters the initial three electricity transport concepts for long distant energy transport are elaborated. The three initial electricity transport concepts are explained below:

1. **Submarine Electric Power Transmission** The energy transmission across the sea is accomplished with high voltage electrical cables between power plants and electricity consumers.

2. **Battery Ship** The energy transport across the sea is accomplished by ship, which transports batteries between power plants and electricity consumers. The batteries store the electrical energy.

3. **Synthetic Fuel** The energy transport across the sea is accomplished by ship, which transports synthetic fuel from power plants to the electricity consumers. The electricity is converted into synthetic fuel close by the power plants. Afterwards synthetic fuel is converted into electricity near the electricity consumers

During the elaboration the three electricity transport concepts have evolved into the following five electricity transport concepts. The five electricity transport concepts are presented below:

1. **Submarine Power Cable Link** The submarine power cable link consists of two HVDC converter stations and two submarine power cables

2. **Battery Ship with Diesel Propulsion** The electricity transport concept consists of two small offshore terminals with converter stations and a large battery ship.
   The large battery ship with diesel propulsion plant runs on heavy fuel oil and diesel fuel oil.

3. **Battery Ship with Electric Propulsion** The electricity transport concept consists of two small offshore terminals with converter stations and a large battery ship.
   The large battery ship with electric propulsion plant runs on stored electricity from the batteries.

4. **Ammonia Fuel with Diesel Propulsion** The electricity transport concept consists of ammonia/LPG carrier(s), a power plant and an ammonia production plant.
   The ammonia production plant produces ammonia from water and nitrogen.
   The ammonia/LPG carrier with diesel propulsion plant runs on heavy fuel oil and diesel fuel oil.

5. **Ammonia Fuel with Ammonia Propulsion** The electricity transport concept consists of ammonia/LPG carrier(s), a power plant and an ammonia production plant.
   The ammonia production plant produces ammonia from water and nitrogen.
   The ammonia/LPG carrier runs on anhydrous ammonia.

These five electricity transport concepts were already explained in the previous chapters.

In addition the energetic and economical performances of the five electricity transport concepts are already determined in the previous chapters. The important characteristics of the five electricity transport concepts for bulk electricity sea transport between power plants and electricity consumers are presented and compared in table 6.1.

Characterisitics	Submarine Power Cable Link	Battery Ship with Diesel Propulsion	Battery Ship with Electric Propulsion	Ammonia Fuel with Diesel Propulsion	Ammonia Fuel with Ammonia Propulsion
Continuous Energy Delivery	**Yes**	**No**	**No**	**Yes**	**Yes**
Energy Storage Ability	**No**	**Yes**	**Yes**	**Yes**	**Yes**
Energy Storage on Demand	**No**	**No**	**No**	**Yes**	**Yes**
Energy Delivery on Demand	**No**	**No**	**No**	**Yes**	**Yes**
Both Directional Energy Transport	**Yes**	**No**	**No**	**No**	**No**
Safety Risks	**Low**	**Medium**	**Medium**	**High**	**High**
Pollution	**No**	**Yes**	**No**	**Yes**	**No**
Susceptible to Oil Price	**No**	**Strong**	**No**	**Weak**	**No**
Realization Time (years)	**10**	**2 or 3**	**2 or 3**	**3 or 4**	**3 or 4**

Table 6.1 The characteristics of the five electricity transport concepts

The electricity transport concepts “submarine power cable link”, “ammonia fuel with diesel propulsion” and “ammonia fuel with ammonia propulsion” are good solutions to achieve continuous bulk electricity transport across the sea according to table 6.1. The benefit of electricity transport concept “submarine power cable link” is electricity transport in two directions. The benefit of electricity transport concepts with ammonia fuel is that they are able to facilitate intermittent power plants. Nevertheless the most attractive solution is determined by the crucial parameters distance and cost per MWh of power plants. Therefore the influence of distance on the five electricity transport concepts is investigated in next paragraph.

6.2 Influence of Distance

The influence of distance is already investigated for each electricity transport concept separately. During the investigation the distance is varied from 0 nautical miles till 6000 nautical miles. As stated before the distance of 6000 nautical miles is the distance between the continents America and Europe. The results of investigation from each electricity transport concept are now combined into the following figures. The figures allow the comparison between the five electricity transport concepts. The influence of distance from energetic perspective will be firstly examined. The delivered energy during 30 years in GWh versus the distance in nautical miles is shown in figure 6.1. The energy losses in % versus the distance in nautical miles are illustrated in figure 6.2.

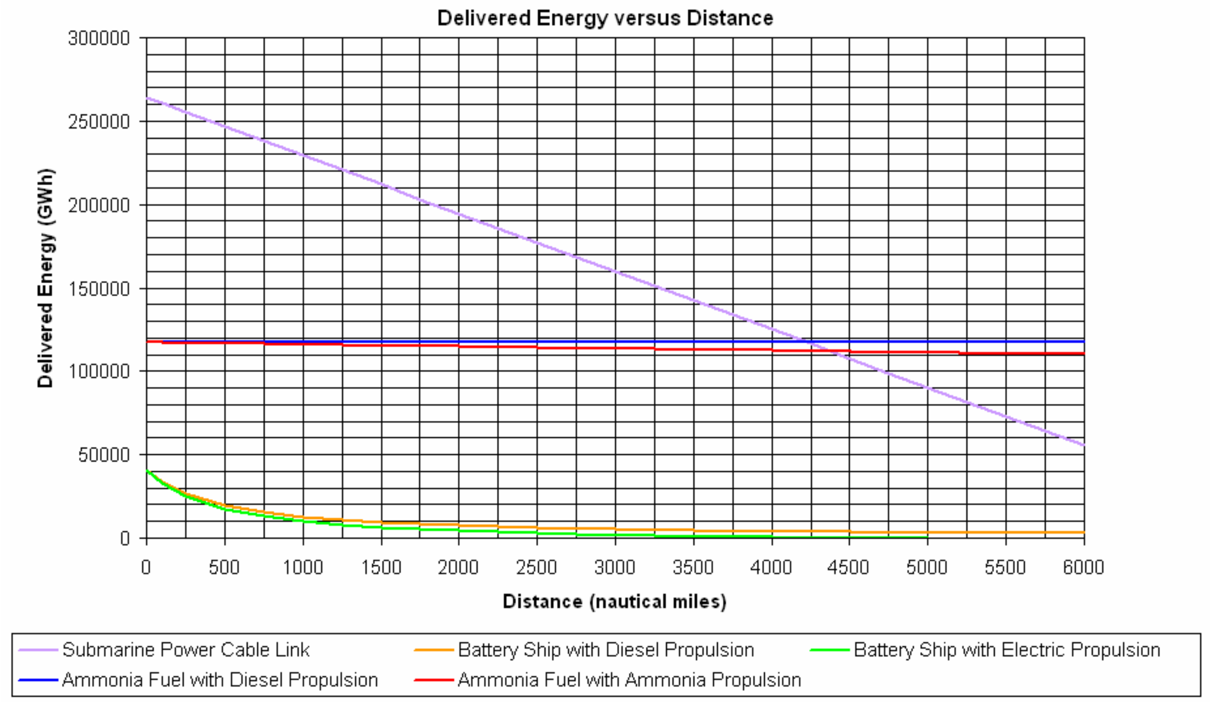

Figure 6.1 The delivered energy during 30 years in GWh versus the distance in nautical miles

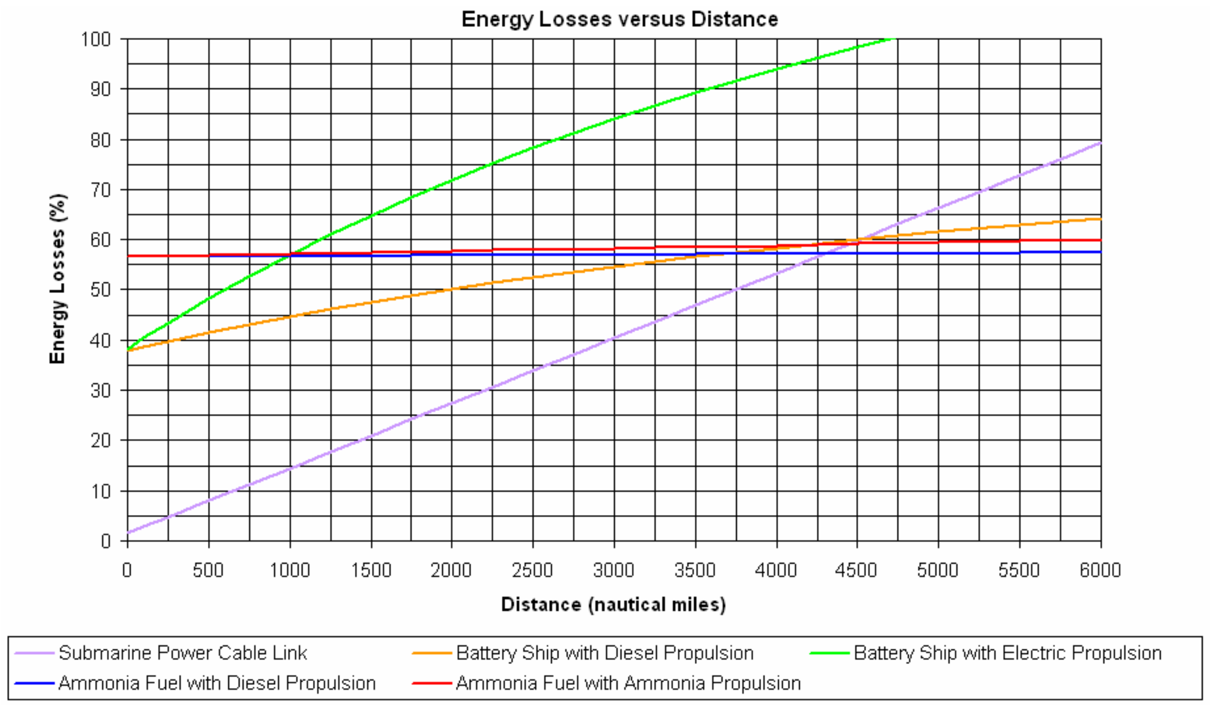

Figure 6.2 The energy losses in % versus the distance in nautical miles

According to figure 6.1 the electricity transport concept “submarine power cable link” has the highest delivered energy till approximately 4250 nautical miles. The delivery energy during 30 years with the electricity transport concept “submarine power cable link” for the distances 500 nautical miles and 1000 nautical miles is respectively 246660 GWh and 229284 GWh.

The annual delivery energy for the distances 500 nautical miles and 1000 nautical miles is respectively 8222 GWh and 7643 GWh. The annual delivered energy is very small in proportion to the annual electricity consumption in the Netherlands. The annual electricity consumption in the Netherlands during the year 2005 is 118500 GWh [119]. The influence of distance on the electricity transport concepts with battery ship and the electricity transport concept “submarine power cable link” is large. The delivered energy decreases, when the distance increases. Beyond approximately 4250 nautical miles the electricity transport concepts with ammonia fuel have the highest delivered energy. The electricity transport concepts “ammonia fuel with diesel propulsion” and “ammonia fuel with ammonia propulsion” are barely influenced by the distance. According to figure 6.1 the electricity transport concept “submarine power cable link” has the lowest energy losses till 4250 nautical miles. Beyond 4250 nautical miles the electricity transport concepts with ammonia fuel are more attractive. The electricity transport concept “battery ship with electric propulsion” has lower energy losses than the electricity transport concepts with ammonia fuel till 1000 nautical miles. Therefore from energetic perspective the electricity transport concept “submarine power cable link” is the most energy efficient solution till approximately 4250 nautical miles. Beyond 4250 nautical miles the electricity transport concepts with ammonia fuel are the most attractive solutions. Furthermore the electricity transport concepts with battery ship are only attractive till approximately 1000 nautical miles from energetic perspective. The influence of distance from economical perspective will be now examined. The cost per MWh of delivered energy in USD/MWh versus the distance in nautical miles is illustrated in figure 6.3. The cost per MWh for energy transport in USD/MWh versus the distance in nautical miles is illustrated in figure 6.4. During the distance variation the cost of power plants is 30 USD/MWh. The capital expenditures in million USD versus the distance in nautical miles are illustrated in figure 6.5.

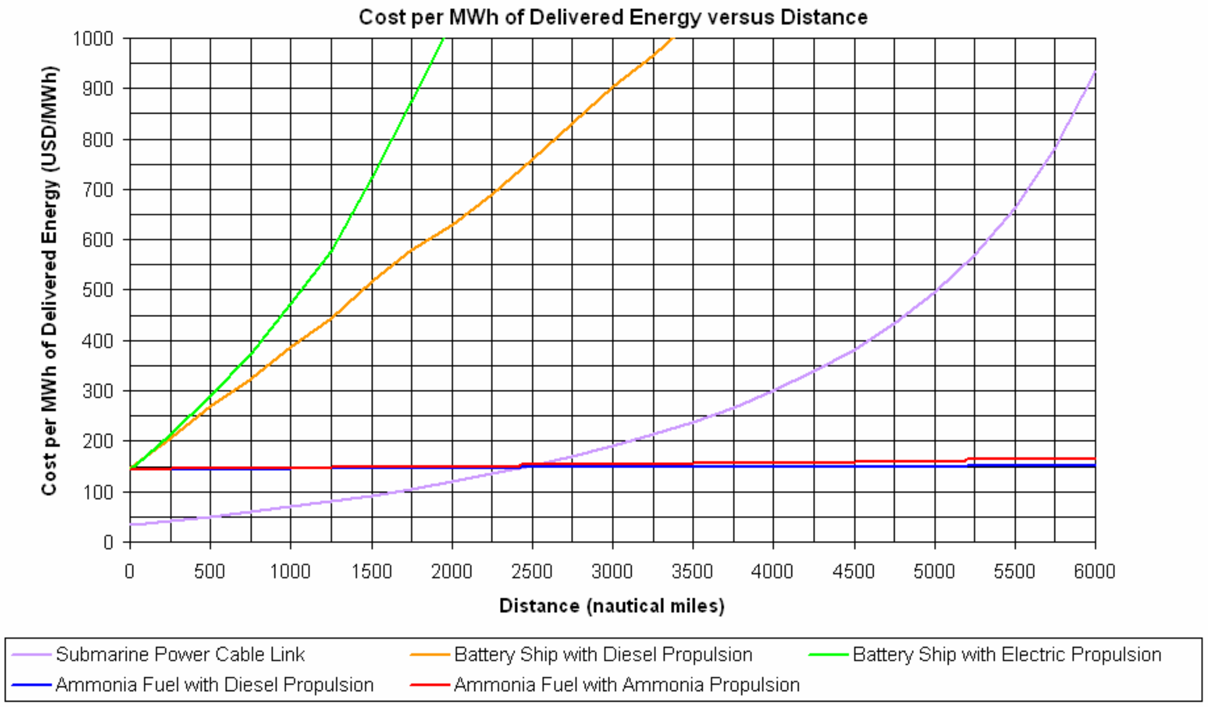

Figure 6.3 The cost per MWh of delivered energy in USD/MWh versus the distance in nautical miles

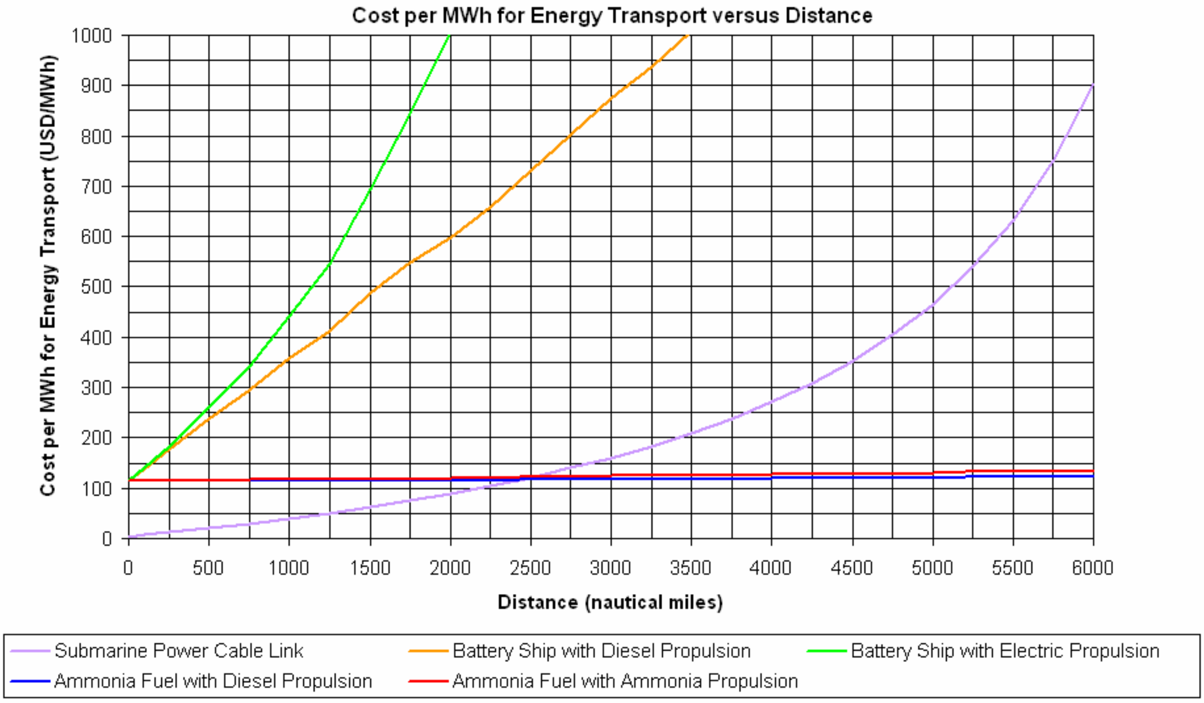

Figure 6.4 The cost per MWh for energy transport in USD/MWh versus the distance in nautical miles

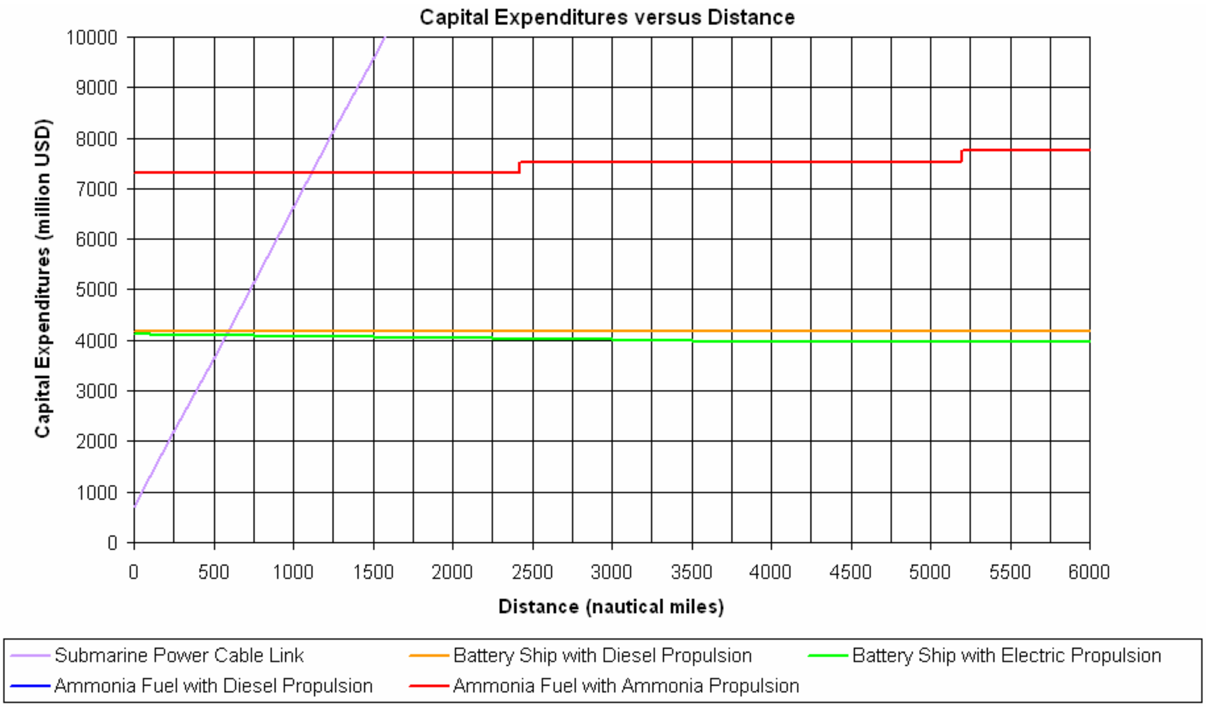

Figure 6.5 The capital expenditures in million USD versus the distance in nautical miles

The figures from 6.3 till 6.5 indicate that the electricity transport concept “submarine power cable link” is the most cost efficient and energy efficient solution till approximately 2500 nautical miles. The distance of 2500 nautical miles would be higher, when the costs of two submarine power cables are lower. Beyond approximately 2500 nautical miles the electricity transport concepts with ammonia fuel are the most attractive solutions, despite they are not the most energy efficient solutions. On the other hand they are the most cost efficient solutions beyond 2500 nautical miles.

The electricity transport concepts with battery ship are very expensive solutions due to the costs of batteries. The electricity transport concepts with battery ship could be attractive solutions till 1000 nautical miles, when the costs of batteries are significantly lower.
Another application for the battery ship would be using the battery ship as floating electrical energy storage. Still the electricity transport concept “submarine power cable link” is the best solution till approximately 2500 nautical miles due to the possibility to achieve electric power transmission in two directions. The main drawbacks of the electricity transport concept “submarine power cable link” are the very high capital expenditures and the long realization time. Besides that the capital expenditures of the electricity transport concept “submarine power cable link” are influenced by the distance. The capital expenditures of the other electricity transport concepts are hardly influenced by the distance.
Summarized the bulk electricity transport should be accomplished with a submarine power cable link till the distance of 2500 nautical miles. Beyond approximately 2500 nautical miles bulk electricity sea transport should be achieved with the electricity transport concepts with ammonia fuel. In the next two paragraphs the bulk electricity transport from Iceland to Scotland and the bulk electricity transport from Iceland to European mainland are examined.

6.3 Iceland/Scotland Electricity Transport

Iceland is a volcanic island lying in the North Atlantic Ocean. The island is located 500 nautical miles north west of Scotland. Scotland is the north part of Great Britain.
Great Britain is a large power consuming area, which needs electricity.
On the other hand Iceland has abundant ‘stranded’ cheap renewable electrical energy sources such as hydroelectric and geothermal energy sources. Therefore it is obvious that the electricity should be transported from Iceland to Scotland. As stated before the distance between the areas Iceland and Scotland is 500 nautical miles. The distance is less than 2500 nautical miles, so a submarine power cable link should be the most cost efficient electricity transport concept according to figure 6.3. The cost per MWh of power plants in Iceland is estimated 30 USD/MWh, but the cost per MWh of power plants could be lower or higher than 30 USD/MWh. Therefore the cost per MWh of power plants is varied from 0 USD/MWh to 150 USD/MWh to determine the influence of the parameter cost per MWh of power plants on the cost per MWh of delivered energy. The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the five electricity transport concepts for the distance of 500 nautical miles is illustrated in the figure 6.7.
The figure 6.7 confirms that a submarine power cable link is the most cost efficient solution for every cost per MWh of power plants. The submarine power cable link between the areas Iceland and Scotland is illustrated in figure 6.6. The cost per MWh of delivered energy in Scotland is 50.57 USD/MWh, when the cost per MWh of power plants in Iceland is 30 USD/MWh. The market price of electricity excluding taxes in the United Kingdom was 51.6 Euro/MWh or 61.92 USD/MWh in 2005 [120]. The market price of electricity excluding taxes in the United Kingdom has increased to 75.4 Euro/MWh or 90.48 USD/MWh in 2007 [120]. Thus the cost per MWh of delivered energy in Scotland is lower than the market price of electricity in the United Kingdom, so consequently the bulk electricity transport from Iceland to Scotland by means of submarine power cable link is profitable.

Figure 6.6 The map of North West Europe [151][152]

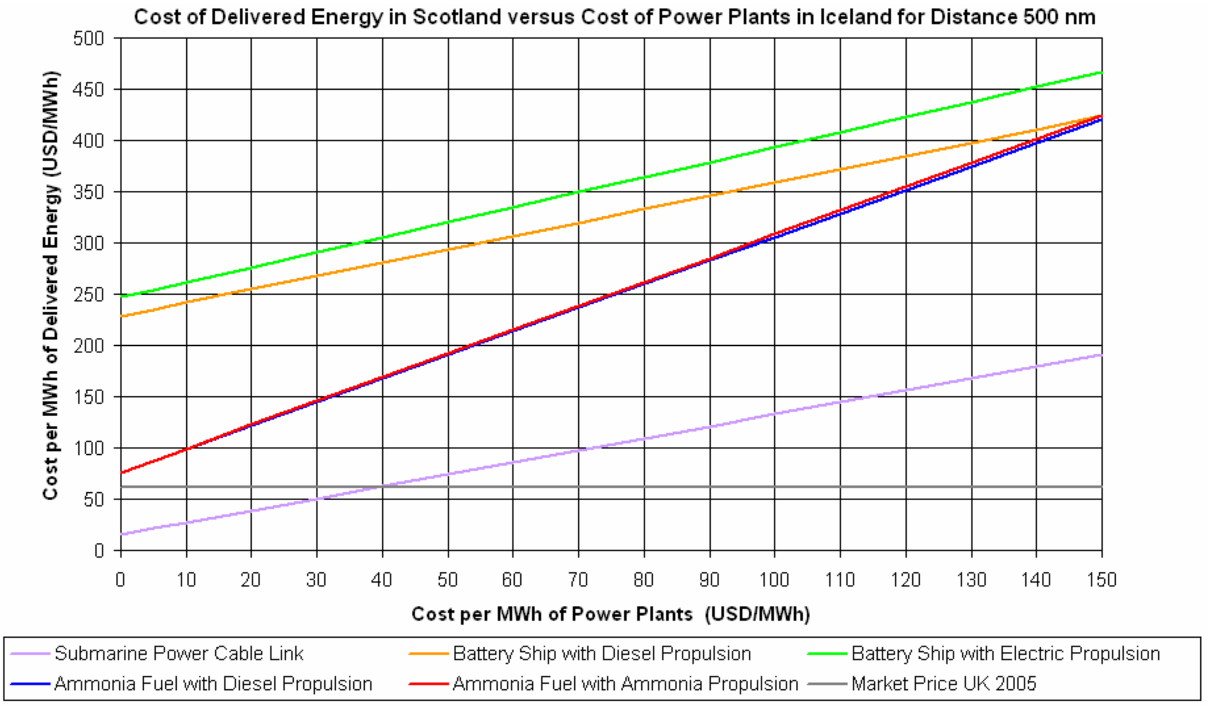

Figure 6.7 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance of 500 nautical miles

6.4 Iceland/European Mainland Electricity Transport

European mainland is likewise a large power consuming area, which needs electricity.
As mentioned before Iceland has cheap renewable electrical energy sources, so the electricity should be transported from Iceland to European mainland. In this case the European mainland is Germany or Netherlands. The distance between the areas Iceland and European mainland is 1000 nautical miles, so the distance is less than 2500 nautical miles. Thus a submarine power cable link should likewise be the most cost efficient electricity transport concept according to figure 6.3. The cost per MWh of power plants in Iceland is estimated 30 USD/MWh, but the cost per MWh of power plants could be lower or higher than 30 USD/MWh. Therefore the cost per MWh of power plants is varied from 0 USD/MWh to 150 USD/MWh to determine the influence of the parameter cost per MWh of power plants on the cost per MWh of delivered energy. The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the five electricity transport concepts for the distance of 1000 nautical miles is illustrated in figure 6.8. The figure 6.8 demonstrates that a submarine power cable link is the most cost efficient solution for every cost per MWh of power plants. The submarine power cable link between the areas Iceland and European mainland is also illustrated in figure 6.6. The cost per MWh of delivered energy in Europe is 70 USD/MWh, when the cost per MWh of power plants in Iceland is 30 USD/MWh. The market price of electricity excluding taxes in Germany was 71.3 Euro/MWh or 85.56 USD/MWh in 2005 [120]. The market price of electricity excluding taxes in Germany has increased to 85.6 Euro/MWh or 102.72 USD/MWh in 2007 [120]. Thus the cost per MWh of delivered energy is lower than the market price of electricity in European mainland, so consequently the bulk electricity transport from Iceland to European mainland by means of submarine power cable link is profitable. Furthermore the electricity transport concepts with ammonia fuel are attractive solutions at very low cost per MWh of power plants, but the electricity transport concepts with ammonia fuel become less attractive at high cost per MWh of power plants according to figure 6.7 and figure 6.8.

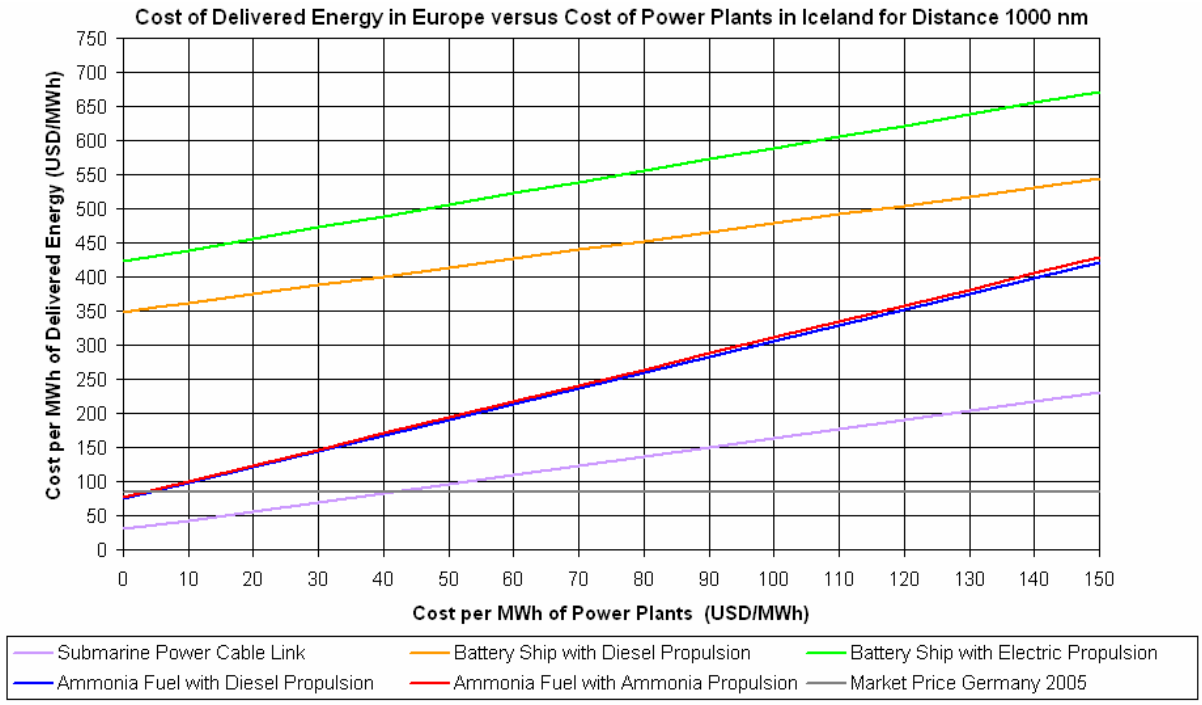

Figure 6.8 The cost per MWh of delivered energy in USD/MWh versus the cost per MWh of power plants in USD/MWh for the distance of 1000 nautical miles

7 Conclusions and Recommendations

In this final chapter the conclusions and the recommendations are presented.

7.1 Conclusions

During the development and the investigation of the different electricity transport concepts to achieve bulk electricity transport across the sea in energy efficient and cost efficient manner the following conclusions were found. The conclusions are divided into chapter 2, chapter 3, chapter 4, chapter 5 and chapter 6.

Conclusions concerning chapter 2

1. Bulk electricity transport by means of synthetic fuel in pipelines is interesting, when both energy transmission and energy storage are required.
2. Electricity transmission by means of electrical cables is suitable for long distant energy transmission across the sea.
3. Wireless energy transmission such as microwave power transmission, laser light power transmission is not suitable for long distant energy transmission across the sea, because it cannot transmit beyond the horizon.
4. The electrical energy storage technologies by means of compressed air storage, batteries and synthetic fuel are suitable for electricity transport by ship.

Conclusions concerning chapter 3

5. The HVDC system is the most attractive technology for long distance submarine electric power transmission.
6. The mass impregnated cable, PPLP solid cable and solid dielectric cable are preferred as submarine power cables.
7. The CSC converter stations are preferred for long distance submarine power lines.
8. The largest energy losses occur in the submarine power cables.
9. The capital expenditures of submarine power cable link rise with 5.92 million USD per nautical mile, when the submarine power cable length increases.
10. The cost per MWh of delivered energy increases, when the distance increases.

Conclusions concerning chapter 4

11. The battery ship should have a very large deadweight due to the economy of scale.
12. The cost per MWh of delivered energy decreases, when the deadweight of the battery ship increases due to the economy of scale.
13. The speed of battery ship should be low to prevent large energy losses.
14. The battery costs of the battery ship should be very low.
15. The cost per MWh of delivered energy decreases, when the output energy density of batteries increases.
16. The largest energy losses occur during sea transport and discharging the batteries.
17. The capital expenditures of battery ship are barely influenced by the distance.
18. The cost per MWh of delivered energy increases sharply, when the distance increases.

19. Currently the battery ship with diesel propulsion plant is more attractive than the battery ship with electric propulsion plant.
20. The battery ship should not be used beyond approximately 4000 nautical miles.

Conclusions concerning chapter 5

21. Synthetic fuels ammonia, hydrogen and DME are attractive for bulk electricity transport by ship.
22. The synthetic fuels ammonia and hydrogen are dangerous chemicals, but hydrogen is not safer than ammonia.
23. Ammonia is a more energy efficient and more cost efficient synthetic fuel than hydrogen, so ammonia is the most attractive synthetic fuel.
24. The power generation with generator sets is cheaper than the power generation with fuel cells, when the cost per MWh of power plants is low.
25. The power generation with fuel cells is cheaper than the power generation with generator sets, when the cost per MWh of power plants is high.
26. The largest energy losses are the energy losses associated with the conversion of electricity into ammonia and ammonia into electricity.
27. The capital expenditures of the energy supply chain with the synthetic fuel ammonia are barely influenced by the distance.
28. The cost per MWh of delivered energy increases hardly, when the distance increases.
29. Currently the ammonia/LPG carrier with ammonia propulsion plant is less attractive than the ammonia/LPG carrier with diesel propulsion plant.

Conclusions concerning chapter 6

30. The bulk electricity transport with submarine power cable link is the most cost efficient and energy efficient solution till approximately 2500 nautical miles.
31. Beyond approximately 2500 nautical miles the bulk electricity transport with ammonia fuel is the most attractive solution according to figure 6.3.
32. The bulk electricity transport with battery ship could be an attractive solution till approximately 1000 nautical miles, when the costs of batteries are significantly lower.
33. The bulk electricity transport with battery ship is a very expensive solution due to the costs of batteries.
34. The bulk electricity transport with ammonia fuel is especially an attractive solution at very low cost per MWh of power plants.
35. The submarine power cable link is the most attractive solution for the bulk electricity transport between Iceland and Scotland and the bulk electricity transport between Iceland and European mainland.
36. The bulk electricity transport between Iceland and Scotland and the bulk electricity transport between Iceland and European mainland are profitable with the current market prices of electricity.

7.2 Recommendations

The recommendations address the areas that require further work and further investigation.
In the light of the previous chapters the following recommendations are made.
The recommendations are divided into two categories: thesis and further work

Recommendations concerning the thesis

- The optimal ship size and the optimal speed of the battery ship should be investigated.
- The safety issues associated with hydrogen and ammonia should be investigated and compared in more detail.
- The ammonia production plant, which produces ammonia from water, should be elaborated in detail to determine the performance and the cost of the ammonia plant.
- The influence of the port dues and the size of the ammonia/LPG tankers for each distance on the cost per MWh of delivered energy should be investigated.

Recommendations concerning further work

- Thermal energy storage for electricity storage should be constructed and tested, because the thermal energy storage for electricity storage has never been tested.
- Research should be performed on heat transport across the sea, so that heat from inexpensive heat sources like geothermal could be transported to the energy consuming areas. In the energy consuming areas the heat could be used as heat or the heat could be converted into electricity.
- The floating submarine power cables should be investigated. The benefits of floating submarine power cables are shorter power cable lengths and less hydropressure acting on the submarine power cables.
- Cheaper submarine power cables should be developed through replacing expensive materials by cheaper materials.
- Cheaper and faster installation methods of submarine power cables should be investigated.
- The current redox flow batteries are too expensive for the battery ship, so significant cheaper redox flow battery with higher energy density should be developed.
- The low density of redox flow batteries makes the application of redox flow batteries in electric boats attractive, so the application of redox flow batteries in electric boats should be investigated.
- Research should be done on CO_2 transport by ship, because from the gases CO_2 and H_2 synthetic fuels could be synthesized.
- The current electrolyzers are too expensive and too small, so larger size atmospheric electrolyzer with significant lower costs and higher efficiency should be developed.
- Research should be performed on more energy efficient and cost efficient ammonia synthesis like solid state ammonia synthesis, which produces ammonia from water and electricity.
- Research should be done on power generation with ammonia, because the utilization of ammonia as fuel in power plants is no common practice.
- The utilization of ammonia in the main propulsion plant of ammonia/LPG carriers should be investigated, as there will be no need for fuel oils.

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Appendix A Energy Intensity

The bulk carrier is a ship used to carry dry bulk cargo such as coal, bauxite, phosphate rock, cement, grain, iron ore, fertilizer, salt, etc. The cargo density ranges from 0.34 ton/m^3 till 1.83 ton/m^3, so consequently the bulk carrier is a weight driven design. The relevant figures are illustrated in figure A1, figure A2, figure A3 and figure A4.

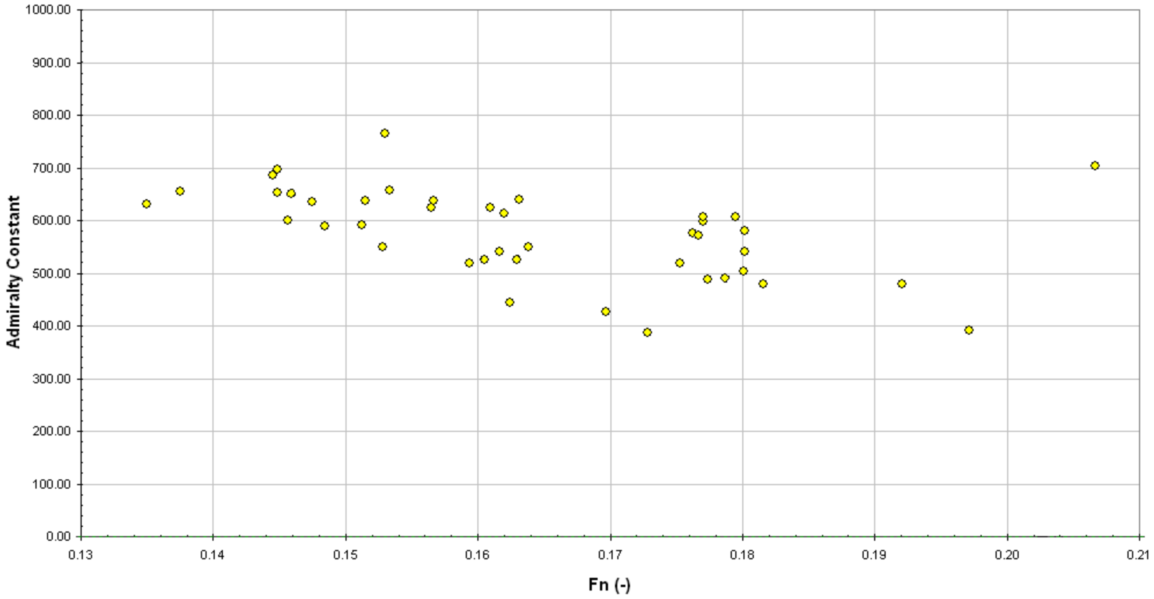

Figure A1 The admiralty constant of bulk carriers versus the froude number [50]

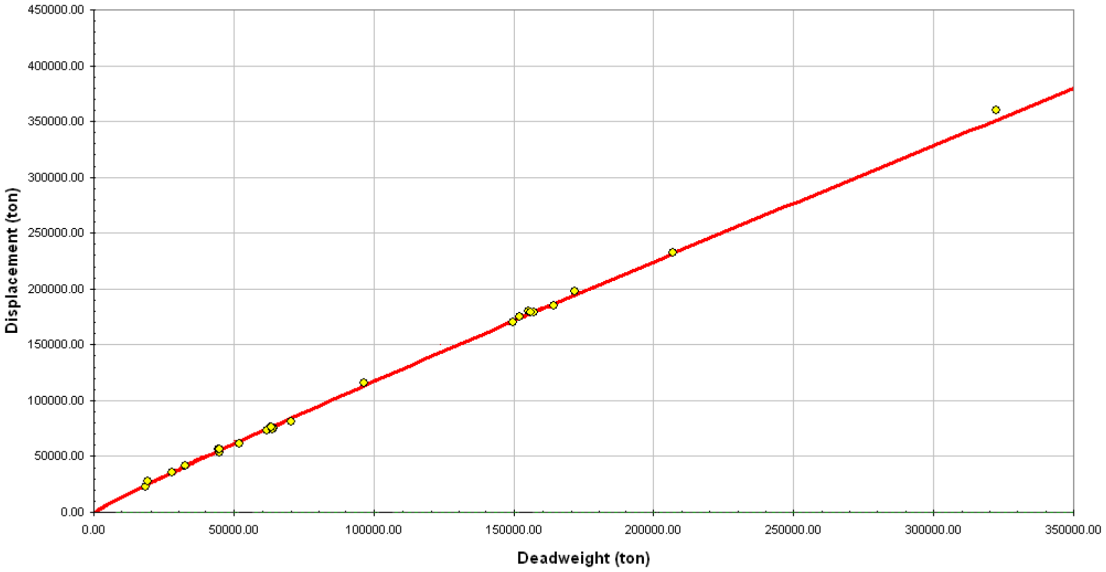

Figure A2 The displacement of bulk carriers versus the deadweight with function $\mathbf{Displacement = 2.38 \cdot Deadweight^{0.94}}$ [50]

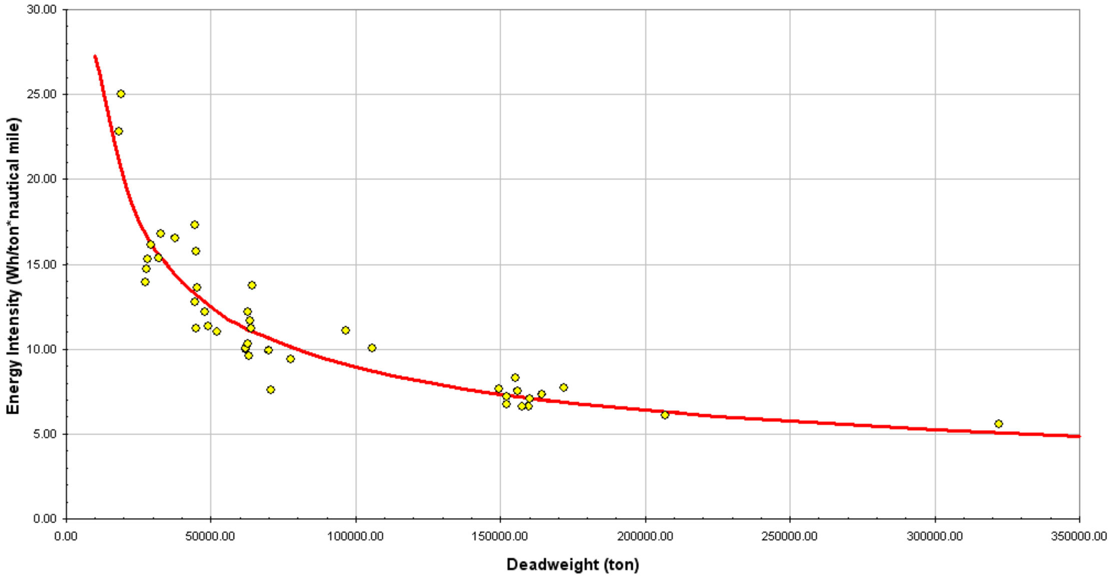

Figure A3 The energy intensity of bulk carriers versus the deadweight
with function **Energy Intensity = 237·Deadweight** $^{-0.48}$ [50]

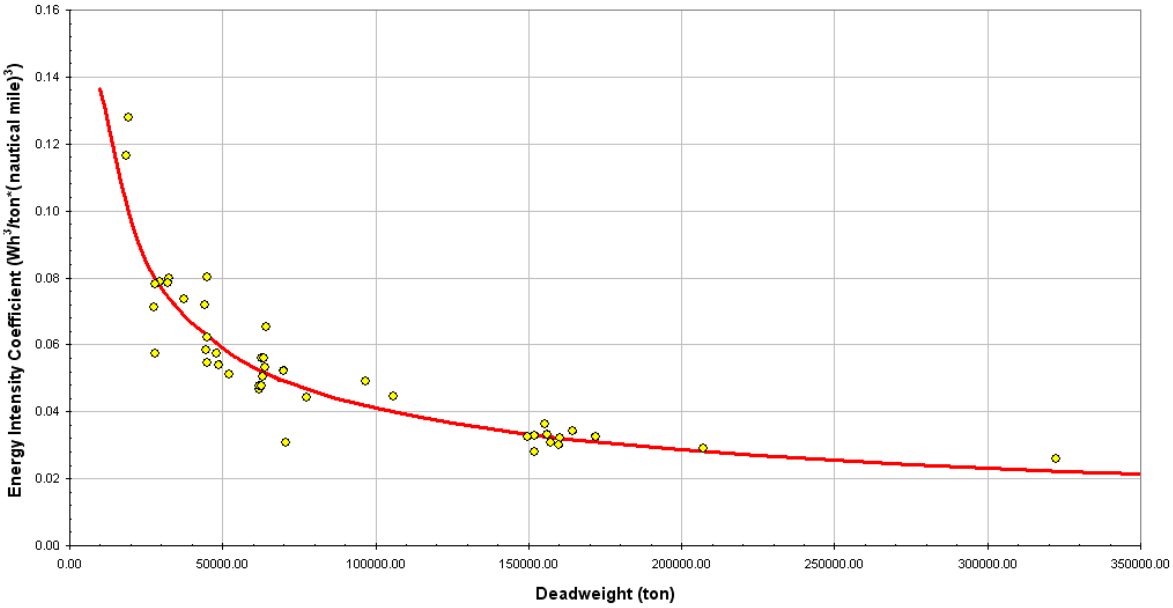

Figure A4 The energy intensity coefficient of bulk carriers versus the deadweight with function **Energy Intensity Coefficient = 16.7· Deadweight** $^{-0.52}$ [50]

The containership is a cargo vessel that carries the cargo in standard boxes so called containers. The containership is a relative fast ship. The cargo density of a container varies from 0.1 ton/m^3 till 0.6 ton/m^3. The cargo density is less than 0.77 ton/m^3, therefore the design of the containership is volume limited. The admiralty constant of the containerships is shown in figure A5. The energy intensity and the energy intensity coefficient of containerships are illustrated in figure A7 and figure A8.

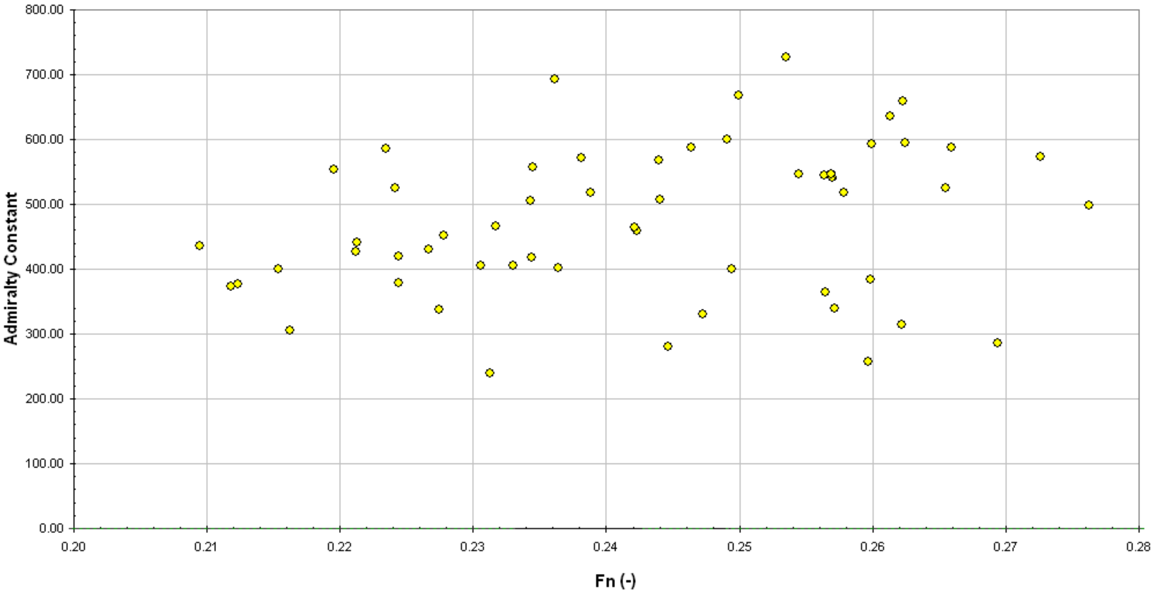

Figure A5 The admiralty constant of containerships versus the froude number [50]

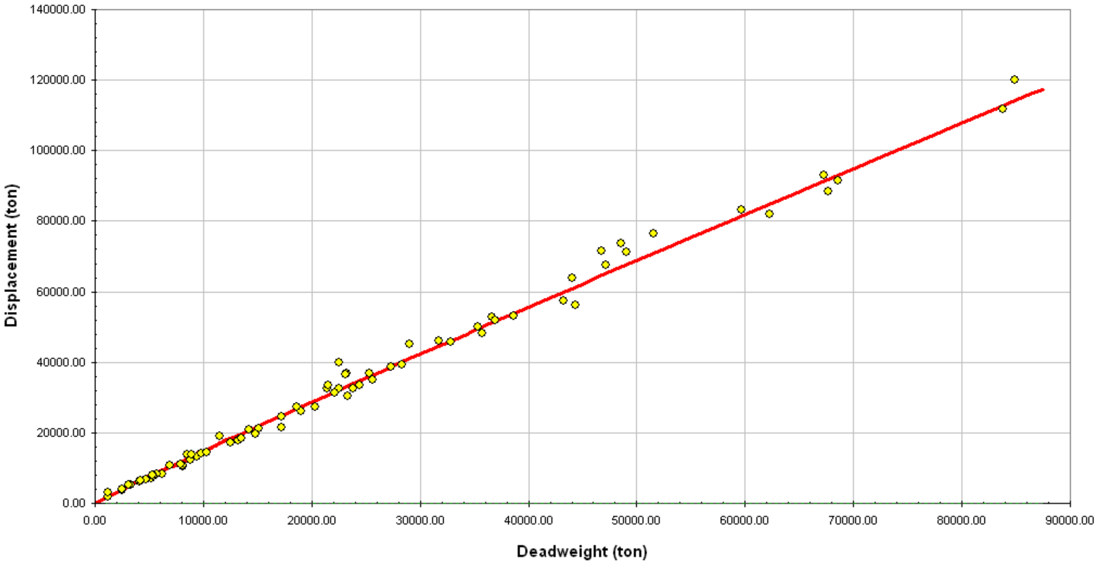

Figure A6 The displacement of containerships versus the deadweight with function $\mathbf{Displacement = 2.25 \cdot Deadweight^{0.96}}$ [50]

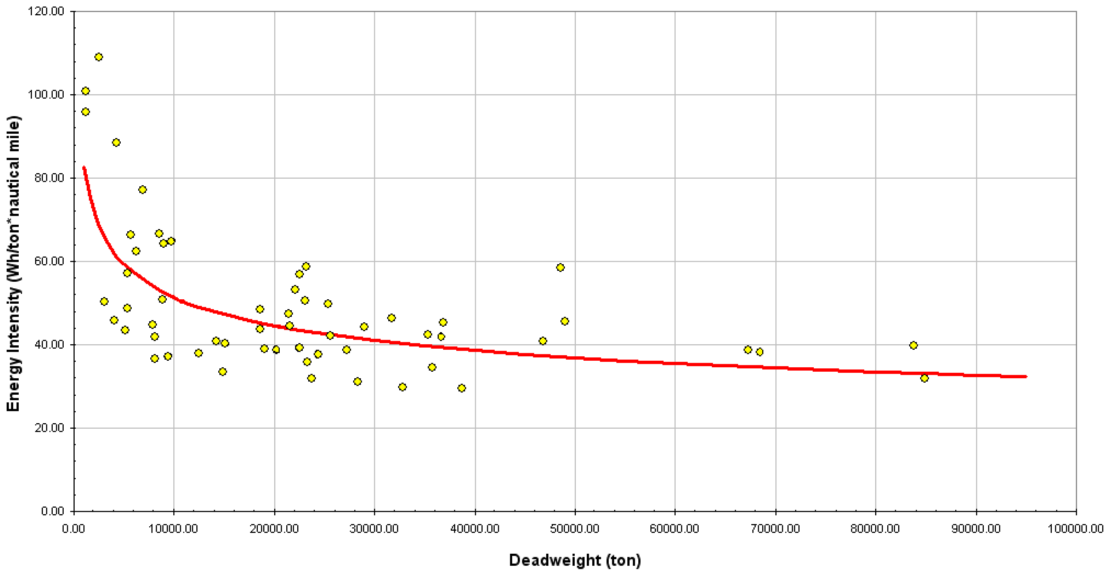

Figure A7 The energy intensity of containerships versus the deadweight with function $\mathbf{Energy\ Intensity = 344 \cdot Deadweight^{-0.21}}$ [50]

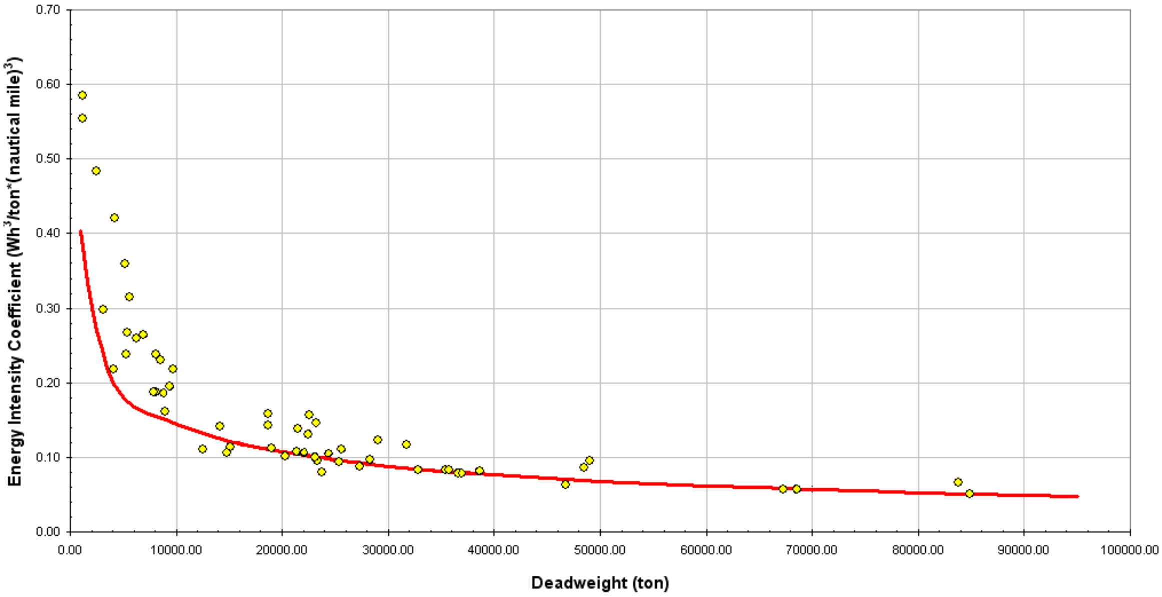

Figure A8 The energy intensity coefficient of containerships versus the deadweight with function $\mathbf{Energy\ Intensity\ Coefficient = 36.5 \cdot Deadweight^{-0.58}}$ [50]

The multipurpose cargo ship is a cargo vessel that carries different dry cargo such as containers and general cargo. The cargo density varies from 0.1 ton/m^3 till 0.7 ton/m^3. The multipurpose cargo ship is a volume based design, because the cargo density is lower than 0.77 ton/m^3. The admiralty constant of the multipurpose cargo ships is shown in figure A9. The energy intensity and the energy intensity coefficient of multipurpose cargo ships are illustrated in figure A11 and figure A12.

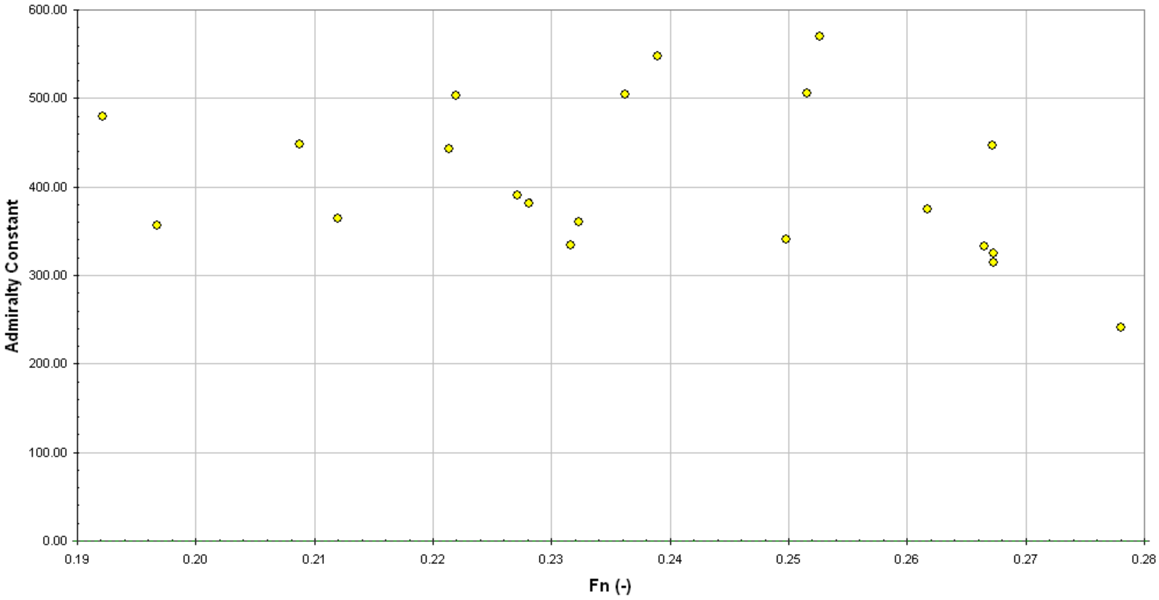

Figure A9 The admiralty constant of multipurpose cargo ships versus the froude number [50]

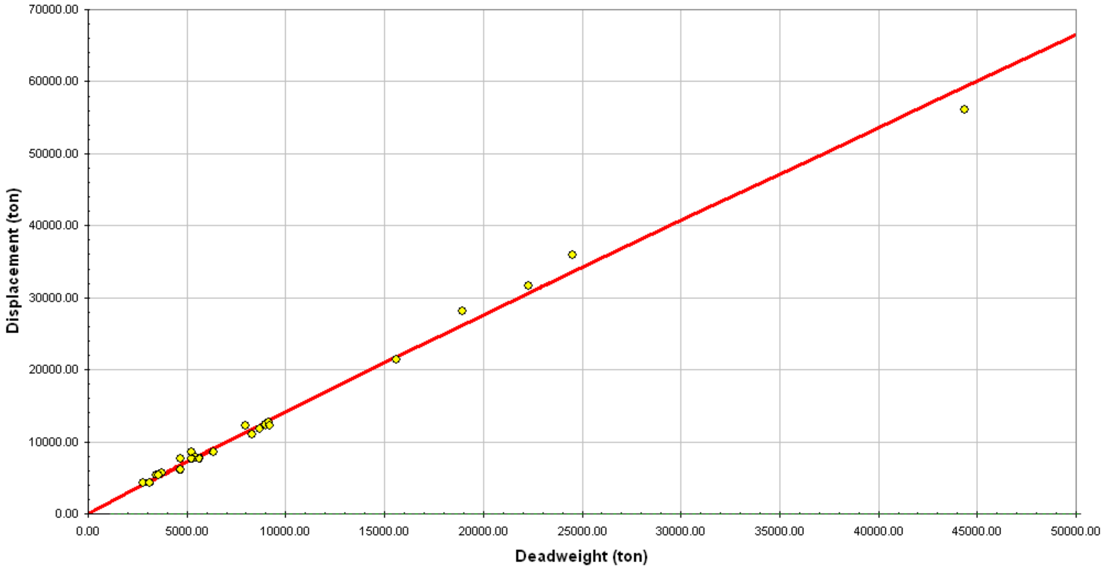

Figure A10 The displacement of multipurpose cargo ships versus the deadweight with function $\mathbf{Displacement = 1.96 \cdot Deadweight^{0.96}}$ [50]

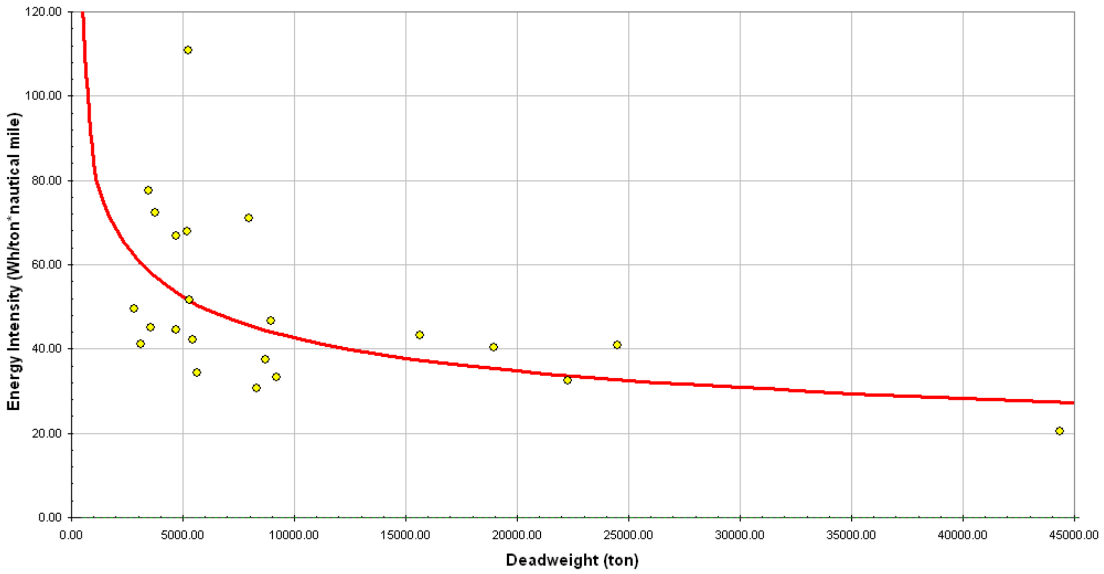

Figure A11 The energy intensity of multipurpose cargo ships versus the deadweight with function **Energy Intensity = 651· Deadweight** $^{\mathbf{-0.29}}$ [50]

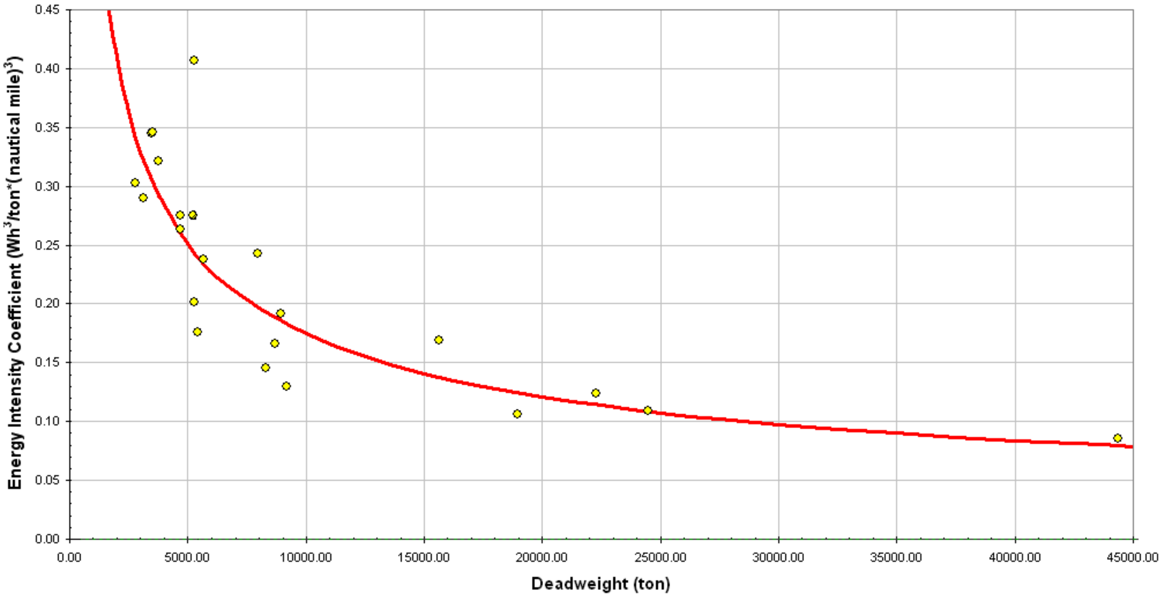

Figure A12 The energy intensity coefficient of multipurpose cargo ships versus the deadweight with function
Energy Intensity Coefficient = 22.8· Deadweight $^{\mathbf{-0.53}}$ [50]

The chemical tanker is a tanker, which carries liquid chemicals in bulk. The tanker is suitable to carry chemical cargo of densities from 0.8 ton/m^3 up to 2.15 ton/m^3. The chemical tanker is a weight based design, because the cargo density is higher than 0.77 ton/m^3.
The admiralty constant of the chemical tankers is shown in figure A13.
The energy intensity and the energy intensity coefficient of chemical tankers are illustrated in figure A15 and figure A16.

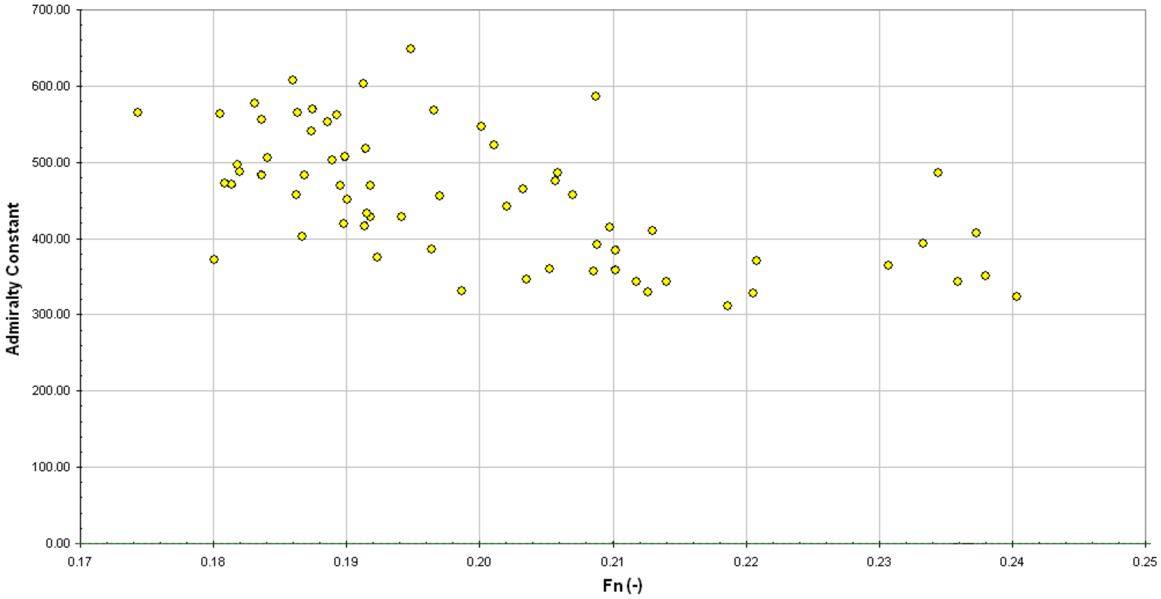

Figure A13 The admiralty constant of chemical tankers versus the froude number [50]

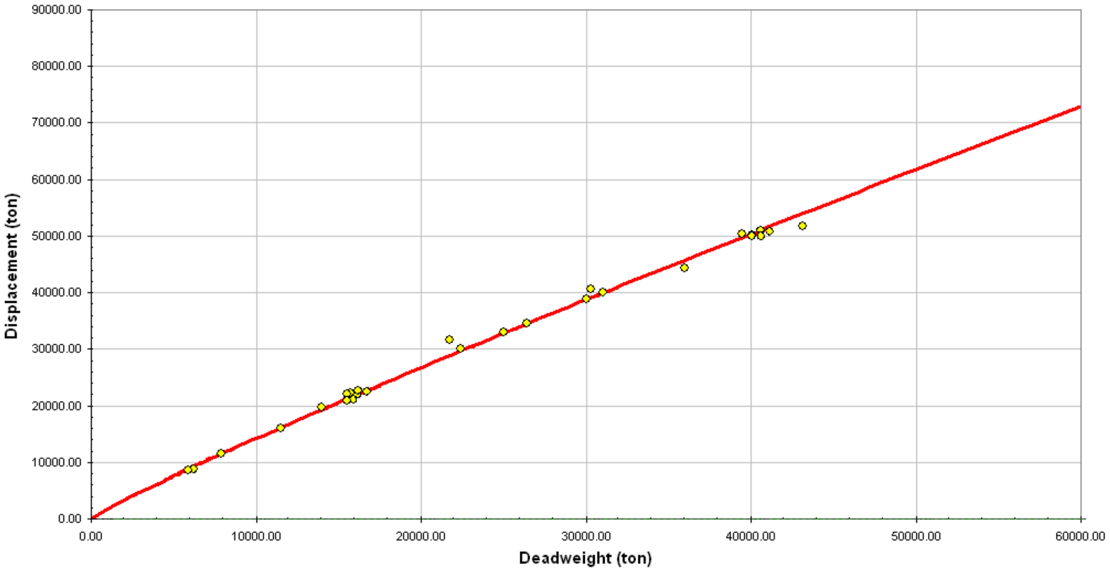

Figure A14 The displacement of chemical tankers versus the deadweight with function **Displacement = 3.17· Deadweight $^{0.91}$** [50]

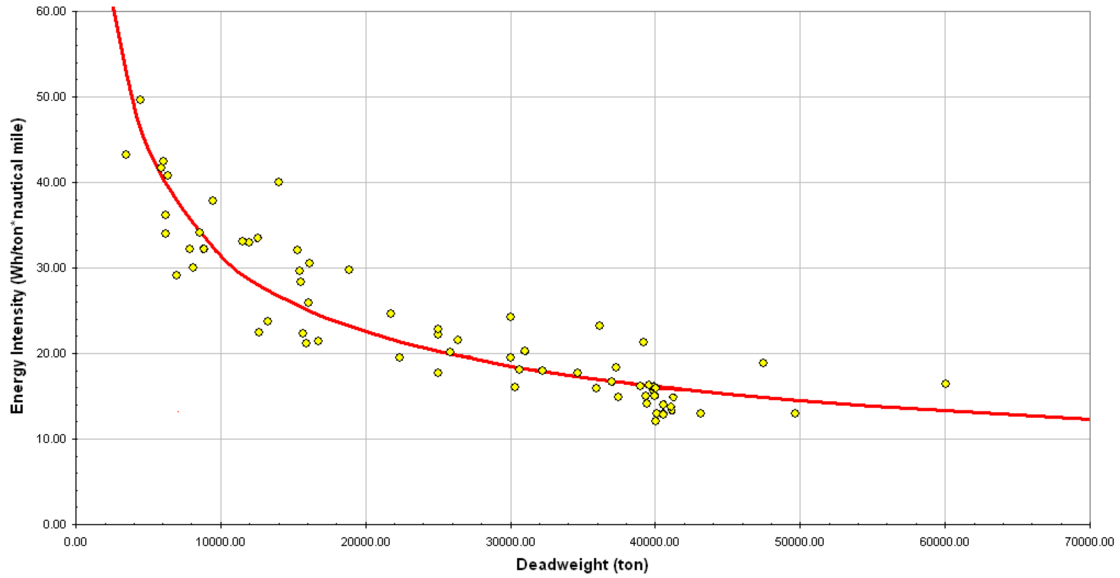

Figure A15 The energy intensity of chemical tankers versus the deadweight with function **Energy Intensity = 262· Deadweight** $^{\mathbf{-0.48}}$ [50]

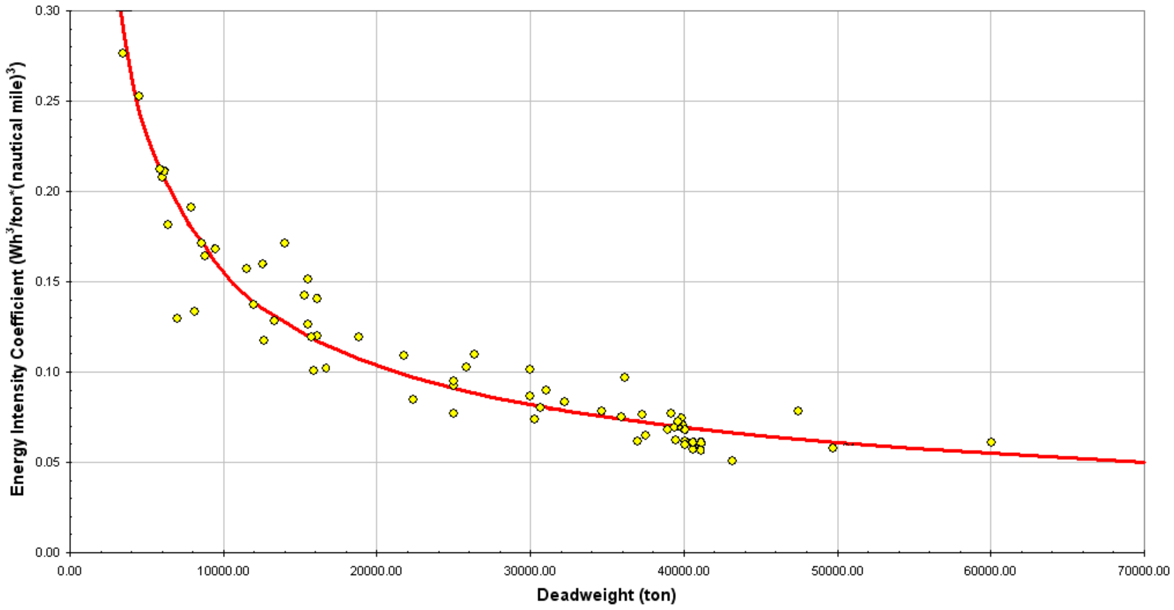

Figure A16 The energy intensity coefficient of chemical tankers versus the deadweight with function **Energy Intensity Coefficient = 31.9· Deadweight** $^{\mathbf{-0.58}}$ [50]

The product tanker is a cargo tanker to transport liquid refined petroleum products, although the product tanker is also capable to carry chemicals such as palm oil and vegetable oil.
In fact, the product tanker is a modified chemical tanker. The product tanker is capable to carry cargoes with the specific gravities from 0.66 ton/m^3 up to 1.54 ton/m^3.
The design of a product tanker is weight limited. The admiralty constant of the product tankers is shown in figure A17. The energy intensity and the energy intensity coefficient of product tankers are illustrated in figure A19 and figure A20.

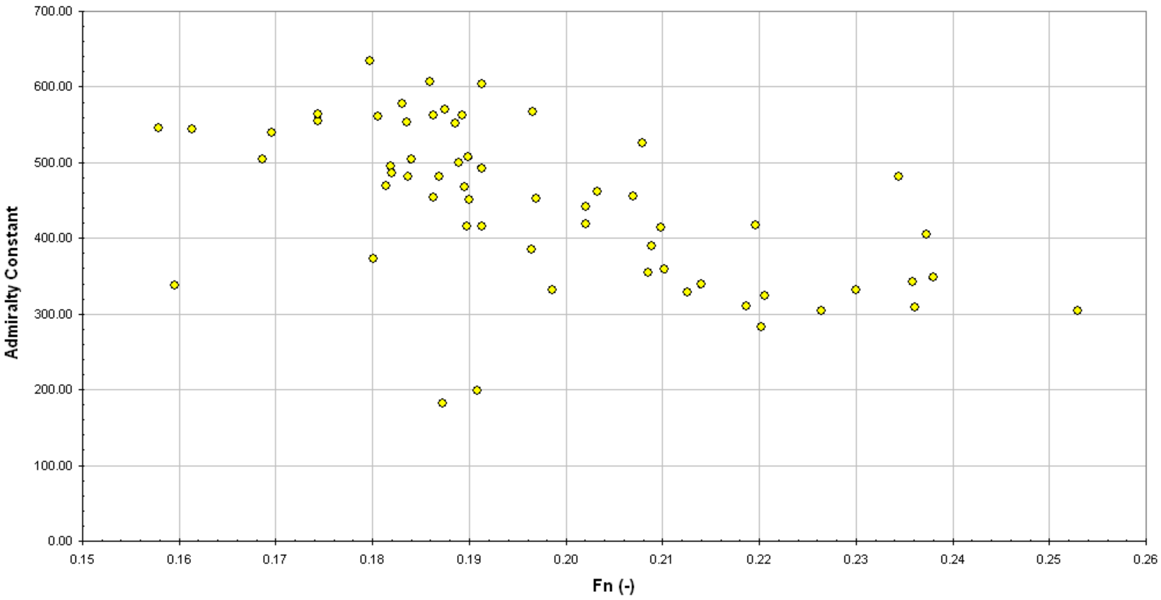

Figure A17 The admiralty constant of product tankers versus the froude number [50]

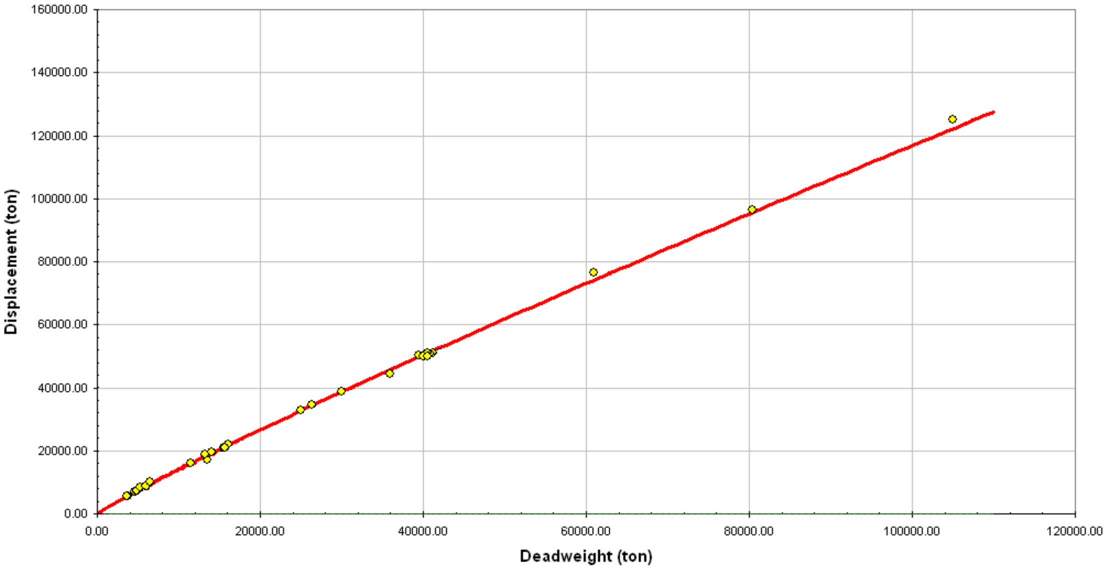

Figure A18 The displacement of product tankers versus the deadweight with function $\mathbf{Displacement = 2.99 \cdot Deadweight^{0.92}}$ [50]

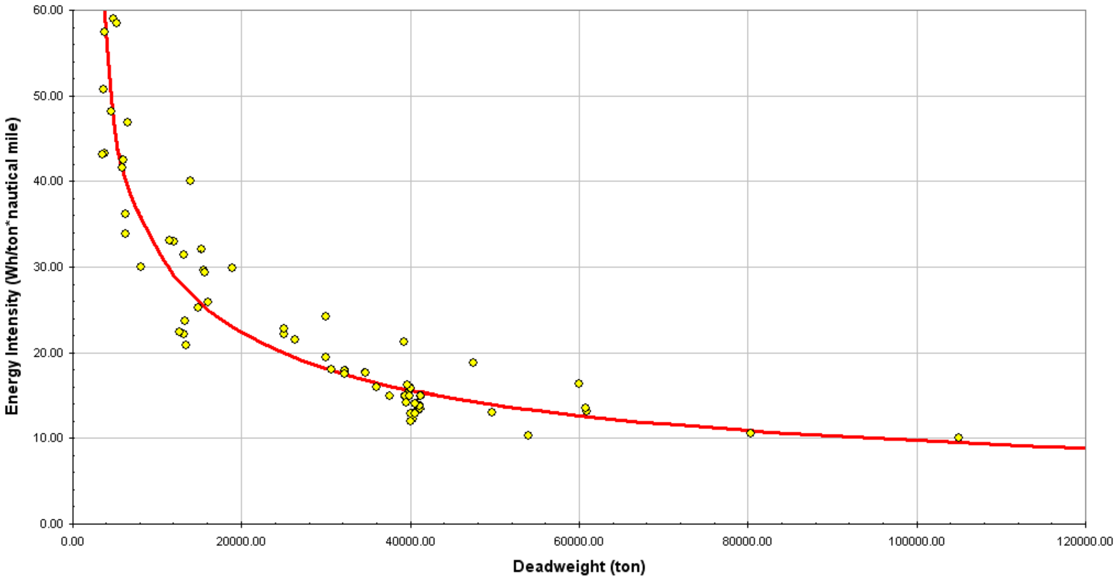

Figure A19 The energy intensity of product tankers versus the deadweight with function $\textbf{Energy Intensity} = \textbf{3808} \cdot \textbf{Deadweight}^{\textbf{-0.052}}$ [50]

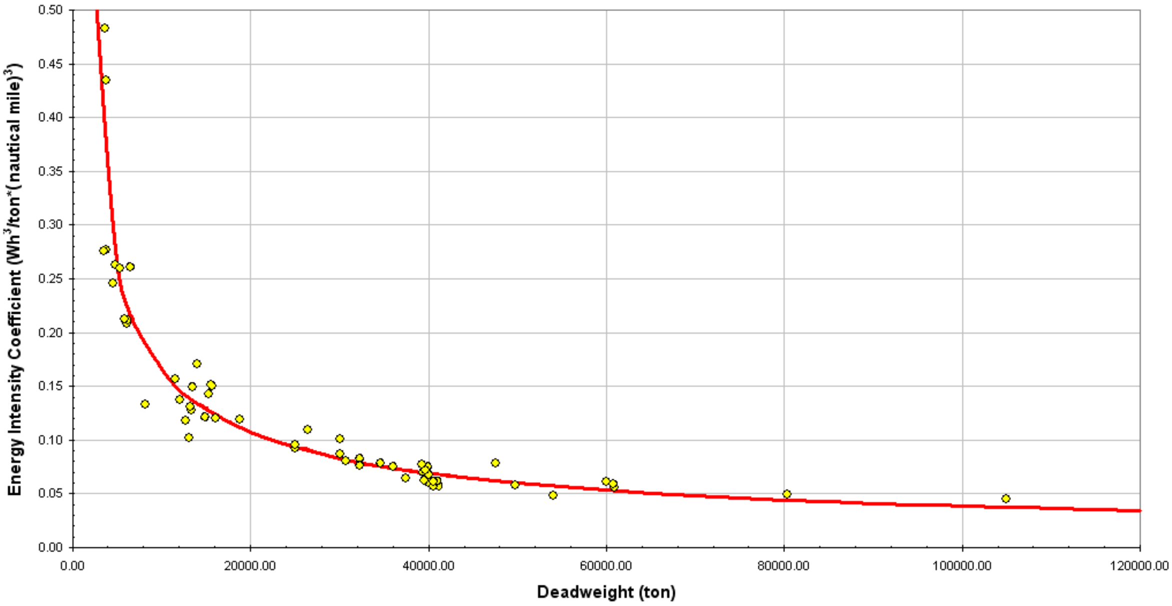

Figure A20 The energy intensity coefficient of product tankers versus the deadweight with function $\textbf{Energy Intensity Coefficient} = \textbf{57.5} \cdot \textbf{Deadweight}^{\textbf{-0.63}}$ [50]

The LNG carrier is a cargo vessel for the transport of liquefied natural gas. The LNG carrier is suitable to carry gas with the densities from 0.42 ton/m^3 up to 0.58 ton/m^3. The LNG carrier is a volume based design. The admiralty constant of the LNG carriers is shown in figure A21. The energy intensity and the energy intensity coefficient of LNG carriers are illustrated in figure A23 and figure A24.

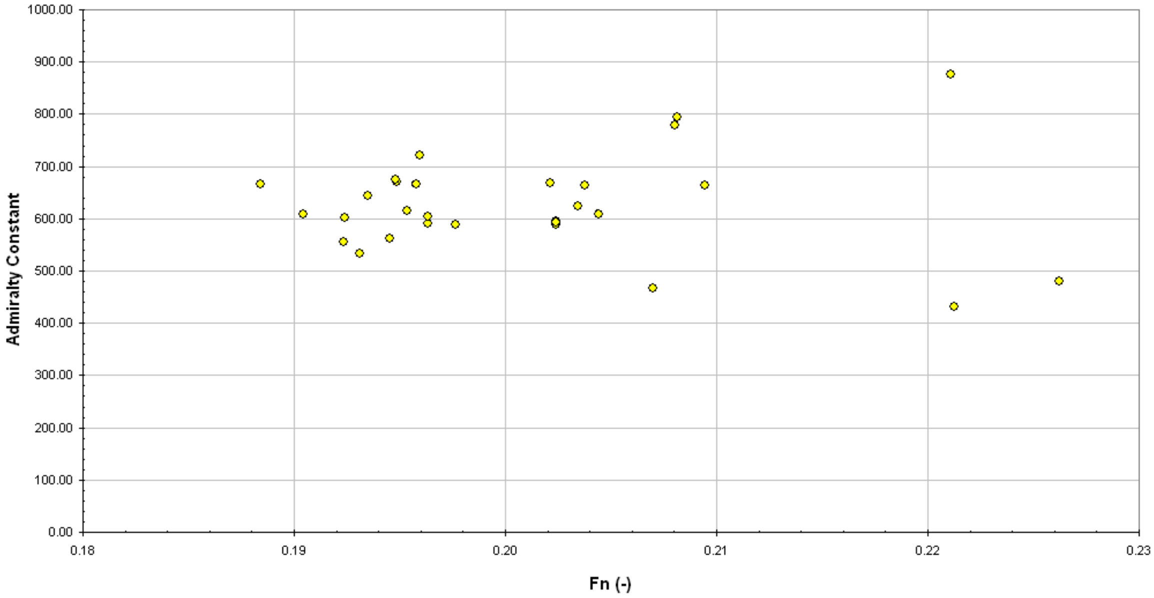

Figure A21 The admiralty constant of LNG carriers versus the froude number [50]

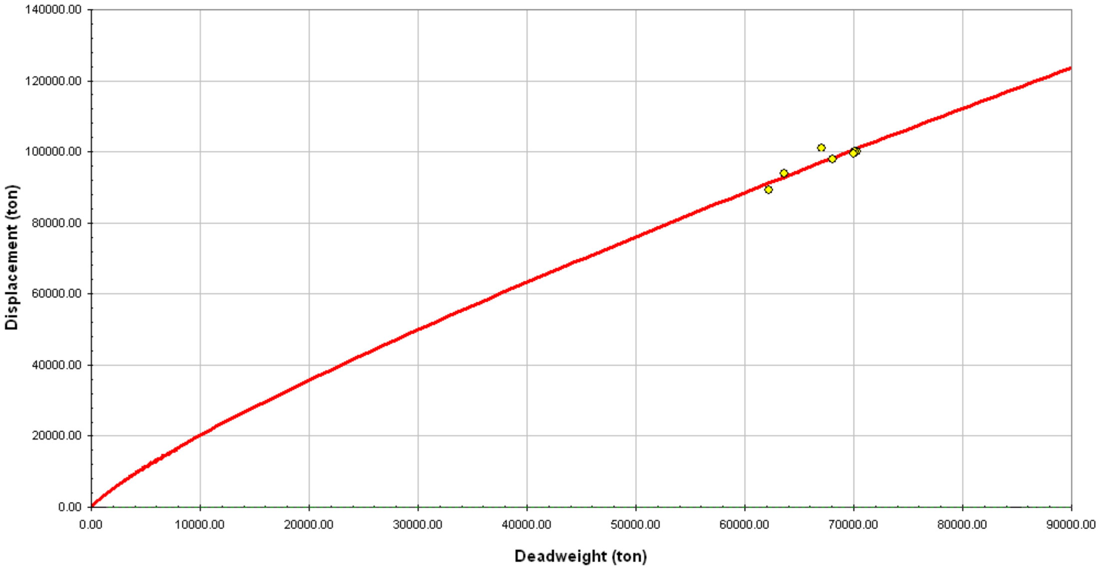

Figure A22 The displacement of LNG carriers versus the deadweight with function $\mathbf{Displacement = 10.1 \cdot Deadweight^{0.83}}$ [50]

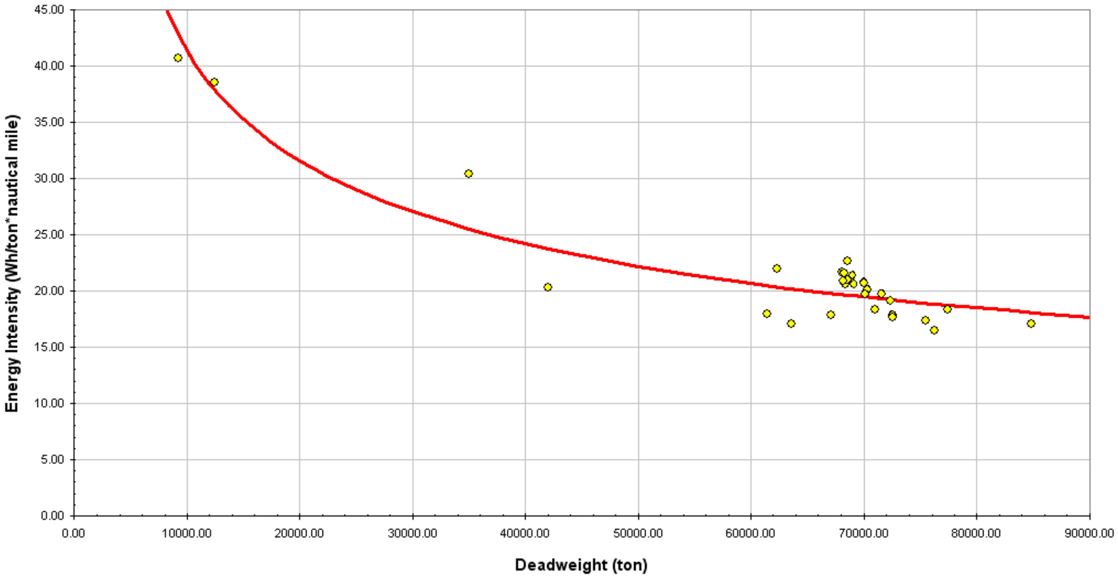

Figure A23 The energy intensity of LNG carriers versus the deadweight with function **Energy Intensity = 1461· Deadweight** $^{\mathbf{-0.39}}$ [50]

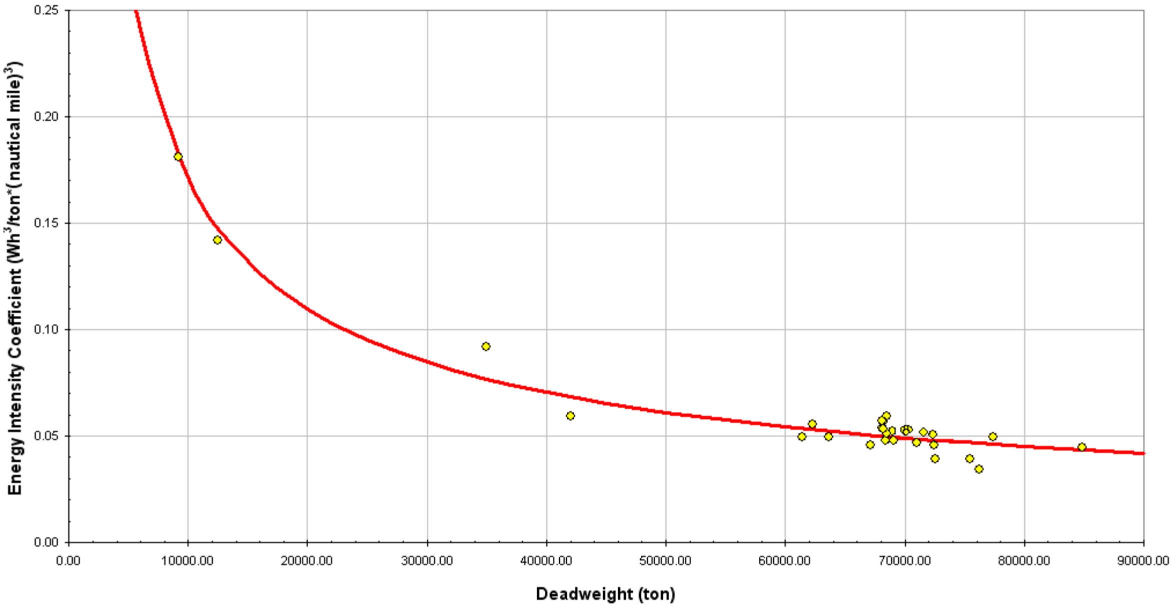

Figure A24 The energy intensity coefficient of LNG carriers versus the deadweight with function **Energy Intensity Coefficient = 63.9· Deadweight** $^{\mathbf{-0.64}}$ [50]

The LPG carrier is a cargo vessel for the transport of a large variety of chemical gases such as LPG, ethane, chlorine, etc. The LPG carrier is suitable to carry gas with the densities from 0.60 ton/m^3 up to 0.97 ton/m^3. The LPG carrier is a volume based design. The admiralty constant of the LPG carriers is shown in figure A25. The energy intensity and the energy intensity coefficient of LPG carriers are illustrated in figure A27 and figure A28.

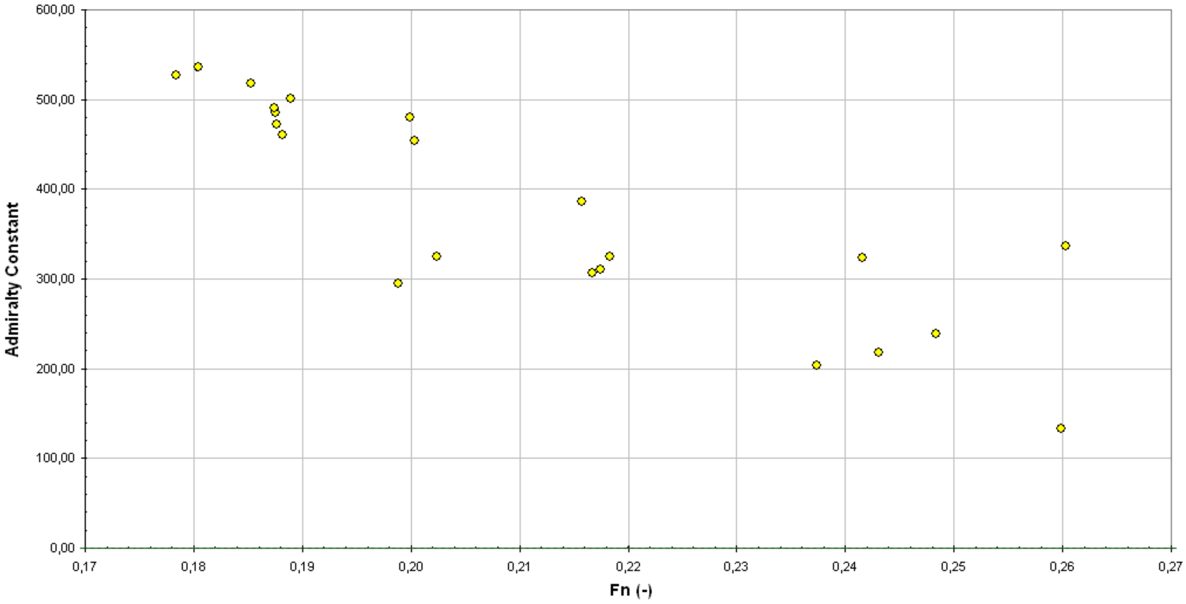

Figure A25 The admiralty constant of LPG carriers versus the froude number [50]

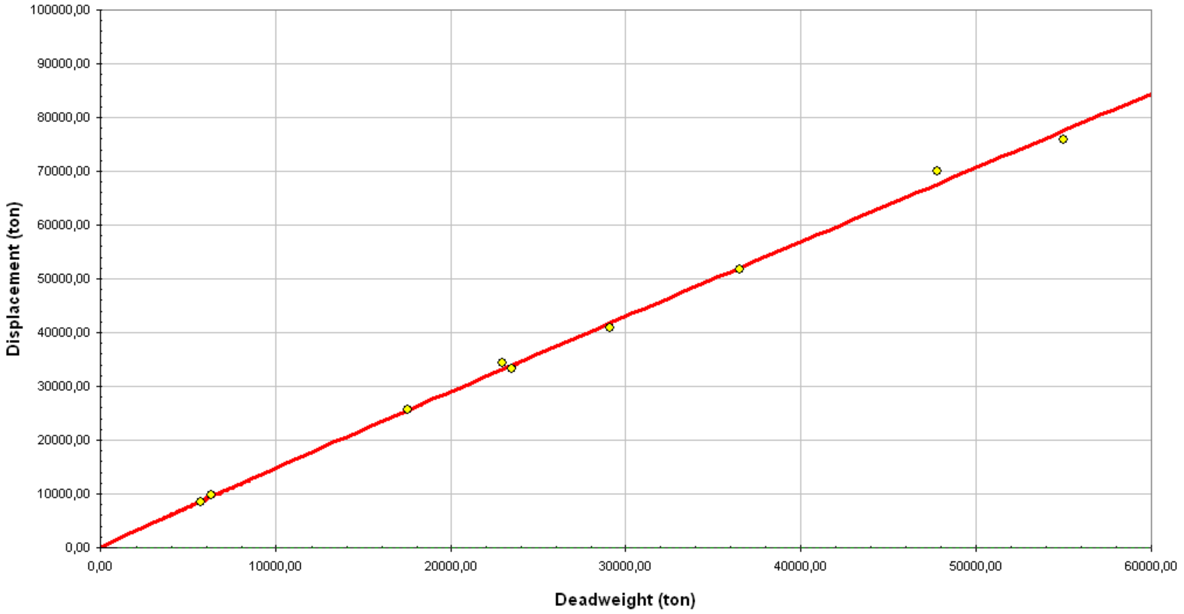

Figure A26 The displacement of LPG carriers versus the deadweight with function $\mathbf{Displacement = 1.91 \cdot Deadweight^{0.97}}$ [50]

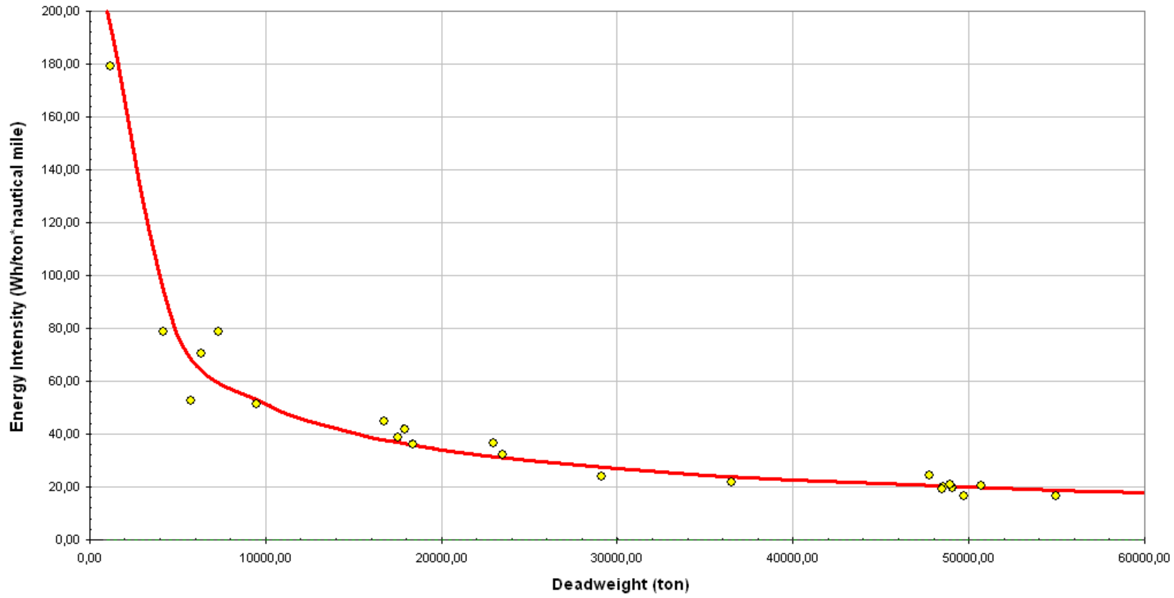

Figure A27 The energy intensity of LPG carriers against the deadweight with function **Energy Intensity = 11842· Deadweight** $^{-0.59}$ [50]

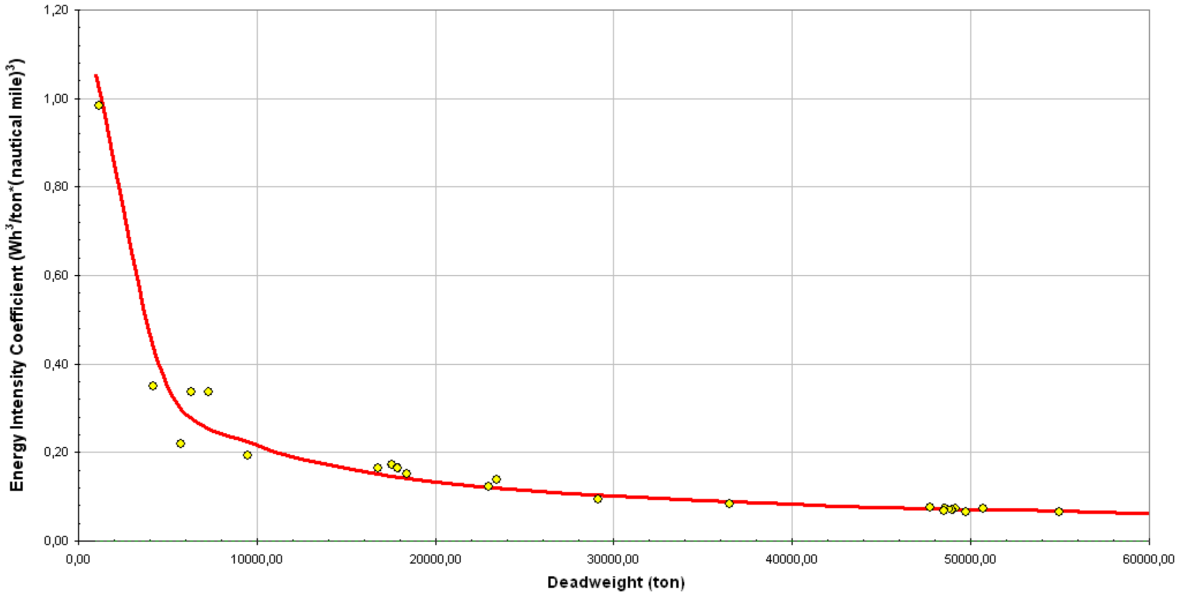

Figure A28 The energy intensity coefficient of LPG carriers against the deadweight with function **Energy Intensity Coefficient = 122· Deadweight** $^{-0.69}$ [50]