Battery boat

Concept study in bulk electric energy sea transport

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TU Delft

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TU Delft

Abstract

Developments in the field of renewable energy technologies have lead to low energy cost in areas with specific characteristics. In the Middle East solar power plants are built for prices around 3 cent per kilowatt-hour and bids below 3 cent have been placed. In Europe wind energy is the second largest source of renewable energy after biomass. Although, wind farms are being built without subsidy the total cost of a wind farm is much higher in the order of 14 cent per kWh and it can decrease to 10 cent by 2030.

In this research an concept study for the transport of electric energy is made to find an answer to the question.

Is it possible to ship electric energy which is delivered in a port between areas of generation and consumption over a fixed distance with the use of a ship and deliver it for a levelised cost of electricity (LCoE) which is competitive in the market of unloading.

The cost of a kilowatt-hour of electric energy in the Dutch market is 8.33 if it is produced by a modern gas fired power plant and if the cost for CO_2-emissions are included according to the current prices in the European emission trading scheme. If higher carbon cost scenario's are applied the price could increase to prices over 17 cent per kilowatt-hour. The concepts in this study are tested against four different carbon emission cost scenario's ranging from 8 euro/tCO_2 to 190 euro/tCO_2.

Most electrical energy is transported by electric energy power grids. For long distance high volume energy transmission a high voltage direct current energy cable is the most efficient way to transport energy but at larger distances the transmission system gets more expensive. In this research the electric cable is used as a reference case which the concept has to outperform.

To test the concepts a non-linear model is made which is solved with Matlab-integrated solvers to find the optimal transport concept. The model works by optimising the main dimensions of the ship. With this optimal ship design concepts are analysed. For this research: a concept based on a hydrogen-carrier (ammonia) and a concept based on thermal energy storage are discussed. .

The hydrogen-carrier concept uses ammonia as a carrier. Ammonia has a high energy content and can be produced with the Haber Bosch process or with Solid State Ammonia Synthesis (SSAS). If the energy is produced using the well known Haber-Bosch process in 2018 the levelised cost of energy is 21.2 and 24.2 cent per kilowatt hour depending on the distance. Developments in the field of electrolysers will reduce the capital investment which can reduce the price to 17.8 to 20.8 cent per kilowatt hour by 2025 if the energy is supplied at 2 cent per kilowatt hour to the ammonia production facility. The SSAS method offers higher energy effincies at lower capital investment cost. The LCOE calculated in this research is 11.4 to 16.4 cent per kilowatt-hour.

The thermal energy storage concept is based on molten salt. Molten salt is being used in concentrated solar power plants as a storage of energy. In the concept used in this project the molten salt is transported to another part where the heat which is stored in the salt is used to generate electricity. The LCOE is already 28.5 cent per kilowatt-hour at a distance of 1,000 nm. The thermal energy storage concept is more expensive than the ammonia concept.

Depending on the distance and the carbon cost scenario's the concept can be competitive to the fixed connection with a cable and fossil fired power plants in the home market. If the low cost carbon scenario's (1 and 2) are applied by lawmakers the concept of electrical energy by sea is not competitive but if politicians would decide to increase the cost for carbon emissions the transport could become competitive. When the carbon emission cost increase to values over 100 euro/tCO_2 the SSAS concept is competitive for distance upto 2,000 nm but it still more expensive than a cable connection. For this distances larger than 4,000 nm and carbon prices according to the 4^{th} scenario (190 euro/tCO_2) the SSAS-based concept can be a competitive energy supplier.

Contents

1 Introduction **1**
1.1 Research question . . . 1
1.2 System borders . . . 2
1.3 Bookmark anchor . . . 2

2 Methodology **3**
2.1 The main concepts used in this research . . . 3
2.1.1 Conversion efficiency . . . 3
2.1.2 Levelised cost of electricity. . . . 4
2.2 Methodology . . . 4
2.2.1 Markets . . . 5
2.2.2 Storage. . . . 5
2.2.3 Transport . . . 5
2.2.4 Concept design . . . 5

3 Energy markets **7**
3.1 Current energy markets . . . 7
3.1.1 Coal based energy . . . 7
3.1.2 Gas trade. . . . 8
3.1.3 Environmental cost fossil fuel energy markets . . . 12
3.2 Renewable energy markets . . . 13
3.2.1 Solar power . . . 14
3.2.2 Wind power . . . 16
3.2.3 Geothermal energy . . . 16
3.2.4 Hydro power . . . 16
3.2.5 Price development renewable energy markets . . . 17
3.3 Conclusion on the energy markets . . . 17
3.3.1 Conclusion on energy markets in the Netherlands . . . 17
3.3.2 Conclusion on the cost of energy generation. . . . 17

4 Fixed connection energy transport **19**
4.1 High voltage AC transmissions . . . 19
4.1.1 Cost estimation HVAC transmission . . . 19
4.2 High voltage DC transmissions . . . 20
4.2.1 High voltage DC LCC. . . . 20
4.2.2 High voltage DC VSC. . . . 21
4.3 Cost comparison of transmission solutions . . . 21
4.4 Conclusions on cable . . . 22

5 Transportation **25**
5.1 Model. . . . 25
5.1.1 Input parameters . . . 25
5.1.2 Storage. . . . 26
5.1.3 Ship . . . 26
5.1.4 Cost definition of the ship . . . 28
5.1.5 General shore facilities. . . . 29
5.1.6 Generated electrical energy . . . 30
5.1.7 Levelised cost of electricity. . . . 30
5.2 Constraints . . . 31
5.2.1 Constraint on depth and length . . . 31
5.2.2 Stability criteria . . . 31

5.3 Sensitivity analysis and modelling criteria . . . 31
5.3.1 Effect of round-trip efficiency and capital cost per kilowatt on LCoE . . . 32
5.3.2 Effect of round-trip efficiency and argo specific energy density on LCoE for set distances . 32
5.3.3 Round trip efficiency and cargo specific energy density . . . 32
5.3.4 Manning cost . . . 33
5.3.5 Fuel cost . . . 33
5.3.6 Conversion efficiencies . . . 33
5.3.7 Energy density cargo . . . 34
5.3.8 Conclusion driving parameters and design proposal . . . 34

6 Energy Storage 39
6.1 Pumped Hydro Storage . . . 39
6.1.1 Conclusions on PHS . . . 39
6.2 Compressed Air Energy Storage . . . 39
6.2.1 Conclusion on CAES . . . 40
6.3 Flywheel Energy Storage . . . 40
6.3.1 Conclusions on FES . . . 40
6.4 Battery Energy Storage Systems . . . 40
6.4.1 Lead-acid batteries. . . . 40
6.4.2 Nickel-cadium batteries . . . 40
6.4.3 Sodium-sulphur batteries . . . 40
6.4.4 Lithium-ion batteries . . . 41
6.4.5 Conclusion on battery storage systems . . . 41
6.5 Flow Battery Energy Storage Systems . . . 41
6.5.1 Conclusions on FBESSs . . . 41
6.6 Thermal storage. . . . 41
6.6.1 Low temperature TES . . . 42
6.6.2 High temperature TES . . . 42
6.7 Hydrogen . . . 42
6.7.1 Liquid hydrogen . . . 43
6.7.2 Compressed hydrogen . . . 43
6.7.3 Hydrogen carriers . . . 43
6.8 Evaluation of storage options . . . 44
6.9 Hydrogen carrier - ammonia . . . 44
6.9.1 Haber-Bosch based . . . 45
6.9.2 Solid state ammonia synthesis based . . . 45
6.9.3 Fuel cells . . . 46
6.10 Thermal energy storage . . . 47
6.10.1 Production . . . 47
6.10.2 Storage . . . 48
6.10.3 Transport . . . 48
6.10.4 Cost . . . 49

7 Concept design 51
7.1 Ammonia based concept . . . 51
7.1.1 Ship dimensions ammonia concept . . . 51
7.1.2 Ammonia model with the Haber Bosch production process . . . 52
7.1.3 Ammonia concept based on Solis State Ammonia Synthesis . . . 55
7.1.4 Conclusions on the ammonia concept . . . 56
7.2 Thermal energy storage concept . . . 56
7.2.1 Main dimension ship thermal storage concept . . . 59
7.2.2 Results for the thermal concept . . . 59
7.3 Conclusion on the transport concepts . . . 61

8 Conclusion and recommendations 63
8.1 Conclusions. . . . 63
8.2 Recommendations . . . 64

A Port tariffs **67**
A.1 Port dues . . . 67
A.2 Piloting . . . 67
A.2.1 Quantity discount on piloting . . . 68
A.3 Harbour towage . . . 68
A.4 Mooring and unmooring . . . 69
A.5 Monitoring, visit reporting and VTS . . . 69
B Propulsive power prediction **71**
C Ship model **73**
Bibliography **75**

1 Introduction

The global trade of goods and resources has a long history with maritime transport. Energy carriers such as coal, gas and oil products are being moved in large volumes using ships. New energy technologies are moving in and are taking over some of the fossil fuel energy markets. The main drivers of this change are: the lower levelised cost of electricity and the need to reduce emissions as agreed upon in the Paris Climate agreement signed by most world leaders. According to this Paris Climate agreement the emissions produced by mankind should be decreased drastically in order to keep global warming below $2°C$.

Renewable energy technologies are getting more mature and are more and more common to invest in. The growing interest in these new technologies is on one hand the need to meet the climate agreements but on the other hand these new technologies have gotten more cost competitive compared to fossil fuel energy technologies. The renewable energy sources can be harvested on a local scale and power our future with wind or solar energy for example but it might not be possible to reach the maximum efficiency for these power installations. The efficiency of a solar energy installation has a strong relation to the number of solar hours per day and the solar irradiance on the location. Areas with better conditions can generate more energy with the same energy installation. Therefore, the cost of generation per kilowatt hour can be lower.

In recent years renewable energy has seen a tremendous growth and large improvements have been made. It is expected by many that solar energy is the cheapest source available in the market. In September 2016 a consortium of Chinese and Japanese companies placed a bid for 2.1 eurocent per kilowatt hour in order to provide 350 megawatts capacity with a solar farm in Abu Dhabi[1]. This is by far the lowest bid ever. There are more ultra low-cost solar farms which achieved a price of 3.5 eurocent per kilowatt hour. It is expected that this trend will continue to bids maybe even below 1 or 2 eurocent. The current energy markets in Europe for fossil fuels, coal and gas cost approximate 5 - 6 eurocent per kilowatt hour excluding environmental cost.

These new developments create an opportunity for new business concepts. On a daily basis energy is shipped in large volumes by ships, pipelines and other transportation modes from regions with large energy resources to regions with major load centers, such as Europe. This business can be expanded to shipping of sustainable generated energy because of the gap for the cost to generate energy between regions.

The challenge with the transport of energy is the form in which it is supplied. Most renewable energy sources generate electric energy for transport purposes this electric energy has to be stored. A common way to transport electric energy is through an electric energy power grid. In this research other modes of transport are assessed as a power grid is not always possible or other transport modes could provide a better cost solution.

In this research a concept study is made in the transport of electric energy. It is assumed that the energy is supplied to a port and is after transport delivered in a port. The delivery and supply is considered to be electric energy.

1.1. Research question

In this report a study is made in the possibilities of storage and shipping of (renewable generated) electric energy over a range of distances. The transport of energy is performed with ships as these allow for bulk transport at a low cost. The transport chain is set to start and end in ports. Therefore, the energy generation

[1] *Fortune Magazine* - A Jaw-Dropping World Record Solar Price Was Just Bid in Abu Dhabi(Fehrenbacher [23])

system is not designed but a cost for the energy supplied in the port is estimated based on market research in which the cost of (renwable) energy generating systems is analysed.

Based on these delineations the main research question is:

Is it possible to ship electric energy which is delivered in a port between areas of generation and consumption over a fixed distance with the use of a ship and deliver it for a levelised cost of electricity (LCOE) which is competitive in the market of unloading.

To give an answer to the main research question a number of sub questions is formed. These questions are listed below:

- What are effective alternative energy carriers to transport electric energy from source to consumer.
- What are the driving parameters for the transport of energy with a ship
- What are the current energy markets
- Define a concept operation and ship design

In this report a concept and feasibility study in the transport of electric energy is performed. The goal is to calculate possible costs for which energy can be delivered in the port of unloading with a confidence interval. To model the uncertainty a Monte Carlo approach is applied to get a better understanding of the chance that a design meets the design criteria for a set of input parameters.

The research project within Damen Shipyards to study the possibilities of transporting electric energy consists of two projects. This research and a research by Rens Reiff. He is working on the in-depth technological side of energy storage for storage systems that can be transported.

1.2. System borders

The research of energy transport can be very broad. Therefore, the research is focussed on the transport of energy with a ship. The transport concept is tested and compared to other transport systems with a fixed connection, such as cables. It is assumed that the energy is delivered in the port of loading by an electric cable and in the port of unloading the energy is delivered to the electric grid. This means that we are only looking into the transport and not electric grid behaviours.

For this study systems are assessed on a high level. In-depth operations of systems are not analysed. During this project another student of the TU Delft, Rens Reiff, has made in-depth study of storage systems in which he studied the physical working principles of storage systems including detailed calculations on the systems.

1.3. Bookmark anchor

The methodology and model which are used in this research are explained in Chapters 2 and **??**. In Chapter 3 the energy markets are discussed in which an answer to the competitive price will be presented. The transport of energy by a physical connection is discussed in Chapter 4. The steps taken to asses the possibilities to transport energy with a ship are discussed in Chapters 6 to Chapter **??** in these chapters the storage options are described and two different transport concepts are discusses. In Chapter 8 the conclusions and recommendations from the project are presented.

2
Methodology

In this chapter an explanation in the methodology and the used scenario's is given. First a description of the used concepts is given. Afterwards a description of the applied methodology is given. The chapter closes with an explanation on the scenarios which are used to describe the different business cases.

2.1. The main concepts used in this research

During this study several main concepts are used. A short description of these concepts is given in this section. It will start with the concept of storage efficiency. Followed by the levelised cost of electricity.

2.1.1. Conversion efficiency

In this study a concept for bulk energy transport is developed the energy is supplied in an electrical form and has to be stored during transport. This means that the electricity has to be converted to a storage medium and back.

Conversion efficiency - from energy to carrier
The first step is to convert electrical energy in a storage form. For example electricity can be stored in a battery (electrochemical storage) to charge a battery more energy is needed as can be stored.

Conversion efficiency - from carrier to energy
The energy which is stored in a carrier has to be regenerated in order to be used as electrical energy. In the regeneration process energy is lost if not all energy can be regenerated from the storage form.

Storage efficiency
Efficiency is a term which is used a lot in the calculation of energy storage devices. Often it is called round trip efficiency or conversion efficiency. To transport energy it has to be stored in some manner for most cases. In this research the focus is on electric energy generated with renewable resources or fossil fuels. The storage of energy consumes electric energy and saves it in a still to be determined form, after storage the energy is supplied back to the grid. The ratio of the energy put in (in kWh) to the energy retrieved from the storage (in kWh) is called round trip efficiency (in %).

When batteries are considered we are always talking about round trip efficiency but when other storage mediums are assessed the steps from energy put in the storage and retrieved from the storage are taken apart. When considering the conversion from electric energy to storage medium the ratio of energy put in (in kWh) to the energy stored in the energy carrier (in kWh) is called the conversion efficiency (in %). The same goes for the conversion from storage to energy put back in the grid. In that case the total energy stored in the carrier at the moment of conversion is compared to the energy which is put back in the grid (in kWh) this conversion efficiency is expressed in percent as well. During the storage period an energy carrier can loose energy due to self-discharge, heat loss or evaporation. This loss is called self-discharge loss and is expressed in percent per day storage. These three efficiencies together form the round trip efficiency. This efficiency can be calculated by multiplying all factors with each other.

Round trip efficiency
Above the storage efficiencies have been described. If these three efficiencies are multiplied by each other the round trip efficiency is calculated. For a storage solution this round trip efficiency is trivial as it describes the overall efficiency of the system.

2.1.2. Levelised cost of electricity

The levelised cost of electricity (LCOE) is an economic calculation to compare different methods of electricity generation on a consistent basis. Different technologies have other cost-breakdowns over their lifetime by expressing them in the LCOE form it is possible to make a comparison. The LCOE takes all the cost involved during the lifetime of an asset and compares this to the electricity generated over its lifetime. This calculation is made upfront of an investment and assumes the production costs and the electricity prices to be known and stable.

Another imporatant part of the LCOE calculation is the discounting of the cash flows by a given discount rate by this way the net present value (NPV) is calculated. This rate can have a large influence on the LCOE costs certainly if the capital investment is large. Equation 2.1 shows the LCOE calculation. The subscript 't' denotes the year in which a investment, expenditure or sale is made.(Agency [5])

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n}(I_t + O\&M_t + F_t + C_t + D_t) * (1+r)^{-t}}{\sum_{t=1}^{n} E_t * (1+r)^{-t}}$$

$$\begin{aligned} I_t &= \text{investment in year t} \\ O\&M_t &= \text{operations and maintenance expenditures in year t} \\ F_t &= \text{fuel expenditures in year t} \\ C_t &= \text{carbon cost in year t} \\ D_t &= \text{decomissioning cost in year t} \\ E_t &= \text{electrical energy generated in year t} \\ r &= \text{discount rate} \\ n &= \text{expected lifetime of system} \end{aligned} \tag{2.1}$$

Throughout the report this equation is used to compare different energy transportation concepts to each other. The unit for the LCOE in the report is megawatt hours (MWh). Every business case is presented and compared with the discount rates 5%, 7% and 10%.

2.2. Methodology

To design the transport solution which delivers electric energy with the lowest levelised cost of electricity a combination of a micro analysis and a macro analysis is used. In Figure **??** a schematic overview of the approach is presented.

In the first step a detailed micro analysis is performed, in which in detail different steps of the transport chain are analysed. Per part of the chain developments in cost and efficiency are given for the long term and short term.

To calculate the possibilities for the energy transport different transport concepts are calculated and tested. Transport of energy can be done with or without a physical link. A physical link could be a cable for electricity or pipeline for a fluid or a gas. Without a physical link transport is possible with a ship, truck, train and so fort in this study for the transport without a physical link only the ship is considered to be a feasible option. This is chosen because of the large scale (distance and capacity) and focus on a low LCOE.

The delivery of energy in a port can be seen as a overall system, which can be devided in smaller sub-systems such as energy production, transport, energy regeneration and storage. Figure 2.1 shows an overall view on the system.

In this system all the blocks have a relation to each other. To transport energy it has to be stored on board of a ship. Storage can be done in many forms and is discussed in Chapter 6.

The research is split over four major blocks: markets, transport, storage, concept design. In which the concept design has the most focus. The aspects of theses blocks are briefly described below.

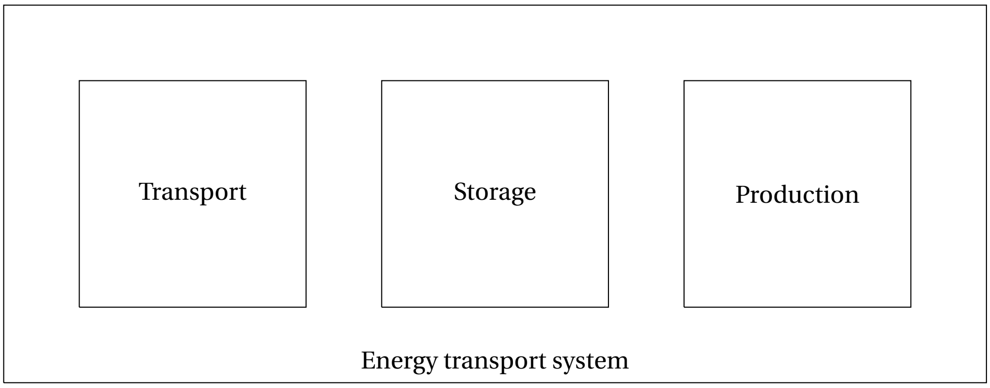


Figure 2.1: Energy transport system

2.2.1. Markets

Before the energy is delivered a few steps are made. The energy is produced, stored, shipped and regenerated. This flow has some resemblance to the structure of the research. The goals of delivering energy for 100 euro per megawatt hour, as defined by Damen Shipyards, has to be validated. This validation is made with a market research in which the energy markets are assessed for price levels and production capacity. This price of 100 euro per MWh is a market price.

The market research also tells more about the financial possibility of the concept. For example if the cost to produce the energy is 50 euro per MWh and the transport, storage and regeneration cost 50 euro per MWh the total cost to deliver the energy in the delivery market is 100 euro per MWh. If the market research shows that the average spot market price of energy is more than the cost of 100 euro: the delivery of energy to another market could be attractive. Therefore, the cost price of energy is trivial in this research. In order to get better knowledge of the possibilities different energy supply forms are studied, fossil and renewable.

Research questions in this phase are:

- What is the market for energy and what is the size
- What does a megawatt hour cost
- Who are stakeholders

2.2.2. Storage

Energy can not always be transported directly or transport in its current form is not the most suitable. Therefore, energy has to be stored and/or converted. The focus of this step is on defining possible storage concepts, including: cost, capacity, feasibility, discharge rate.

2.2.3. Transport

Energy is usually not produced at the same location at which it is consumed, so it has to be transported. The transportation of energy is the second phase in this study. The main focus in this research is transportation by ship, whoever ships do transport large amounts of energy but energy is also transported by physical connection like pipeline (gasses and liquids) and cable (electricity). To test the final maritime concept it is tested against other forms of transport.

Focus for this part is on:

- How is energy transported.
- What is the cost for transportation

2.2.4. Concept design

The transport of energy with ships is a mature business, but this is mostly oil and other fossil fuels. The transport of electric energy by ship is a new concept which is not common. Most likely the design of the concept will have a lot of uncertainties.

The major uncertainties are expected in the cost of storage systems, cost of conversion systems, cost of regenerations systems and energy conversion efficiencies. To be able to give a sound answer on the question whether it is feasible to ship electric energy an approach is chosen in this research in which the input parameters are randomly distributed over an input range. With this approach it is possible to give a range in which the results of the design are applicable considering the set boundaries on the input parameters.

3
Energy markets

3.1. Current energy markets

Since the beginning of the industrial revolution in the late 18^{th} century the consumption of energy has increased rapidly. The main resources to fuel this growth were the ever expanding fossil fuel economies. The developed countries are large consumers of energy and are large scale energy importers as they cannot produce their energy demand themselves. Traditionally this has been the trade in coal, oil and gas. As renewable energy sources, such as solar, wind, tidal, biomass and geothermal, are getting better to harvest a growth in this trade can be seen. In this section the current energy markets will be briefly described to sketch a size of their businesses.

3.1.1. Coal based energy

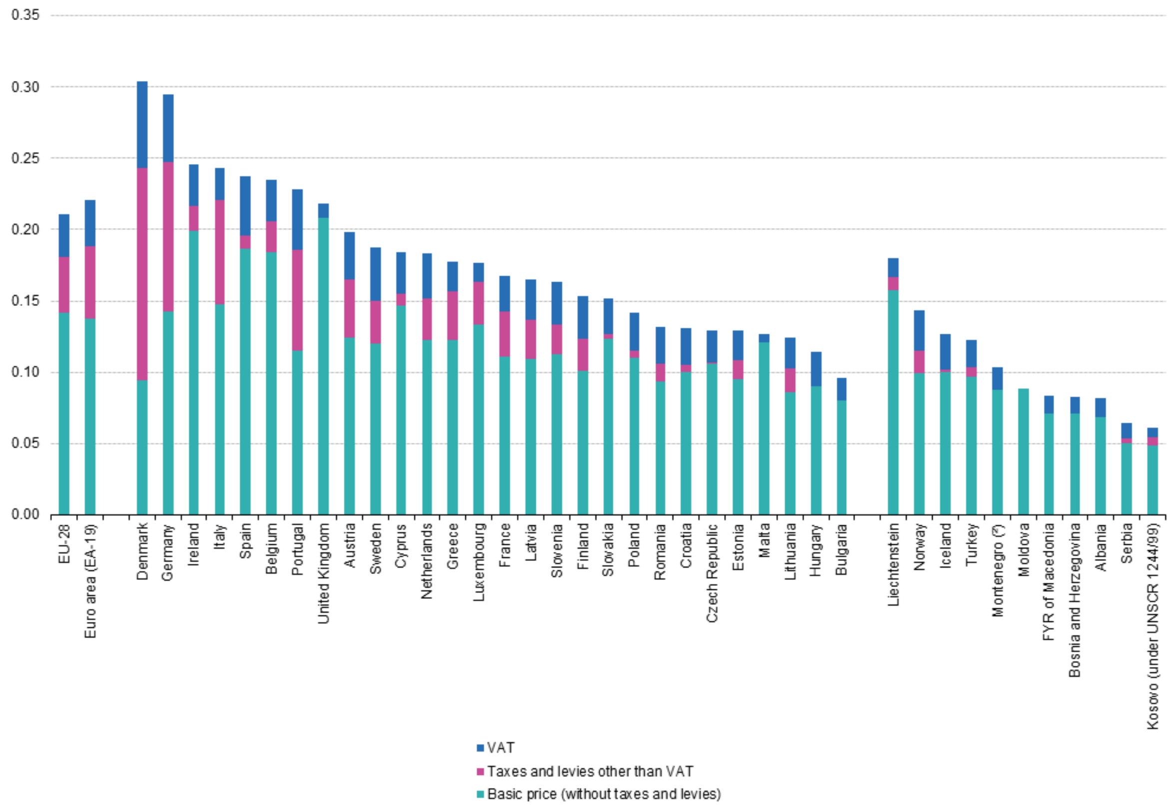
In 2014 the global coal trade accounted for 1,400 million tonnes (MT), with the majority flowing from the two largest exporters: Indonesia (417 MT) and Australia (287MT). The largest importers for coal are China, India, Japan, South Korea and Europe. Although the coal import has a considerable volume the largest share of the production is used for domestic consumption. The coal is used in power generation and industrial applications. The last ten years more than 30% of the electricity consumed globally is produced with coal.(p.l.c. [52])

The Netherlands imported 52.1 MT in 2014 (Glo [1]) and are fully depending on imports for their energy generation with coal, which accounts for 28% of the total in 2014. The share raised to 35% in 2015 due to lower prices for coal on the global markets. The renewable energy sources are growing in the Netherlands but the majority of electricity is generated by fossil fuels.

Coal fired energy plants are amongst the largest polluters in the world. The new energy plants in the Netherlands have a substantial higher efficiency of 46% compared to average global efficiency of 30%. Although this much higher efficiency the emissions of the plants are considerable. The newest energy plants emit 743 gCO_2/kWh, a gas fired energy plants emits 298 gCO_2/kWh, which is much higher than alternative fossil fuels and not to mention the renewable energy sources. A windmill has a CO2-emission equivalent of 12 gCO_2/kWh. The industry points out that the emissions of a coal fired energy plant can be reduced with Carbon Capture and Storage (CCS) this would eliminate the emissions of the plants because all emissions are captured and stored in old gas fields. In the region of Rotterdam several options for storage are suitable but gas fields have a limitation on their capacity. A major drawback of the CSS is the high demand for energy which ranges between 25% to 40% of the generated electricity. The estimated increase of the cost are between 21% to 91%. In 2015 a demonstration project capturing 1.1 million ton of CO_2 from the coal fired power plant in the port of Rotterdam per year should have started but it had been delayed. Mid 2017 the project to capture carbon has been terminated.(Financieel Dagblad [24])

The challenges for the coal fired power plants are not over and their future is grim as the Dutch government plans on closing them before 2030.(VVD and CDA and D66 and ChristenUnie [62])

Energy generated in a coal fired power plant is in the current markets a cheap and reliant energy source. Large energy plants in the Netherlands can produce a kilowatt-hour of energy for prices in the range of 5 to 6 eurocent. By 2030 this price can be anywhere in the range of 6 to 11.5 eurocent if it assumed that the plants do not close but they do capture carbon emissions as demanded by government agencies.



(¹) Annual consumption: 2 500 kWh < consumption < 5 000 kWh.
(²) Taxes and levies other than VAT are slightly negative and therefore the overall price is marginally lower than that shown by the bar.

Figure 3.1: Electricity prices for household consumers, second half 2015 (EUR per kWh) YB16(Eurostat Statistics Explained [22])

The cost at which electric energy is sold to households and industrial consumers is sold at a different price level of the cost of the energy plant due to transmission systems, taxes and levies. If the base price is considered excluding taxes, levies the price of a kilowatt-hour of energy would cost a Dutch household consumer in the Netherlands 12 eurocent per kilowatt-hour as visualised in Figure 3.1. Industrial consumers pay a lower base price of 7 cent per kilowatt-hour (Figure 3.2).

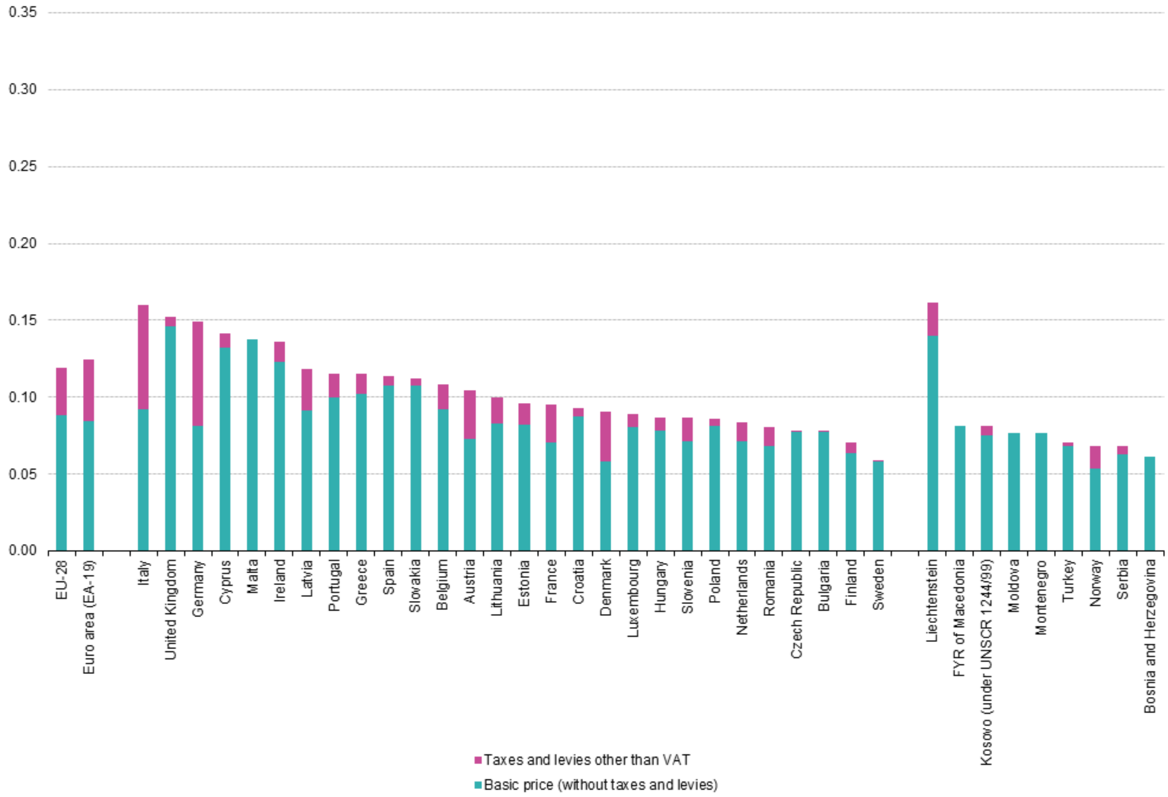
3.1.2. Gas trade

Natural gas is accountable for a quarter of the world's energy demand, of which 10% is liquefied natural gas (LNG). The LNG market saw a growth of 13.1 MT in 2016 to a volume of 257.8 MT. This total volume is produced by only 18 countries. Asia-Pacific countries represented 38.6% of total exports, the Middle East has a second position with 35.3%. Qatar remains the single largest producer of LNG with a share of 30.0% of total global exports.

The largest consumers of LNG are located in the Asia-Pacific and Asia basin with a consumption of 72.4% of the world's supply of LNG. The drivers of this consumption are Japan, South-Korea and China (rep. 32.3%, 13.1% and 10.4%). Europe is a growing market for LNG but is far smaller than the Asian regions due to large natural gas supplies in Europe and Russia.

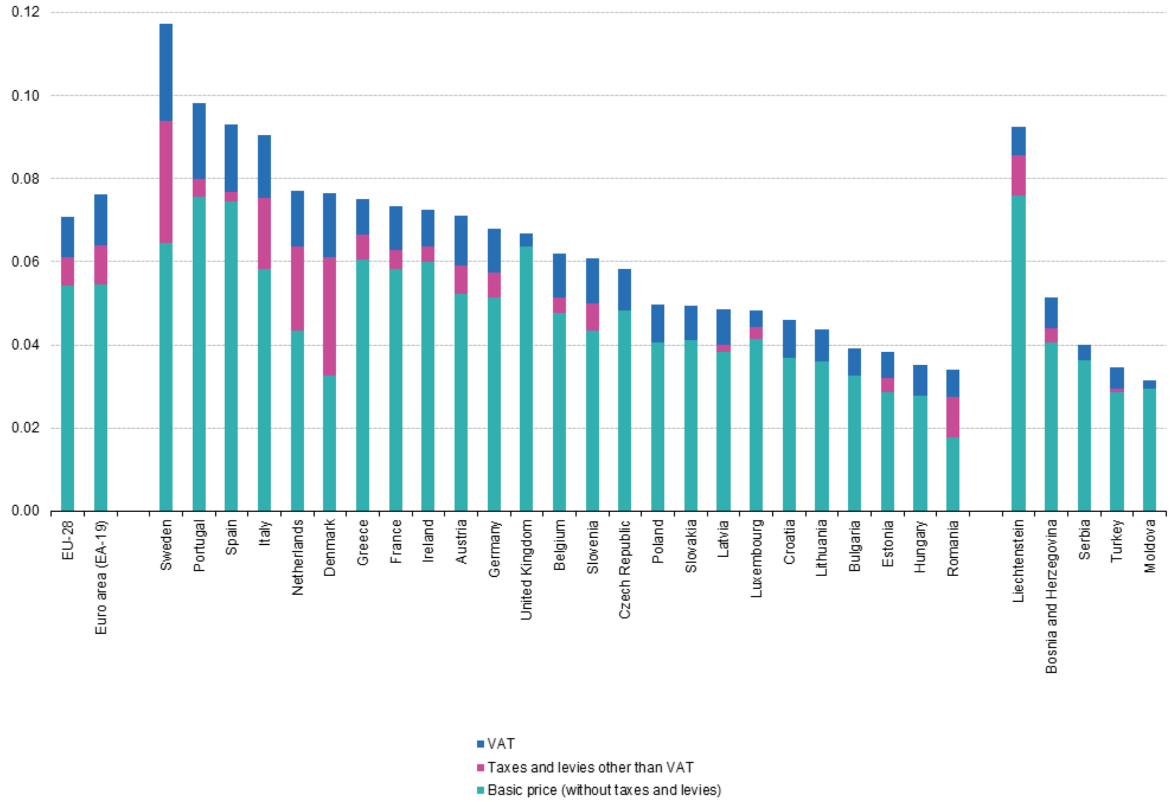
In 2015 the Asian and Pacific regions remained the driver of demand growth however, nuclear restarts in Japan and economic weakness in China have slowed the growth of LNG demand. Unless the slight higher demand in Europe. The growth of supply in 2015 is mainly driven by Australia with an increase of 15 MT. The trade between the basins is visualised in Table 1. The trade in the Asia-Pacific is the largest with Japan as driving force with trade from Australia and Malaysia, respectively 22.6 and 15.4 MT.

In the Netherlands natural gas costs on average 7.5 eurocent per kWh for households which is about the European average(Eurostat Statistics Explained [22]). Figure 3.3 shows the prices of electricity for European households. Industrial consumers can buy natural gas at much lower rates in the Netherlands in the order of 3 eurocent per kWh of energy stored in gas as can be seen in Figure 3.4.



(¹) Annual consumption: 500 MWh < consumption < 2 000 MWh. Excluding VAT.

Figure 3.2: Electricity prices for industrial consumers, second half 2015 (EUR per kWh) YB16(Eurostat Statistics Explained [22])



(¹) Annual consumption: 20 GJ < consumption < 200 GJ. Finland: not available. Cyprus and Malta: not applicable.

Figure 3.3: Natural gas prices for household consumers, second half 2015 (EUR per kWh) YB16(Eurostat Statistics Explained [22])

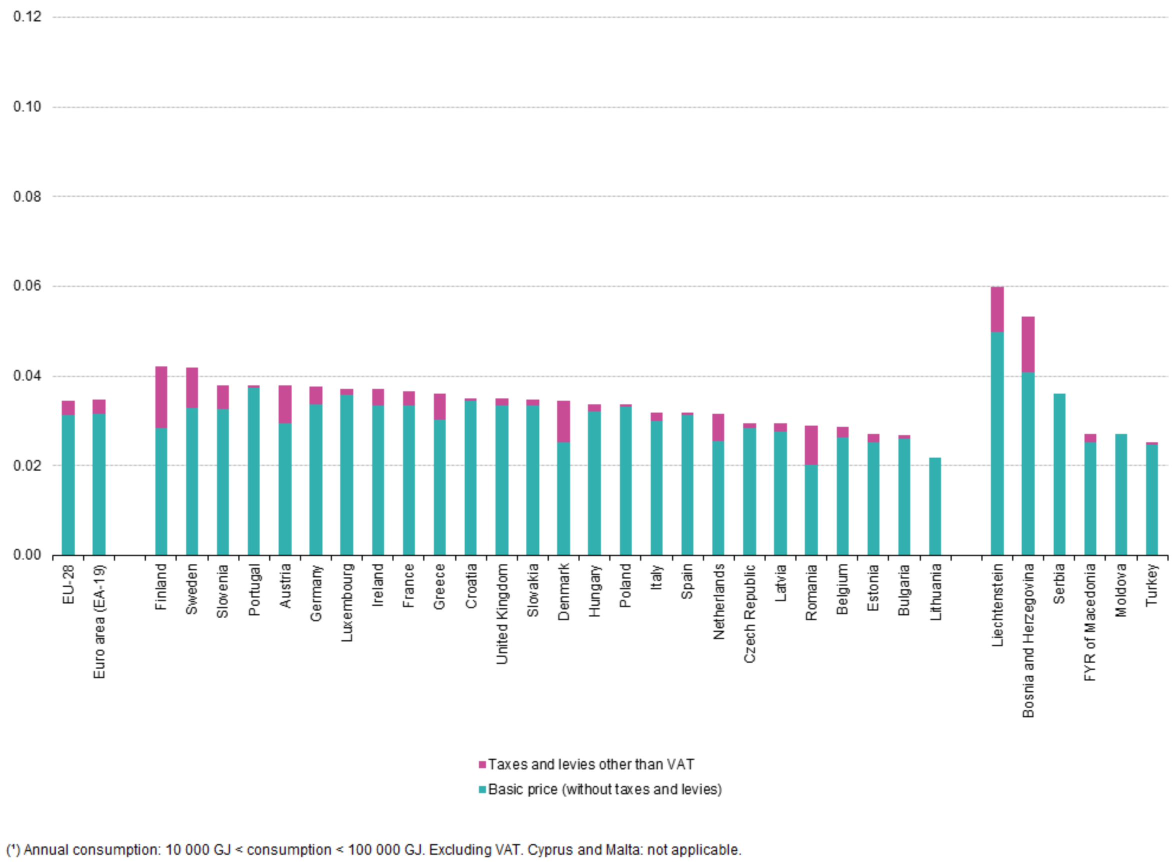
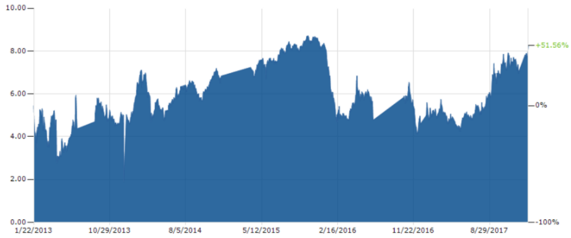


Figure 3.4: Natural gas prices for industrial consumers, second half 2015 (EUR per kWh) YB16(Eurostat Statistics Explained [22])

(a) CO_2 European emission allowances since 2009(Euro ton/CO_2)



(b) CO_2 European emission allowances 5 year history (Euro ton/CO_2)

Figure 3.5: CO_2 European emission allowances charts (Business Insider [14])

The gas which is shipped around the globe to local markets can be used for electricity generation. The energy stored in gas can be converted in electric energy through a steam or gas turbine. One of the reasons why markets are shifting to more consumption of gas over coal is the significant reduced emissions if gas is used. When gas is used to generate electricity 45% less CO_2 is emitted for the same amount of energy if it is compared to a coal-fired power plant.(Agency [6]) Electric energy generated gas-fired power plants is linked to the natural gas price. Capital costs for gas-fired power plants have been substantial lower than for coal plants. Hence gas-fired power plants are the cheapest power source in many countries.

If gas is used to generate electricity in a power plant the conversion efficiency of the energy in gas to electrical energy is about 42% for a turbine generator and operational cost and maintenance is 0.5 cent per kWh(Mekhilef et al. [49]). The cost of gas for industrial consumers is 3 cent per kWh if this is multiplied by the efficiency of a turbine generator a cost of 7.14 cent per kWh is derived for a kWh of electric energy generated by a gas fired power plant.

3.1.3. Environmental cost fossil fuel energy markets

On the 4^{th} of November 2016 the Paris Climate Agreement came into force. The goal of the agreement is to keep global warming well below 2.0°C by reducing greenhouse gas (GHG) emissions. The parties that signed the agreement are considering the use of carbon pricing on global GHG emissions.

Prices are being put on carbon emissions as these cause global warming. Many people have already put a price on the GHG emissions and estimations of the cost have a large deviation. If the prices which are being put on the emission by governments a wide range is observed. In 2017 the range ran from less dan US$1 up to US$126/tCO_2e. The average price of the GHG emission increased but about three quaters of the covered emissions were priced below US$10/t$CO_2$e. Higher prices for emissions will be needed to increase the economic impact of carbon pricing.(World Bank; Ecofys [64])

The policy governments adopt has lots of variations. In Europe all countries have implemented the European Unions Emission Trading Scheme (EU ETS). This system makes it possible to charge emission throughout the European Union but the prices which are paid for the emission rights are very low. Figure 3.5 shows the 5 year price for the emission rights and the full history of the commodity. The price of an emission right started at 15 euro on October 2009 but has decreased to 8 euro/tCO_2 with values below 4 euro/tCO_2 on some trading days.

Some countries have adopted taxes on CO_2 alongside the EU ETS. The design concept has a focus on the Netherlands and CO_2-taxes have not been adopted in the Netherlands yet. To put a price on the emission of CO_2 a few scenario's are defined to calculate the cost of energy including the environmental cost. These scenario's are:

1. The price of the EU ETS at end 2017 (8 euro/tCO_2) with an increase of of 5% per year. This is the low carbon tax scenario.

2. A price of 25 euro/tCO_2 with a yearly increase of 5% (Luckow et al. [46])

3. The highest carbon tax rate in force in 2018. This is the rate of Sweden 107 euro/tCO_2 (US$126/t$CO_2$) with an increase of 5% per year as well

4. The last scenario is the price which should be put on carbon emissions according to some scientist: 190 euro/tCO_2 with a yearly increase of 5%.

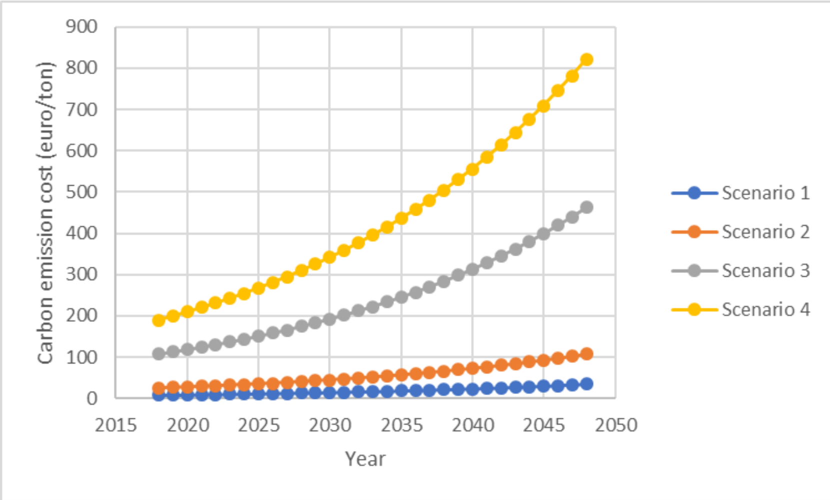


Figure 3.6: Scenarios for carbon emission cost (Euro /tCO_2)

Over the lifetime of a project the carbon emission cost are expected to rise. The listed scenarios are visualised in Figure 3.6. The listed scenarios are included in the cost calculation of fossil based energy sources. With this calculation it will be possible to compare the fossil fuels to renewable energy sources including their social carbon cost.

The data on the emission per kilowatt-hour of energy for coal and gas fired power plants is added to the cost (resp. 743 gCO_2/kWh and 298 gCO_2/kWh). For the first scenario with a low carbon cost the coal based energy plant is cheaper than a natural gas power plant with a LCoE of 8.15 cent per kWh if the discount rate is 5% if the discount rate increases to 7% the natural gas power plant is more cost effective. As soon as the second scenario comes into play the natural gas power plant is cheaper than the coal based energy plant, the results are presented in Table 3.1

Table 3.1: Levelised cost of electricty for fossil fueled energy plants including carbon cost scenarios

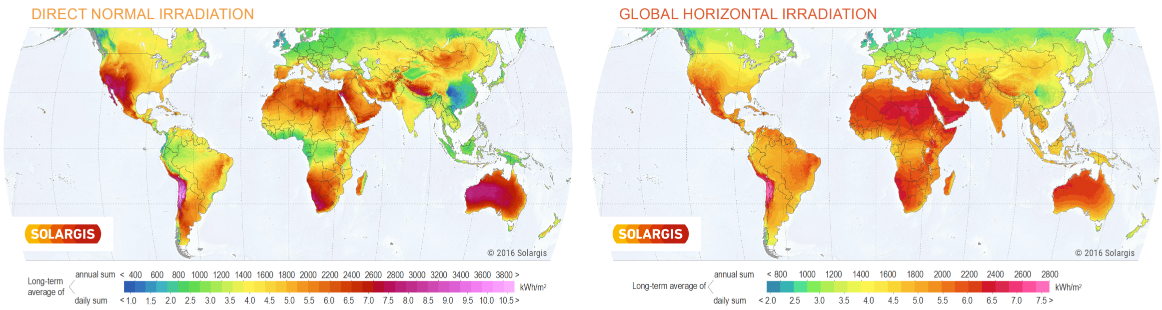
Source	Discount rate 5% Coal	Natural gas	Discount rate 7% Coal	Natural gas	Discount rate 10% Coal	Natural gas
Scenario 1	8.15	8.20	8.35	7.93	8.72	8.53
Scenario 2	10.51	9.15	10.54	9.20	10.70	9.33
Scenario 3	21.94	13.74	25.27	13.45	20.22	13.15
Scenario 4	33.51	18.38	31.83	17.74	29.86	17.01

The calculation of the LCoE including carbon cost shows that in most scenarios and discount rates the natural gas power plant performs better than the coal fired power plant. This calculation does not include the cost of emission of SO_2, NO_x, CO and PM. If these were included the cost of coal would increase even more but as the natural gas power plant already outperforms the coal these cost are not added to the calculation.

The concept design made in this research will be compared to the fossil fuel power plants as well as other renewable energy sources. The values taken for the comparisson with the fossil power plants will be the values for the natural gas power plant as it outperforms the coal fired power plants except for the lowest carbon cost and the lowest discount rate combination.

3.2. Renewable energy markets

Energy generated with natural resources which are constantly being renewed are renewable energy resources and have been given a lot of attention in recent years because they are getting more cost effective, besides they produce no harmful emissions and pollution unlike conventional fuels. Hydroelectric energy is in use since the middle of the last century on an industrial scale but the use of other renewable resources has a shorter history. Due to drastic cost and efficiency improvements these energy resources might be serious competitors for the conventional energy industries in the decades to come.



(a) Direct normal irradiation (b) Global horizontal irradiation

Figure 3.7: World solar resource maps(Solargis [57])

In this section a short description of the most relevant energy resources is given.

3.2.1. Solar power

The sun generates an abundance of energy which is very predictable. This energy is higher in areas 20° to 30° north and south of the equator as can be seen in Figure 3.7. The solar energy is given as normal irradiance and horizontal irradiance. Together these form the solar power available in an area. This energy can be harvested with different methods at this moment photovoltaic is the most common technology for most applications. The light can also be concentrated and than be used to heat a driving fluid, concentrated solar power (CSP), which is only applied in large installations.

Photovoltaic

The photovoltaic (PV) panels can be seen on many houses or large solar farms nowadays and these are the most used solar power technology worldwide.

The solar cells convert sunlight into direct current electricity which can be used to charge a battery or supply energy to the power grid. The photovoltaic material in the cells form the core material for the PV panel. When the sunlight hits te panel a current starts moving between the copper wires on the panel.

New developments in the field of PV are on going and efficiencies are expected to increase up to 35% which is close to the theoretical maximum efficiency for a PV installation. With this increase of the efficiency it is possible to generate more energy with the same amount of surface area. This together with the ever increasing production capacity leads to a drop of the price for electricity generated with PV panels. It is expected that the cost for a kWh of electric energy will cost 1 to 2 cents on some locations. This depends on the intensity of the solar power for the location, hours of sunlight per day, the cost of land area.

The amount which a photovoltaic panel can generate is based on the solar irradiation but also on the working temperature. If a panel gets too hot the production potential decreases. The regions with the largest PV potential are the Himalaya and Southern Andes due to the combination of a very high solar irradiation and low temperatures(>1,800 kWh/kW)(Kawajiri et al. [40]). Figure 3.8 shows the potential a photovoltaic system can produce per kilowatt of installed capacity if the irradiation and temperature effects are taken in account. Based on this figure interesting generation areas for a north-south transport concept towards Europe would be: off the coast of Morocco, South Atlantic ocean east of Brazil, Namibia for example. These locations all lay in the band 20° to 30° north of the equator and 20° to 30° south of the equator. If the information of the areas which are suitable for solar farms is combined with data on seaports a seaports which are attractive for the concept can be selected. Figure 3.9 shows the locations for solar plants which are suitable for the concept as they are located close to sea ports. For this research the ports in Morocco and southern Africa are of interest as transport to the Netherlands is chosen and this is the shortest vertical line. The typical distances are in the range 2,000 to 2,500 nm and the range of 5,000 to 5,500 nm. These locations would offer a higher yield per panel which reduces the cost per kilowatt-hour which could make the earlier mentioned 1 or 2 cent per kilowatt-hour possible.

Concentrated Solar Power

By concentrating direct-beam solar irradiance a liquid, gas or solid is heated and in a downstream process this heat is used to generate electricity. The operating principle of the concentrated solar power (CSP) technology

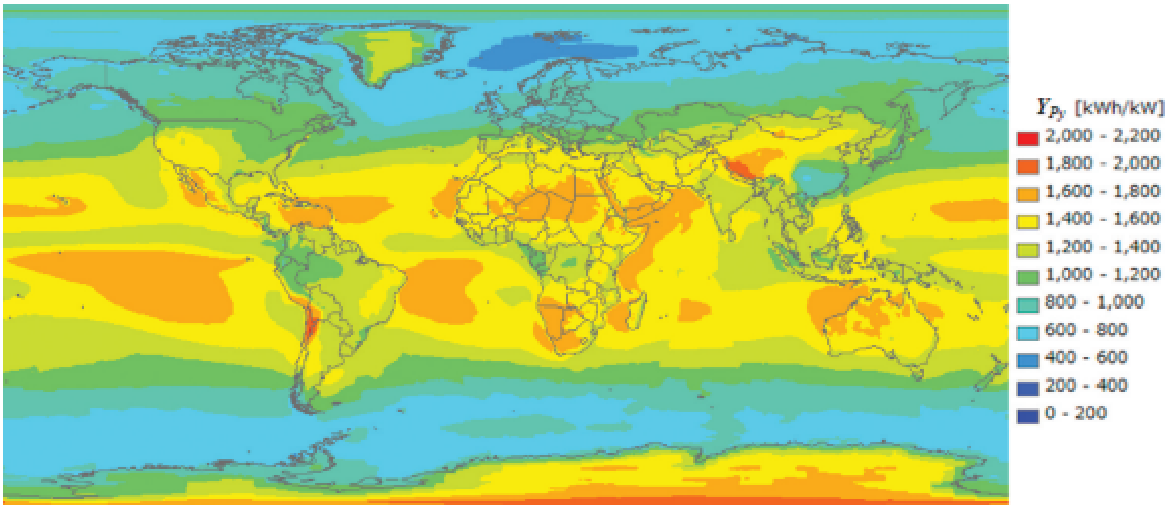


Figure 3.8: Global potential map of PV energy generation by c-Si PV module.(Kawajiri et al. [40])

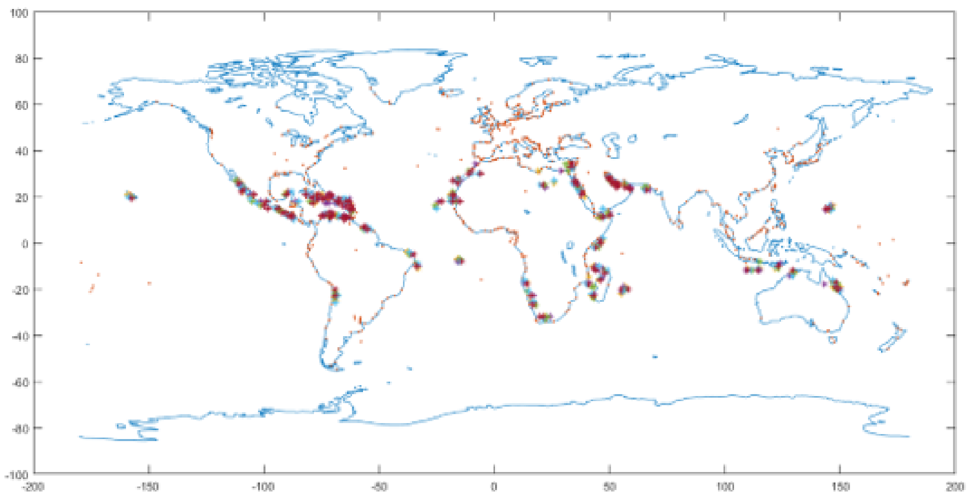


Figure 3.9: Possible locations for large scale solar farms close to seaports

shows a lot of resemblence to conventional fossil fuel fired power plants but it uses solar power instead of burning fuels.

The system uses direct sunlight or Direct Normal Irradiance (DNI) not dispersed by clouds, dust or fumes in the atmosphere. To operate properly a site needs to get a lot of direct sunlight. Values in the order of 2,000 kWh/m^2/year minimum or 2,800 kWh/m^2/year for the best locations is suggested.

Because a CSP power plant generates energy with heat it is possible to store energy in the conducting material. This energy can be stored for peak loads or for medium term storage (3-7 days).

Although CSP is able to generate more energy per square meter than PV systems it is only applicable for large industrial scale power plants. The prices for CSP will be higher compared to PV in the range of 7-8 cents per kWh but this includes the possibility for energy storage.

3.2.2. Wind power

Wind energy is the largest source of renewable energy in the Netherlands(voor de Statistiek [61]). The growth of this sector is certainly offshore tremendous with ever bigger wind parks being built in the North sea. In the Netherlands wind energy is produces 1.4% of the total amount of energy produced in 2016. The wind energy is harvested onshore and offshore (resp. 72% and 28%).(Centraal Bureau voor de Statistiek [15])

More wind energy is generated onshore but the most improvements and growth is expected from the offshore wind market. The first offshore wind farm was built in 1991 in Denmark with a capacity of 4.95 megawatt. At the end of 2016 the total offshore wind capacity in Europe was 12,631 megawatt with 72% installed in the North Sea.(Europe [21])

By going offshore wind turbines can generate more energy due to stronger winds and it offers countries with a limited land area a source of clean energy with the option to use land area for other purposes. The other benefit of offshore wind is that it allows for a larger economy of scale from large wind turbines which reduces the capital investment for a delivered capacity.

Although new contracts for offshore wind parks see still lower bids of 0.044 euro per kWh but this is only for the energy generated by the wind turbine. If the total cost for the electricity are taken in account with the installation and the electric cables to the shore a price the levelised cost for electricity is is about 0.14 euro per kWh. Bloomberg expects the cost for wind energy in Europe to drop to 0.085 euro per kWh in 2035.(Bloomberg [12]) Wind energy onshore is less expensive than offshore wind energy but due to a high population density far more wind energy in the Netherlands can be harvested offshore than onshore. Furthermore, offshore wind energy does not suffer of the 'not in my backyard'-problem many people tend to have towards onshore wind energy.[1] But the cost of onshore wind energy is comparable or competitive to fossil fired power plants at ranges. The best onshore locations can produce wind energy for 6 cent per kilowatthour in the Netherlands this could have a potential generation of 37 TWh. The total potential generation for the Netherlands is 148 TWh and most wind turbines could produce energy for less than 7 cent per kWh and a 92.5% of the energy could be produced for 8 cent per kWh. In 2015 only 4.6% of the generation potential was exploited (McKenna et al. [48]) .

3.2.3. Geothermal energy

Heat from the earth is a provider for energy for many applications, from complex power plants up to simple heat pumping systems for households. This heat energy, known as geothermal enery, can be found in many places.

3.2.4. Hydro power

The most mature renewable energy technology is the hydro power. With the use of dams in rivers large basins with water are created in the last century. By controlled releasing of the water over a height difference the energy in the water can be harvested with turbines. This technology allows for large amounts of energy but it has a strong geographical requirements due to the use of dams. Therefore, not many locations are suitable for this technology.

Furthermore, the investment costs are large and the cost per kWh are not likely to get any lower than the are at the moment. This technology has a proven track record but it is not expected to grow much in the decades ahead.

[1] This does not express the personal opinion of the writer.

3.2.5. Price development renewable energy markets

The energy markets are highly volatile markets which are analysed very much. With all this research into prices and movements of the market it is still not known precisely how they will develop. New technologies such as improvements on photovoltaic panels, more cost effective wind turbines, improved fossil fuel technologies or new acquired resources for coal and gas have a influence on the supply side of the equation. On the other side of the equation we find changing markets, growing consumption through economic development.

This combination of supply and demand have an influence on the price which is paid for energy. Prognoses and estimations for future development of both markets are made on a daily basis.

Solar energy in optimal locations will most likely offer the most energy for a low price as bids in the Middle East already dive the 3 cent per kilowatt-hour figure with bids below 2.5 cent. It is assumed that based on the historic development in the solar energy industry and the research effort which is put into it by large manufacturers the price for solar energy can reach the 1 or 2 cent per kilowatt-hour value before 2030. This does require optimal locations for the panels.

3.3. Conclusion on the energy markets

The goal of this chapter is to give an answers: what are the energy markets and what does a kilowatt-hour of energy cost. An answer to these questions in necessary to define a framework in which the transport concept has to operate.

3.3.1. Conclusion on energy markets in the Netherlands

The prices for fossil fuel power plants have a strong relation to the cost of their emissions. In this study only the cost of the CO_2-emission are included to the cost for power generation. From that calculation it is concluded that a natural gas power plant is better performing than coal fired power plant. Therefore, the concept will be tested against the natural gas power plant. The reference values for the natural gas power plant are summarized in Table 3.2.

Table 3.2: Reference LCOEs natural gas power plant

	Discount rate		
	5%	7%	10%
Scenario 1	8.20	8.33	8.53
Scenario 2	9.15	9.20	9.33
Scenario 3	13.74	13.45	13.15
Scenario 4	18.38	17.74	17.01

If the reference LCOEs for the natural gas power plants are compared to renewable energy sources the offshore wind energy for example already outperforms fossil fuel for some scenarios. At the end of Section 3.2.2 the cost for wind energy as calculated by Bloomberg were given: for 2017 the estimated a cost of 14 cent/kWh and this decreases to 8.5 cent/kWh by 2035. The cost for wind energy in 2017 can only compete with fossil fuel if the high carbon taxes are charged which are only charged by Sweden (scenario 3) or should be charged according to some scientists (scenario 4).

The cost of wind energy in 2035 can compete with all fossil fuel scenarios. Only at the very low carbon tax rate the natural gas power plant is more cost competitive, for all other scenarios it is more expensive than wind energy.

Therefore, the concept will be tested against the natural gas power plant for all scenarios and against offshore wind energy. The cost for wind energy is depending on the year at which the concept gets into operation.

3.3.2. Conclusion on the cost of energy generation

The other important cost of energy in this concept is the cost at which energy can be generated in the port of unloading. It is found that photovoltaic solar panels can generate energy at a cost of 2 cent per kilowatt-hour(Fraunhofer ISE [25]). These two cost prices are used in the rest of this report.

The price of the solar energy is depending on the location. If a location has a higher direct and indirect solar irradiance more power from the sun can be harvested. The regions in the belt of 20° to 30° north and south of the equator are the areas with the best conditions. The distance to the Netherlands is in the order of 2,000 to 3,000 nautical miles for the northern belt and 5,000 to 5,500 nautical miles for the southern areas.

4

Fixed connection energy transport

Energy can be transported with or without a fixed connection. In this research the goal is to develop a electric energy sea transport concept based on ships so without a fixed connection. As a reference case to compare the transport concept against a fixed connection energy transport system is selected. For this concept a transmission of energy through cables is chosen. A pipeline to transport a chemical could have been chosen as well but this would mean conversion of electric energy to a chemical and back. Chapter 6 handles the chemical energy storage and will go in more detail about the large cost drivers and conversion losses of electric energy to an energy carrier and back. Besides large chemical plants would have to be built to convert the energy.

The majority of transport of electric energy is done with cables nowadays. These cables can be used for indoor energy transport up to transport between countries. The cables can be over ground, underground or subsea. The transport of energy on a large scale with cables always uses high voltage currents to reduce losses. The current maximum voltage is already higher than 1,000 kV. The energy can be transported with a direct current (DC) or amplitude current (AC). In the next sections an AC and DC system are described.

4.1. High voltage AC transmissions

High voltage AC transmissions (HVAC) have become a leading technology in electrical networks. The low voltage from generators is increased to much higher voltage levels in order to reduce expensive efficiency losses during transmission. The system uses transformers to raise the voltage level, which is a much cheaper approach than the AC/DC converter stations used for high voltage DC systems (HVDC). If the electricity is transmitted over long distances with low or medium voltages high efficiency losses occur, the use of high voltage AC systems (400 kV or more) have much lower losses and are therefore a more cost effective solution for long distances. The development of AC systems technology is focussed on increasing the transmission voltage. When the voltage level is doubled the transmission capability increases by a fourfold. So in most countries the development of the electricity grid is characterized by new layers with higher and higher voltages.

Today, the highest voltage HVAC used is around 800 kV for overhead lines. The Canadian company Hydro Quebec, for instance, operates a massive 735 kV transmission system using overhead lines; the first line was in operation 1965. 1,000 kV and 1,200 kV AC have been tested in several test installations and even short-term commercial applications. There are several challenges involved in building such lines and new equipment needing to be developed includes transformers, breakers and switches.

A major advantage of an AC transmission system is the flexibility with connecting loads and generators to the grid along the transmission route. If the system passes highly populated areas with many local generator it is possible to connect these to the grid. These generators can be small or large, so from a solar panel to a large scale energy plant. A major disadvantage of a HVAC system are the large costs for transmission of large capacities (>1,000 MW) over long distances (>1,000 km). These cost are caused by the need for additional equipment which is required to keep the high voltage levels along the transmission route.

4.1.1. Cost estimation HVAC transmission

The cost of a transmission link consist of installation cost, operational cost and the losses which occur over the lifetime of the system. An HVAC transmission link is built with different components:

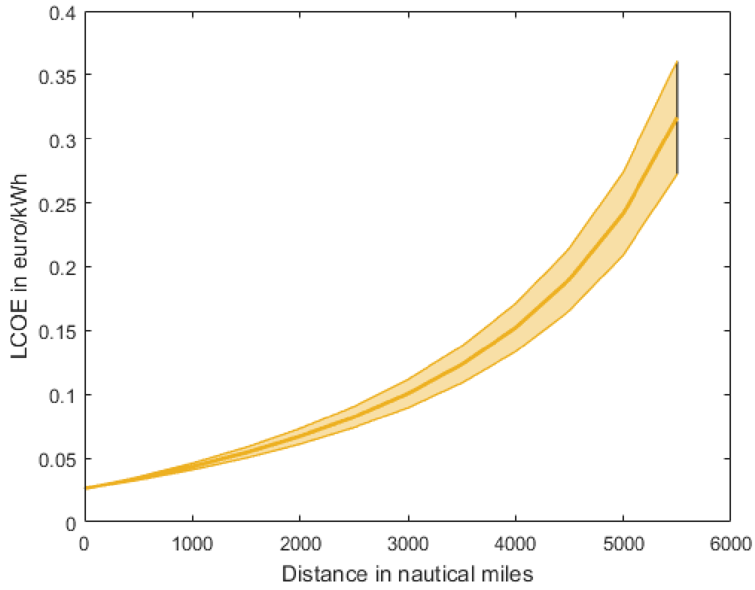


Figure 4.1: Cost of HVAC transmission an increasing distance

- HVAC submarine transmission cables including installation
- transformers depending on grid voltage
- compensation unit, thryistor controlled reactors

The cost of the compontents can be estimated based on quotes in literature and built HVAC transmission links. The cost of the transformers has a relation to their power rating:

$$C_{trans} = 0.03327 * P^{0.7513} \tag{4.1}$$

Where: P: The rated power of the transformer in MVA
C_{trans}: The cost of the transformer in million euros

The cost of the cables of a HVAC submarine transmission are estimated between 500 and 750 Euro per kilometre per megawatt. Another large factor in the cost of transmission is the loss of energy during transport. The loss of energy through a HVAC link are estimated at 7% loss per 1,000 kilometre. The cost for the compensation units are included in the cost of the cables per kilometre.

If the

The result of the calculation is shonw in Figure 4.1.

4.2. High voltage DC transmissions

Over long distances high voltage DC transmissions can be favourable over HVAC systems as they suffer from less energy losses and offer larger capacities. HVDC systems can be divided in two major technologies: HVDC line commutated converter (HVDC LCC) and HVDC voltage source converter (HVDC VSC). These two systems are explained in the next sections.

4.2.1. High voltage DC LCC

The first HVDC technologies was the line commutated converter (LCC). The first commercial LCC HVDC link was installed in 1954 between the island of Gotland the Swedish mainland. The length of the link was 96 km and it was rated at 20 megawatt and used a 100 kV submarine cable. Since this first commercial link, many HVDC LCC links were installed around the planet. These links were used for the interconnecting of power systems or for the transmission of bulk power over long distances.

China is developing the HVDC connections with the Changji-Guquan HVDC link. This link will connect the Northwest to eastern China and sets world records in terms of voltage levels, capacity and distance.(ABB [2]) The system is designed to send 12 gigawatt of electricity over a distance of 3,000 km. These massive numbers are possible due to the ultra high voltage of 1,100 kV.

With a LCC HVDC the energy is converterd from AC to DC and back to DC with transformers, the typical efficiency for this proces is in the range of 97% to 98% and depend on the design detail of the transformer stations but even higher efficiencies in the order of 99% are possible with the latest technologies according to manufacturers.(high voltage cable unit in Sweden [33]). The major advantage of LCC HVDC over an HVAC system are the low losses - in the order of 2 to 3% for a 500 MW transmission over 100 km. In addition, the a single cable can transmit larger volumes than a HVAC transmission or HVDC voltage source converter (VSC). The disadvantage of a HVDC LCC is the lack of power support capability, the system need a strong HVAC network on both sides of the connection. Building a back bone structure based on a HVDC LCC connection is technically challenging and only possible with specialised equipment, such as Static Synchronous Compensators, because the structure has to support on the underlying HVAC network.

4.2.2. High voltage DC VSC

The voltage source converter (VSC) based HVDC technology is relatively new and is made possible due to advances in high power electronics, namely Insulated Gate Bipolar Transistors (IGBTs). Pulse Width Modulation (PWM) can be used for the VSC converter, as opposed to the thyristor line-commutated converters used in conventional HVDC technology.

The first commercial VSC-based HVDC links was installed by ABB on the Swedish island of Gotland in 1999. It is 70 km long, with 60 MVA at ± 80 kV. The link was mainly built in order to provide voltage support for the large amount of wind power installed in the South of Gotland. Since 1999 many projects are developed, mainly in the offshore wind sector.

The total efficiency of a VSC-based HVDC system is slightly less than that of a HVDC LCC system but efficiency is expected to improve with future technical developments. The significant advantages of VSC-based HVDC solutions are its power support capabilities, such as independent control of active and reactive power. In addition, a VSC-based HVDC link does not require a strong AC network, it can even start up against a non-load network. Building up a VSC-based HVDC back bone network will be technically easier than using LCC-based HVDC technology. However, multi-terminal HVDC VSC systems are also new for the power industry.

4.3. Cost comparison of transmission solutions

The cost of transmitting electricity is dominated by the investment cost of the transmission lines and by the electricity losses during transmission. At present, overhead lines are predominant since costs of overhead lines are about 20% of that for ground cables. The transmission losses of HVAC overhead lines are roughly twice as high as those of HVDC. On the one hand, the cost of overhead lines is similar for the lower voltage level but at 800 kV HVDC lines are much less expensive than comparable AC lines. On the other hand, AC/DC converter stations for HVDC technology are considerably more expensive than the transformer stations of AC systems. Therefore, for shorter distances and lower voltages AC is typically the most economical solution, while HVDC lines are applied at distances well over 500 km.

The most economical system design is typically a combination of HVAC and HVDC technology. HVAC is a cost-effective and flexible solution over medium distances (up to 1,000 km), for instance to distribute power along the route to different load centres or to collect locally distributed generation and transmit the surplus electricity to other regions. HVDC technology can be used as an overlaying network structure to transmit bulk power, i.e. large capacity, over long distances to the areas where the energy is needed. An HVDC Super Grid will have only a very limited number of connection points, because the substation (converter station) costs are significant.

The line cost for a HVDC system are lower per unit length compared to a HVAC system with the same reliability due to fewer conductors and if applicable smaller tower size. However, the converters which are necessary for the systems cost two to three times as much for a HVDC system. From distance of 500 km and more HVDC systems can be the most economical system depending on the demands for the system. When a subsea system is considered the break-even distance on which DC is the preferred option over AC is no more than 25 km.(**?**])

The losses in the system are a large driver of the cost-benefit analysis of the HVAC or HVDC link. As stated

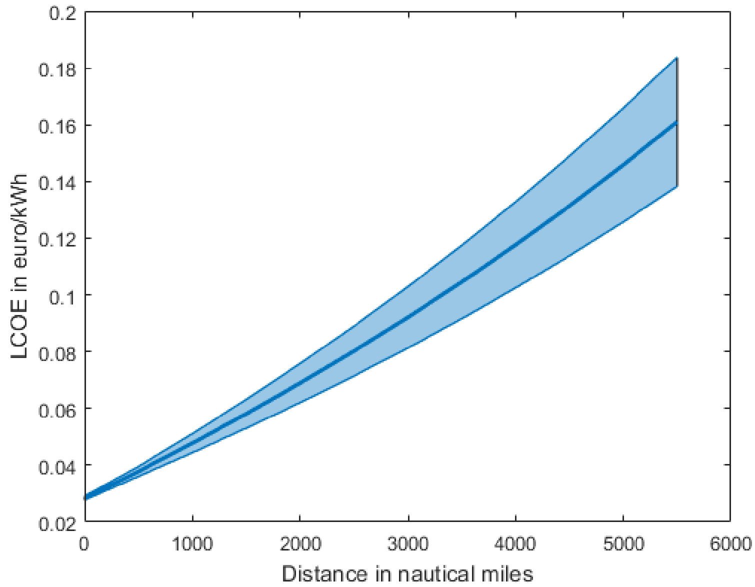


Figure 4.2: Levelezid cost of electricty for a 2 gigawatt HVDC submarine power link

before the losses in the HVDC solution are much smaller than those in the HVAC link, over a distance of 1,000 km typical losses are 3% for HVDC compared to 7% for a HVAC system.(Siemens [56]) The cost for a state-of-the-art LCC converter is about 80,000 - 150,000 euro per megawatt. The costs for a kilometre of electric cable is 750 - 1,100 euro per kilometre per megawatt the cost have a strong relation to the cost of copper(Xiang et al. [65]).

Maximum capacity for a ABB mass-impregnated submarine HVDC bipole link: 2,000 MW at 600 kV [33]. Submarine cable assumed as reference case for ship. The availabilty is set at 97% - 98% the cost to transport electric energy is shown in Figure **??**

4.4. Conclusions on cable

From the results of this comparison it the HVDC transmission is chosen as an reference case for the transport concept. If the concept based on ships does not outperform this reference case is is not viable.

The main driver for the comparison is cost of the transmission. It will be hard for a transport concept by ship to outperform the energy transmission through a cable but there might be possibilities on larger distances. The reference price for electricity for consumers in te Netherlands is 7.89 cent per kWh. If the distance gets larger than 2,500 nm a HVDC tranmission of low cost (renewable) energy is more expensive than generation in the Netherlands.

The main driver of the cost for a HVDC transmission are the high capital investment necessary for the cable link. Another keynote for the cable is that the longest transmission ever built do not even come close to the 2,500 nm or more.

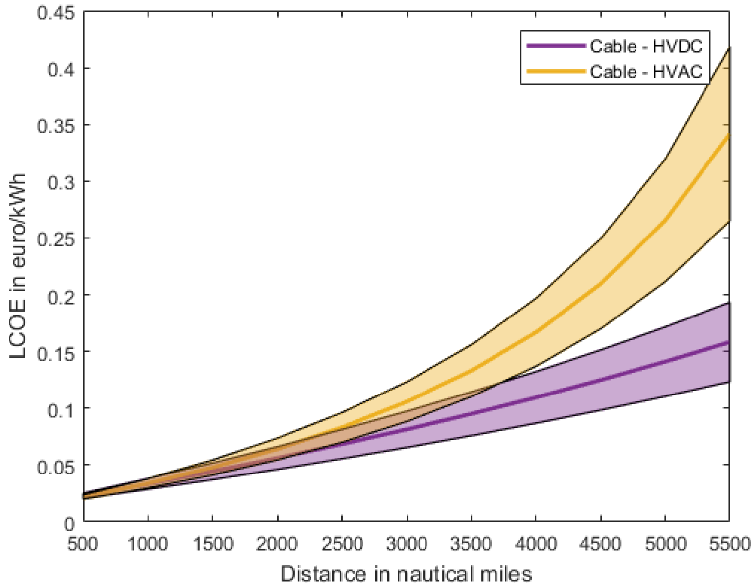


Figure 4.3: Comparisson between HVAC and HVDC transimission link

5
Transportation

In the previous chapters the framework for the transport concept are described. The input values for the cost of energy and price at which it should be delivered are given as well as a reference case in which energy is transported with a cable. The transport of energy can be divided in major components: transport and storage. In this chapter a calculation for the transport is presented. This calculation focusses on the ship and gives estimates for ship dimensions and cargo capacity. The results given in this chapter give values for the selection of storage methods. In the next chapter the storage of bulk energy is handled.

5.1. Model

The concept of transporting energy over the world has a long history. The changes in society might fuel the need to transport renewable energy sources over the planet. As described in chapter 6 there are multiple ways to store energy. The energy has to be regenerated in the port of unloading, which can be done with a large variety of techniques depending on the storage form.

The combination of methods to store, regenerate and transport energy is the bases for the cost and efficiency of the concept. To test the different combinations to find the optimum with the given requirements a non-linear model is built for this research. The model consists of different building blocks which are varied for the different concepts. This chapter explains the general transport model and the sensitivity of the model in order to get design values for the storage methods. The concept specific components of the model will be discussed in the chapters in which these are explained.

For the transportation model a constrained single-criterion optimization problem is solved. A single-criterion optimization problem involves $K \leq 1$ criteria and can be formulated in the form:

$$\begin{aligned}
&minF(x) = [f_1(x), f_2(x), f_3(x), \dots, f_K(x)] \\
&x = [x_1, x_2, x_3, \dots, x_K]^T \\
&\text{subject to the equality and inequality constraints} \\
&h_i(x) = 0, i = 1, \dots, I \\
&g_j(x) \geq 0, j = 1, \dots, J
\end{aligned} \tag{5.1}$$

The optimization problem is solved in Matlab which returns a minimum value for a multi variable function which is constrained. To solve the non-linear model the 'fmincon' solver is used. This built-in application in Matlab offers good performance and is therefore selected as a solving tool.(Hart and Vlahopoulos [30])

5.1.1. Input parameters

The goal of the model is to determine the lowest cost for the transport of electric energy. Together with the cost to produce the energy this will make up for the total cost of electricity, known as levelised cost of electricity (LCOE).

The ideal generation areas for energy are located in areas with a low population density and most consumers can be found in areas with a high population density. The distance between these areas is an input-parameter for the model. The focus on distances is just over 2,000+ nautical miles and 5,000+ nautical miles.

So the output of the model will have a relation to the delivered energy in the consuming area and the distance over which the energy is transported. Within the model variance is included for several parameters such as the cost of the energy in the port of loading.

5.1.2. Storage

If energy is produced and transported it can not always be used directly. During transit energy has to be stored or the production is higher than the demand or there is an interval between deliveries. In all these cases energy has to be stored either on board or on shore. As described in Chapter 6

5.1.3. Ship

The ship model is based on six input parameters for the main dimensions of the ship and service speed. With these parameters the displacement, steel weight of the ship, outfitting are estimated. The machinery cost and weight depend on the installed power which is estimated through a resistance calculation based on Holltrop & Mennen. In this subsection the weight calculation of the general ship model is explained.

- L = length (m)
- B = beam (m)
- D = depth (m)
- T = draft (m)
- C_B = block coefficient (-)
- V_k = speed (knots)

The first value which is calculated in the model is the displacement (Δ), which is related to the length, beam, draught and block coefficienct of the ship. The density of the sea water is not set at 1,025 kg per cubic meter but at 1,030 kg per cubic meter in order to correct for the displacement of appendages. The formula for the displacement is given below:

$$\Delta = \rho_{\text{sea}} * L * B * T * C_b \tag{5.2}$$

where: Δ = Displacment in ton
ρ_{sea} = Density of sea water in ton per cubic meter
L = Length ship in meters
B = Beam ship in meters
T = Draught ship in meters
C_b = Block coefficient

The steel weight (W_S) and weight of the outfitting (W_O) are estimated based on length, beam, depth and block coefficient (Parsons and Scott [51]). The formulas used in the model are given below.

$$W_S = 0.034 * L^{1.7} * B^{0.7} * D^{0.4} * C_b^{0.5} \tag{5.3}$$

$$W_O = 0.5 * L^{0.8} * B^{0.6} * D^{0.3} * C_b^{0.1} \tag{5.4}$$

where: W_S = Steel weight of the ship in ton
W_O = Outfitting weight of the ship in ton
L = Length ship in meters
B = Beam ship in meters
D = Depth ship in meters
C_b = Block coefficient

The weight of the machinery (W_M) is calculated based on the propulsion power with the method described by Watson.(Watson [63]) The power demand for the ship is calculated in this model with the parameters for length, beam, draught, block coefficient and speed.

For this calculation the approach described by J. Holtrop and G.G.J. Mennen is used[34] [35]. The method calculates the power demand based on the wetted surface of the ship. With the wetted surface and the appendages on the ship a resistance calculation is performed. The results of the calculation are the input for the power demand calculation of the ship. This method calculates the power at maximum continuous rating (MCR), which is set at 85% of the installed power.

With the estimated necessary power for the ship the weight for the machinery is estimated by:

$$W_M = 0.72 * (P)^{0.78} \tag{5.5}$$

where: W_M = Weight of machinery in ton
P = Installed power in kilowatt

The sum of the steel weight, weight of the outfitting and weight of the machinery form the light weight of the ship. The deadweight of the ship is equal to the displacment minus the lightweight.

$$DWT = \Delta - Wls \tag{5.6}$$

where: DWT = Deadweight in ton
Δ = Displacement in ton
Wls = Lightweight of the ship in ton

The deadweight of the ship gives is a value for the carrying capacity of the ship but this is not equal to the cargo it can carry. Because fuel ,consumables for the crew, fresh water etc. have to be subtracted first.

To calculate the fuel consumption per day equation 5.7 is used. In this equation the specific fuel consumption is set at 170 g/kWh (MAN Diesel & Turbo [47]). With this value the fuel consumption per day can be estimated.

$$\text{FC}_{\text{day}} = SFC * P_{MCR} * 24 \tag{5.7}$$

where: FC_{day} = Fuel consumption per day in ton
SFC = Specific fuel consumption in ton per day
P_{MCR} = Power at MCR (85%)

The days at sea are calculated by dividing the round-trip distance by the distance the ship travels per day ($24 * v_k$). For this model it is assumed that the ship can carry enough fuel for the total round trip with a five day surplus.

$$W_{\text{fuel}} = \text{Fc}_{\text{day}} * \left(\frac{distance}{24V_k} + 5\right) \tag{5.8}$$

where: W_{fuel} = Weight of the fuel on board in ton
FC_{day} = Fuel consumption per day in ton
V_k = Speed in knots

In this model the consumables for the crew, fresh water etc. are taken as a function of the deadweight. The expression used is given below:

$$DWT_{\text{misc}} = 2 \cdot DWT^{0.5} \tag{5.9}$$

where: DWT_{misc} = Miscellaneous deadweight in ton
DWT = Deadweight of the ship in ton

With the calculated weight for the fuel and miscellaneous deadweight the cargo carrying capacity can be calculated. The formula used in the general model is given by:

$$DWT_{\text{cargo}} = DWT - W_{\text{fuel}} - DWT_{\text{misc}} \tag{5.10}$$

where: DWT_{cargo} = Cargo carrying capacity in ton
DWT = Deadweight in ton
W_{fuel} = Weight of the fuel on board in ton
DWT_{misc} = Miscellaneous deadweight in ton

In this subsection the weight calculation for the ship model is given. The deadweight available for cargo is used in the rest of the model to calculate the cargo the ship moves. Cargo specific requirements necessary for the transport model are discussed in the section which belong to the transport concepts. These requirements can be for example tanks to store chemicals.

5.1.4. Cost definition of the ship

The cost of the ship are divided in the cost for the ship itself and the voyage related cost. First the ship related cost are discussed and the section will continue with the voyage related cost.

The cost of the ship are related to the weight of the steel, the weight of the outfitting and installed power. The cost for the pumps on boards of the ship add cost to the ship as well and are therefore also included in this calculation. Equation 5.11 gives an expression for the cost of the ship

$$C_{\text{ship}} = 2.35 * \left(* W_S^{0.85} + 3500 * W_O + 2400 * P_{\text{installed}}^{0.8} \right) \tag{5.11}$$

where: C_{ship} = Cost of the ship in euro
W_S = Steel weight of the ship in ton
W_O = Weight of the outfitting in ton
$P_{\text{installed}}$ = Installed power in kilowatt

The cost for the insurance and maintenance of the ship per year are set at 10% in the model.

$$C_{\text{IM}} = 0.1 * C_{\text{ship}} \tag{5.12}$$

where: C_{IM} = Cost for insurance and mainentance

The cost to operate the ship also relate to the cost of manning and stores. These cost are calculated with(Hart and Vlahopoulos [30]):

$$C_{\text{manning}} = 72244 * DWT^{0.3} \tag{5.13}$$

The manning cost and the cost for insurance and maintenance are fixed cost which occur every year.

The voyage related cost of a ship are variable cost which have a relation to a particular voyage. The main items are fuel cost, port dues, pilot assistance, tugs and canal dues. To calculate the fuel cost the fuel consumption is taken and the length of a voyage plus a margin of 5%. The following expression is used for the fuel cost:

$$C_{\text{fuel}} = 1.05 * \text{FC}_{\text{day}} * \frac{\text{distance}}{24V_k} * C_f \tag{5.14}$$

where: C_{fuel} = Fuel expenditures per voyage in euro
FC_{day} = Fuel consumption per day in ton
C_f = Cost fuel (euro/ton)

Every time a ship makes a port call it has to pay the port authority seaport dues and dues to third parties for assistance by tug boats, mooring, un-mooring and shifting of the ship, piloting and other services.

The total seaport dues including pilotage to be paid in the port of Rotterdam ($C_{\text{port fees}}$) are related to the Gross Tonnage, draught, deadweight tonnage, length and number of port calls per year. The calculation of the port fees is described in Appendix A. The port fees are assumed to be the same for both ports (loading and unloading). In the port of Rotterdam the fee for chemical/gas tankers, bulk carriers and general cargo ships is the same. Therefore, one tariff class is used in this calculation.

The voyage cost per year can be calculated with (Stopford [59]):

$$C_{\text{voyage}} = \left(C_{\text{fuel}} + C_{\text{port fees}} + CD\right) * \text{RTPY} \tag{5.15}$$

where: C_{fuel} = fuel cost for main engines
$C_{\text{port fees}}$ = port dues, pilot and tug assistance, port administration
CD = Canal dues
$RTPY$ = Number of round trips per year

The cost for the ship per year are equal to the voyage cost times the round trips per year as described by Equation 5.15 and the manning cost plus the cost for insurance and maintenance (Equation 5.12 and 5.13). The investment cost for the ship are equal to the cost of the ship (Eq 5.11) plus concept specific components.

5.1.5. General shore facilities

The model is bounded at the gate of the port it is assumed that energy is delivered in electric form to the transport concept. This energy has to be stored on board, in an electric form of any other composition. The shore facilities allow for the conversion from and to storage materials.

If energy is converted to a storage composition the installations which produce this energy carrier consume energy. The equation below is used to calculate the cost of the production facility.

$$C_{production} = \frac{m * U}{(D_S + D_P) * \eta_C * 24} * C_P \tag{5.16}$$

where: m = mass of cargo loaded
U = specific energy density cargo
η_C = conversion efficiency
D_S = sea days
D_P = port days
C_P = cost production unit in euro per kilowatt

In the port of unloading the energy has to be regenerated to electric energy which can be supplied to the grid. Systems which deliver energy to a grid are expressed in kilowatt as well but than the power they deliver and not the power they consume which leads to a slightly different equation.

$$C_{regeneration} = \frac{m * U * \eta_C}{(D_S + D_P) * 24} * C_R \tag{5.17}$$

where: m = mass of cargo delivered
U = specific energy density cargo
η_C = conversion efficiency
D_S = sea days
D_P = port days
C_R = cost regeneration unit in euro per kilowatt

5.1.6. Generated electrical energy

The transport concept delivers energy in the port of unloading. The energy which is stored on board of the ship as to be regenerated back to electricity which can be supplied to the power grid. Equation 5.18 is used to calculate the amount of energy which is delivered to the power grid per year.

$$E_t = m * U * \eta_C * RTPY \tag{5.18}$$

where: E_t = electrical energy generated in year t
m = mass of cargo delivered
U = specific energy density cargo
η_C = conversion efficiency
$RTPY$ = number of round trips per year

The energy on board of the ship has to be delivered to the ship. Equation 5.19 is used to calculate the amount of energy which is necessary per year to load the ship. It is almost the same equation as the one for the energy delivered but the cargo has to be divided by the conversion efficiency as more energy is necessary to load the ship than can be stored.

$$F_t = \frac{m * U * RTPY}{\eta_C} \tag{5.19}$$

where: F_t = fuel expenditures in year t
m = mass of cargo loaded
U = specific energy density cargo
η_C = conversion efficiency
$RTPY$ = number of round trips per year

5.1.7. Levelised cost of electricity

With all the input on cost and energy generation capabilities of concept the levelised cost of electricity (LCoE) can be calculated. The LCoE is already introduced in Chapter 2 as this is the final calculation in the model and eventually all results of the different concepts are compared on this value.

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} (I_t + O\&M_t + F_t + C_t + D_t) * (1+r)^{-t}}{\sum_{t=1}^{n} E_t * (1+r)^{-t}} \tag{5.20}$$

where: I_t = investment in year t
$O\&M_t$ = operations and maintenance expenditures in year t
F_t = fuel expenditures in year t
C_t = carbon cost in year t
D_t = decomissioning cost in year t
E_t = electrical energy generated in year t
r = discount rate
n = expected lifetime of system

The sum of the cost of the ship, the cost of the shore facilities toghether with concept specific investments form the total investment (I_t). The voyage related cost are equal to the operations and maintenance expenditures ($O\&M_t$).

The energy which is necessary to load the ship in the sun-belt regions as described in Chapter 3 are the fuel expenditures (F_t). The fuel which is consumed by the ship is already part of the operations and maintenance expenditures.

In Chapter 3 the carbon cost are briefly discussed as well the values which are used for the four scenarios will also be used for the carbon cost (C_t).

The decomissioning cost for the shore facilities are neglected and for the ship a scrap value based on the lightweight ship is used for the decomissioning cost (D_t) so for this model these cost are negative.

One of the most important parameters in this equation is the electrical energy generated (E_t).

All values are calculated based on their net present value, for this calculation three different discount rates are applied (5%, 7% and 10%) these are described in the LCoE-equations as r.

5.2. Constraints

The ship model is constrained by a set of constraints as listed in Table C.1 which is added in Appendix C. The constraints limit the possibilities for the ship design within a feasible region as can be seen in equation C. These constraints are used in Matlab to calculate the optimal solution for each set of input parameters.

5.2.1. Constraint on depth and length

The main dimensions for the ship are limited by the ports which the ship calls. Most ports in the solar belt on the west coast of Africa are small. Therefore the length and depth of the ship are limited. The maximum length of the vessel can not exceed 152.4 meter (500 feet) and the depth ranges from 6.1 to 13.7 meter depending on the port. The constrained on the maximum depth is set at 10 meter as this includes most ports (2 in Morocco, 2 in Mauritania, 1 in Namibia and 1 in South Africa). The possible ports are listed in Table 5.1.

Country	Port	Lat/Long	Depth	Length	Source
Morocco	Agadir	30° 26' N / 9° 38' W	15.0 m	upto 160 m	http://www.worldportsource.com
Morocco	Kenitra	34° 16' N / 6° 35' W	6.1 m	upto 152.4 m	http://www.worldportsource.com
Morocco	Safi	32° 19' N / 9° 12' W	9.1 m	upto 152.4 m	http://www.searates.com
Namibia	Walvis Bay	22° 57' S / 14° 30' E	10.0 m	upto 152.4 m	https://www/ports.com
South Africa	Cape Town	33° 54' S / 18° 26' E	13.7 m	over 152.4 m	https://www/ports.com
Mauritania	Nouadhibou	20° 49' N / 17° 3' W	12.2 m	upto 152.4 m	https://www/ports.com
Mauritania	Nouakchott	18° 2' N / 16° 2' W	10.0 m	upto 152.4 m	https://www/ports.com

Table 5.1: Depth and length constraints of ports with oil terminals in the areas of loading

5.2.2. Stability criteria

The concept design has to satisfy a set of basic stability conditions. In this phase of the design process a preliminary calculation of the lever arms can be omitted, since this process is very time consuming and also requires precise lines plans. Therefore, nominal values for the freeboard and GM are specified. The values have to give an acceptable lever arm curve. In the model the following equations are used to estimate the values for KB, BM and KG(Bertram and Schneekluth [11]):

$$\begin{aligned} KB &= T(0.9 - 0.3 * C_M - 0.1 * C_B) \\ BM &= \frac{\frac{C_{WP}}{12} * B^2}{T * C_B} \\ KG &= 1 + 0.52 * D \end{aligned} \tag{5.21}$$

$$\text{where:} \quad C_{WP} = \frac{C_B}{0.471 + 0.551 * C_B}, \qquad C_M = 0.95$$

5.3. Sensitivity analysis and modelling criteria

The sensitivity analysis on the general ship model showed that the round-trip efficiency, cargo specific energy density and investment cost on the shore facilities are the main drivers of the concept. The balance between these parameters can make or break a concept design. The influence of the ship on the LCoE is minor. In this section the sensitivity analysis and results will be discussed. The results of the analysis will be used in to select suitable energy carriers.

5.3.1. Effect of round-trip efficiency and capital cost per kilowatt on LCoE

The round-trip effeicieny and capital cost per kilowatt will most likley have a substantial influence on the LCoE. To test the influence the LCoE is calculated for different capital investments ranging from 0 to 10,000 euro per kilowatt over a round-trip efficiency range of 0.1 to 1. The results for two distances are shown in Figures 5.1 and 5.2. These distances are a reuslt of the conclusions in Chapter 3. In this calcultion a specific energy density for the cargo of 13,000 kWh/ton is assumed, equal to diesel fuel.

The impact of the capital investment on the LCoE mainly results in a vertical shift of the LCoE-line. For low values per kilowatt the line shifts down otherwise it goes up.

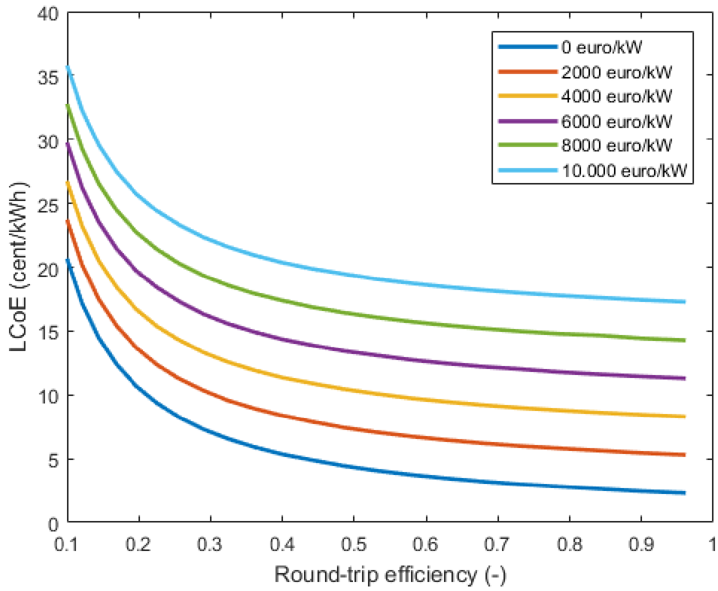


Figure 5.1: Effect of capital cost per kilowatt over round trip efficiency on the LCoE at 2,000 nautical miles

5.3.2. Effect of round-trip efficiency and argo specific energy density on LCoE for set distances

The same calculation as for the relation between round-trip efficiency and capital investment cost have been performed for the relation between round-trip efficiency and the cargo specific energy density. It is expected that there is a relation between the two parameters because if the cargo specific energy density increases the value of the cargo increases and therefore the relative cost to transport the cargo drops. The results for this distances 2,000 nm and 5,000 nm have been plotted in Figures 5.3 and 5.4. From the results it can be concluded that a higher energy density has a positive effect on the levelised cost of electricity. When the energy density is over 1,000 kWh/ton the increase of the energy density does not result in much lower costs. It can also be seen that the trends for both figures show the same path: a higher round trip efficiency results in a lower cost but this effect is smaller for the higher energy densities.

The two figures only differ in the cost for the relative low energy densities. At 2,000 nm the 100 kWh/ton trend starts at 55 cent/kWh for a 0.1 round-trip efficiency and improves to 13 cent/kWh for the higher round-trip efficiency. For the 5,000 nm calculation the trend is comparable but the cost start at 75 cent/kWh and improve to 30 cent/kWh.

5.3.3. Round trip efficiency and cargo specific energy density

For the next set of calculations the round-trip efficiency is set at fixed values of 25%, 50% and 75% and the distances and cargo specific energy density are varied. The result of the calculation is shown in Figures 5.5, 5.6 and 5.7. The results are similar to those from previous calculation: a higher round-trip efficiency results in a lower levelised cost of electricity and a higher cargo specific energy density results in a lower cost price. Again the 1,000 kWh/ton mark can be seen as a design goal if the concept must stay under 10 cent/kWh for example. For the high carbon cost scenario's number 3 and 4 when the fossil fired power plants cost respectively more

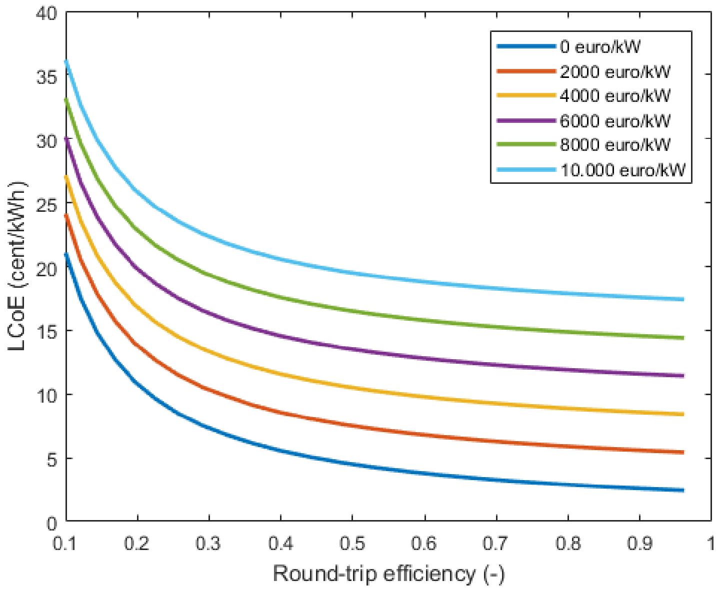


Figure 5.2: Effect of capital cost per kilowatt over round trip efficiency on the LCoE at 5,000 nautical miles

than 13.4 cent/kWh and 17.7 cent/kWh the lower cargo specific energy densities are possible as long as the round-trip efficiency is high.

5.3.4. Manning cost

The cost of the crew have little influence on the cost of the ship concept. The cost which occur through conversion losses in the loading and discharging process exceed the cost of the crew by a lot.

5.3.5. Fuel cost

The start of the design process is made on basis of a parameter study of the most influential parameters. The model is designed around the optimisation of the ship parameters and takes in information about conversion-to-storage-efficiency, storage-to-conversion-efficiency, energy characteristics of energy carriers, the capital investment cost to store energy on board and costs of installations to make the conversions possible.

In this part of the research the parameters are tested on a blank sheet. The goal of this test is to find the driving parameters of the concept. Therefore, the previously listed parameters are tested stand alone and against each other to try and see what the behaviour of goal value is. In this way the boundaries of the parameter can be calculated. With that information a selection of possible concepts can be made which can be calculated in more detail.

In the next part the effect of the parameters is discussed in more detail. For all these calculation the cost to buy electric energy to start the process is set at 1, 2 and 3 eurocent per kilowatt-hour. This value will be varied in the design of the concepts as this value is not depending on the design of the transport concept but is driven by the supplier of energy.

5.3.6. Conversion efficiencies

The conversion of energy to a storage medium and back to energy usually results in a loss of some of the energy. The conversion efficiency has a significant influence on the LCOE. In Figure 5.8 the resulst of a calculating is visualised. In this calculation the conversion efficiencies are taken from 40% to 90% for both steps. The round trip efficiency which follow is 16% to 81%. The capital investment cost are fixed at 1 euro per kilowatt and 1,000 euro per kilowatt and the distance is set at 3,000 nautical miles. Figure 5.9 shows a calculation but at a shorter distance of 1,500 nautical miles. Obviously is is clear that a high round trip efficiency is always better but it does not really matter which of the conversion efficiencies is higher and for shorter distances it is less important.

If the capital investment is really small a round trip effficiency of 25% is the minimum which must be achieved in order to have a chance of reaching the goal value for the LCOE of 0.10 euro/kWh. This value can

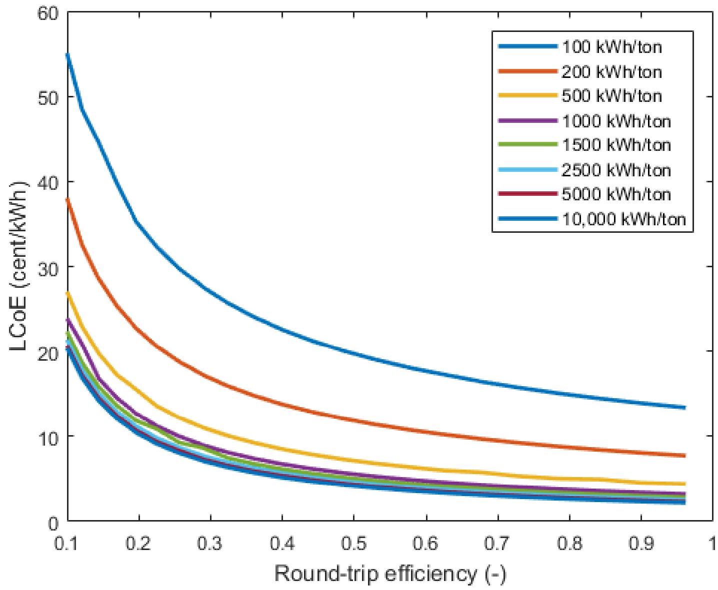


Figure 5.3: Effect of cargo specific energy density over round trip efficiency on the LCoE at 2,000 nautical miles

be explained by the goal value and the cost at which energy is acquired in this calculation. The goal value is for example 0.10 euro/kWh and the cost is 0.025 euro/kWh, follows:

$$\frac{\text{Cost}}{\text{Goal value}} = \frac{0.025}{0.1} = 0.25 = 25\%$$

In this discourse the cost to transport energy are neglected. Hence the necessary round trip efficiency should be larger than 25%.

If the capital investment is larger (1,000 euro/kW) this round trip efficiency should be larger than 40%. Furthermore, if the distance gets shorter the necessary round trip efficiency decreases to about 35% in the scenario with the high capital costs. If the capital investment cost is small the distance does not have much influence on the necessary round trip efficiency.

5.3.7. Energy density cargo

The energy density in the cargo is different for different sorts of energy carriers. For example a ton of diesel is 13,000 kWh/ton and a lead-acid battery holds only 47 kWh of energy per ton. In this subsection the influence of the specific energy density of the cargo is calculated for a set of round trip efficiencies and a variation of distances.

The result for this calculation is presented in Figure 5.10. In this Figure it is clearly visible that if the specific energy density increases the levelised cost of electrical decreases rapidly. This can be explained by the fact that the model demands a set power to be delivered at the end consumer of 200 megawatt with a continuous supply. If the specific energy denisty is low more mass has to be transported or the speed has to be increased.

If this is seen from with a different view the: the LCOE as a function of the density and distance for a given round trip efficiency it is also visible that a specific energy density of more than 2,000 kWh per ton results in a almost flat surface for all the distance at which the round trip efficiency determines the height of the plane.

5.3.8. Conclusion driving parameters and design proposal

For the selection of the transport concepts the conversion efficiencies, specific energy density and capital investment cost are the driving parameters. The cost of the ship does not have much influence if the specific energy density is high. For a smaller specific energy density (<1,000 kWh/ton) the cost of the ship do have a significant influence.

For the selection of energy carriers and storage mediums a goal should be a high cargo specific energy density of more than 1,000 kWh/ton but preferably more than 2,500 kWh/ton. The round-trip efficiency has a large influence on the levelised cost of electricity and this should be more than 25% but again if higher

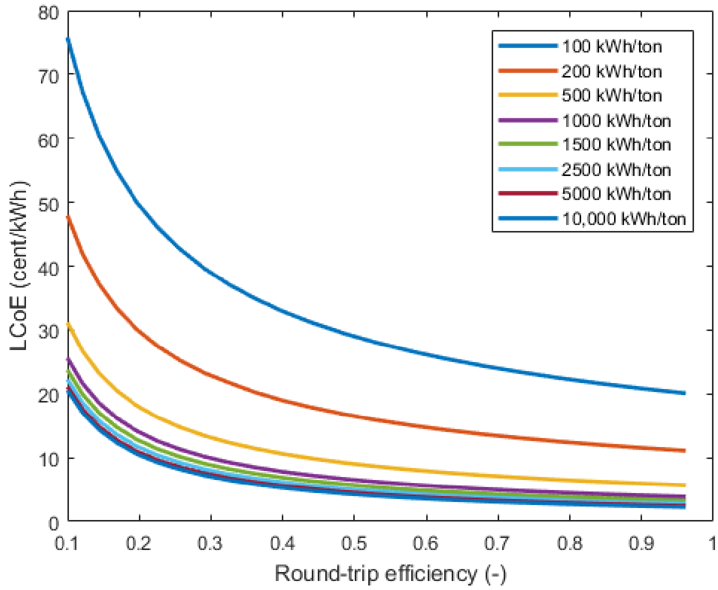


Figure 5.4: Effect of cargo specific energy density over round trip efficiency on the LCoE at 5,000 nautical miles

values are possible this is strongly recommended. The capital investment cost off course should be as low as possible but it is most likely hard to tell in advance what a concept costs. Therefore, this driver will not be selected as selecting parameter.

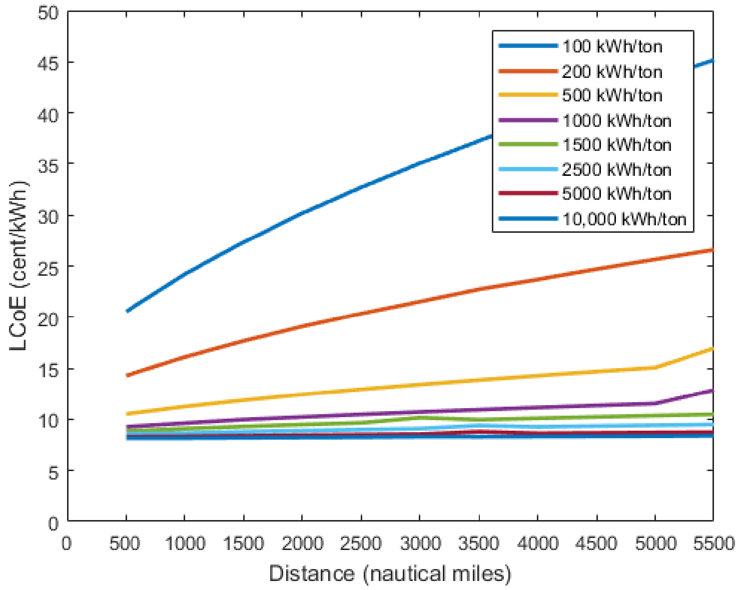


Figure 5.5: Effect of cargo specific energy density over distances in nautical miles and a round trip efficiency of 25%

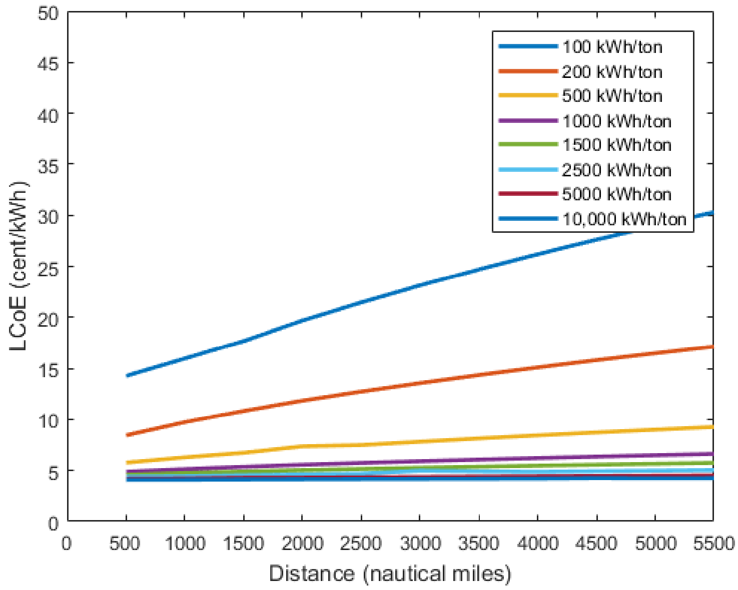


Figure 5.6: Effect of cargo specific energy density over distances in nautical miles and a round trip efficiency of 50%

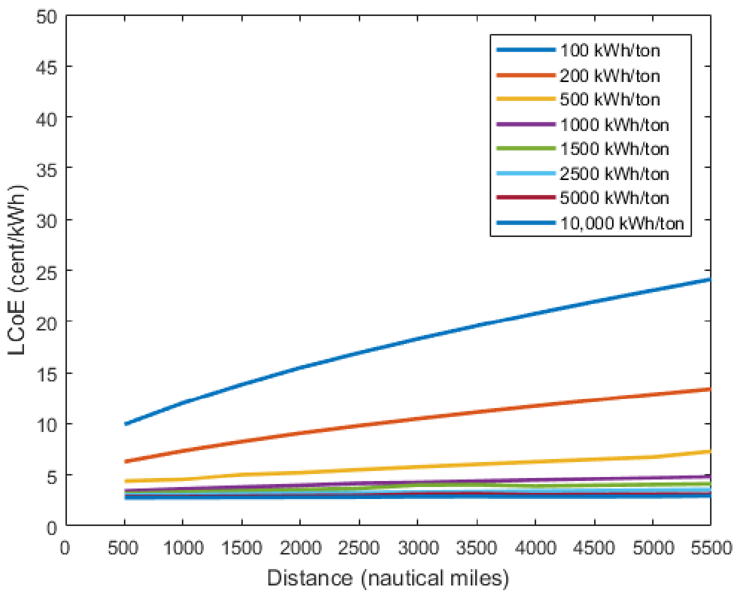
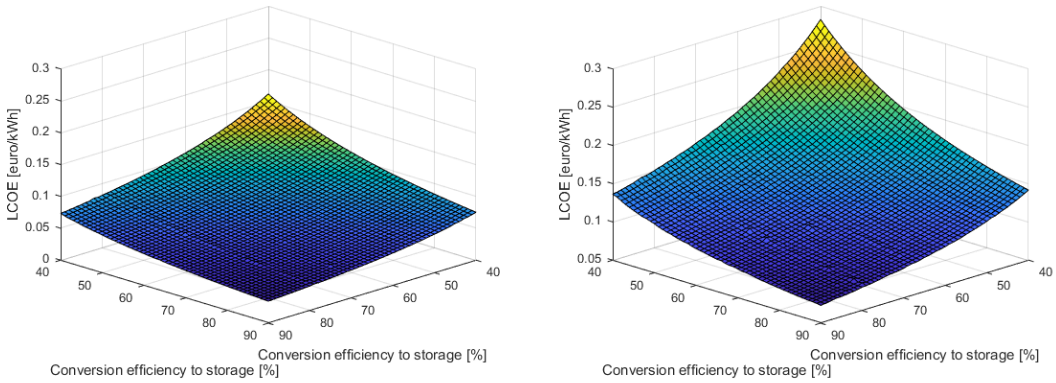


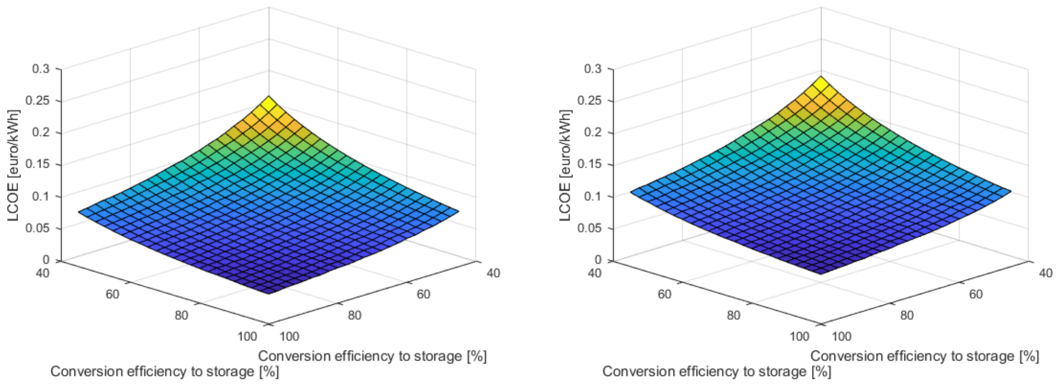
Figure 5.7: Effect of cargo specific energy density over distances in nautical miles and a round trip efficiency of 75%



(a) Capital investment 1 euro/kW

(b) Capital investment 1,000 euro/kW

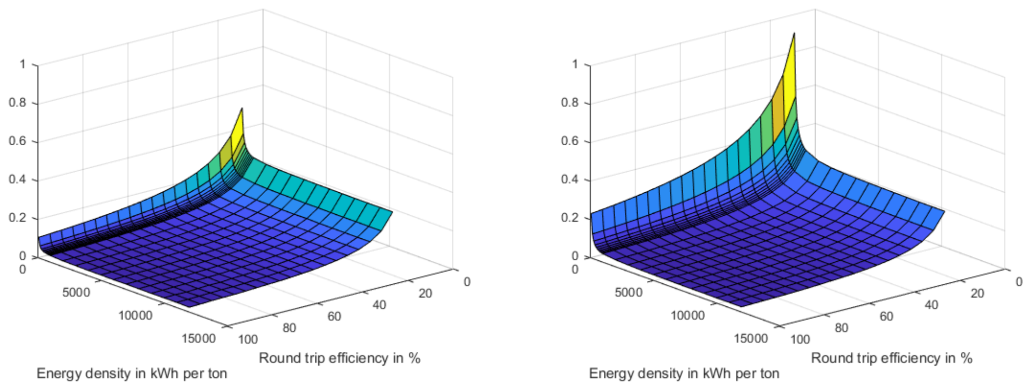
Figure 5.8: Influence of conversion efficiencies on LCOE at 3,000 nm



(a) Capital investment 1 euro/kW

(b) Capital investment 1,000 euro/kW

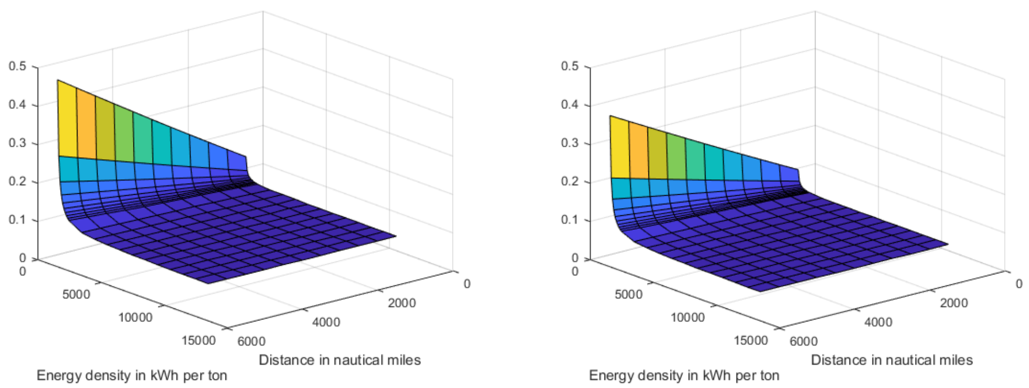
Figure 5.9: Influence of conversion efficiencies on LCOE at 1,500 nautical miles



(a) Distance is 1,500 nautical miles

(b) Distance is 4,500 nautical miles

Figure 5.10: Influence of energy density and conversion efficiency



(a) Round trip efficiency is 40%

(b) Round trip efficiency is 60%

Figure 5.11: Influence of energy density and distance on LCOE

6
Energy Storage

The generation and usage of electric energy will not always be in balance, or direct usage may not be possible because energy is generated in an area far away from the energy consuming area.Therefore, energy will have to be stored for short or long times. At this moment a lot of research is done into the field of energy storage. This research is powered by the upcoming of different renewable energy sources, such as: solar, wind and tidal. Electric Energy Storage (EES) can be categorized in the form the energy is stored, which are: mechanical, electrochemical, electrical, thermochemical, chemical and thermal.

A short description of the principles and potential capabilities of different EESs is presented in this section.

6.1. Pumped Hydro Storage

The conventional pumped hydro storage (PHS) consists of two water reservoirs. The water in the high basin represents the potential energy or stored energy. This technique is by far the largest and most mature storage technique and it represents 99% of the global storage capability. If this technique is combined with a solar energy plant the energy could be stored by pumping water from the lower reservoir in the high reservoir when the production of energy is larger than the demand. The energy can be retrieved by releasing water from the high reservoir through hydro turbines which are connected to generators.

The PHS has a large energy rating, long lifetime, high efficiency and very small self-discharge losses.(Díaz-Gonzaález et al. [19]) The benefits of the system are large if it is applied to store large amounts of energy but it has high geographical requirements, a relative low energy density and it has a slow response to fluctuations. Due to its geographical requirements this is not a possible storage method for transport purposes. Typical values are 70%-85% and storage capacities are virtually unlimited as these only depend on the size of the reservoirs. The storage duration could be long as self-discharge of the system is negligible(Barbour et al. [9]). Energy can be stored if the conditions are right but for a solution in which the storage medium has to be shipped this is not possible. It can be used as a stationary storage medium.

6.1.1. Conclusions on PHS

Pumped hydro energy storage is the largest bulk electric energy storage system as 99% of the existing storage systems use this technology. The system stores gravitational potential energy by elevating water. This water is stored in large basins. This storage method is therefore not possible for transportable solutions and will therefore not be further discussed in this report.

6.2. Compressed Air Energy Storage

The compressed air storage (CAES) uses compressors to compress air and store it in a underground storage (salt cavern, mines, natural gas field) or an above-ground system of containers and pipes. When there is a demand for energy the air is released and mixed with natural gas, and burned with a gas turbine to generate electricity. Current research is focussing on developing fabricated storage tanks in order to remove the geological dependency and to increase the pressure, which has a positive effect on the efficiency and storage capabilities. The high power and energy capacity ratings make CAES an interesting technique to store energy. With the developments in the fabricated storage tanks it is possible to make this system more flexible in usage, so it could be installed in ports or onboard of ships.

The specific energy for this system is in the range of 3.2 to 5.5 Wh/kg at a price of 10 to 70 euro per kWh of storage capacity. The efficiency of the system is 70%(Akinyele and Rayudu [7]).

6.2.1. Conclusion on CAES

Although the round trip efficiency of the CAES and cost for the storage capacity are well within the preferred range. The specific energy density of the system of 3.2 to 5.5 Wh/kg is far below the minimum viable goal value of 100 Wh/kg. CAES is not a suitable storage method for concept due to the low energy density.

6.3. Flywheel Energy Storage

In a flywheel energy storage unit (FES) the energy is stored in a large rotating metal body. This body is often a metal disc, which is placed in a vacuum compartment to reduce mechanical loss. The FES is charged by accelerating the rotor to very high speeds in the order of 20,000 to 50,000 rpm. The energy is mechanically stored with a rotating rotor, this energy is retrieved by using the FES as a generator. The flywheel then releases its rotating energy. The specific energy density of a FES is well over 200 kWh/ton for a high speed system(Liu and Jiang [45]).

The FES has a low power rating when compared to PHS and CAES but it is large when compared to battery systems. The FES can be charged and discharged very fast which makes it possible for the system to respond to fluctuations in power demand or supply. Therefore, it is a very good system to increase quality of energy supply. Due to its high self-discharge at a mimimum rate of 20% of the stored capacity(Hadjipaschalis et al. [29]) it is not possible to store energy with a FES for a long time.

6.3.1. Conclusions on FES

The FES does have a specific energy density which is high enough to be transported but the self discharge is too high to make it a suitable energy carrier for this research. .

6.4. Battery Energy Storage Systems

Batteries are the most common technology to store energy and some technologies already exist for more than 140 years but new techniques are still being developed. The energy is stored in the form of electrochemical energy, in a set of multiple cells. The cells can be coupled parallel, in series or in both ways in order to obtain a certain capacity and voltage. In a battery each cell consists of two conductor electrodes and an electrolyte. The electrolyte enables the flow of ions between the electrodes. The battery energy storage systems (BESS) rely on low-voltage cells, which are connected to obtain certain capacities and voltages.

6.4.1. Lead-acid batteries

The lead-acid battery is the most mature battery. This technique has a cycle life of 1,200 to 1,800 cycles with an efficiency of 75-80%. The lifetime of a lead-acid battery is 5-15 years and the low self-discharge of <2-5% per month make these batteries capable of storing energy for a long time. The battery has poor operating results if the ambient temperature gets too high or too low. Compared to other batteries the lifetime is short but the main disadvantage lies in the necessity for periodical water maintenance and low specific power and energy (30-50 kWh/ton and 180 kW/ton).(Divya and Østergaard [20]) The cost for lead-acid batteries are low compared to other batteries at 60 euro/kWh of storage capacity.(Albright et al. [8])

6.4.2. Nickel-cadium batteries

The nickel-cadmium battery offers better technical characteristics than the lead-acid battery but it costs more than 10 times as much as a lead-acid battery but does suffer a higher self-discharge 5-20% per month. The battery can make more than 3,500 cycles with little to no maintenance. Two major drawbacks of nickel-cadmium batteries is the toxicity of the metals and the memory effect. Specific energy density of these batteries is 45-80 kWh/ton.

6.4.3. Sodium-sulphur batteries

A relatively new technology is sodium-sulphur batteries. Although relatively new a Japanese manufacturer provides batteries with a capacity of 151 kWh/m^3 and a efficiency of 85%, besides the batteries are for 99%

recyclable, require low maintenance and suffer little to no self-discharge. The cost per kWh of capacity is estimated at 425 euro/kWh and expected to fall to 200 euro/kWh by 2030.

6.4.4. Lithium-ion batteries

Lithium-ion batteries (Li-ion) constitute the last battery technology described in this section. These batteries are widely used for small electronic devices, such as telephones and laptops, to large applications such as electric cars and stationary energy storages. The performance and range size of the batteries is largely related to the active materials of the electrodes and the electrolyte. The specifications for the Li-ion batteries are promising as they offer high energy density and specific energy (170-300 kWh/m^3 and 75-125 kWh/ton). Li-ion batteries have a high cycle life of 3,500 cycles but suffer low self-discharge rates of 1% per month. The cost of a battery storage system is 300 euro/kWh. These costs are estimated to go towards 150 euro/kWh by 2030 due technological developments.(Kairies [38])

6.4.5. Conclusion on battery storage systems

The battery storage system are not suitable for long distance energy transport. Lead-acid and nickel-cadium batteries have a energy density which is too low and certainly the nickel-cadium batteries have a considerable self-discharge rate. Li-ion and sodium-sulphur batteries have a higher energy density which could be high enough but these battery systems are far too expensive with prices far above 300 euro/kWh of capacity. Future developments could bring these down but prices would have to fall by more than 90% to be a possible energy carrier for this concept.

6.5. Flow Battery Energy Storage Systems

Flow battery energy storage systems (FBESS) operating principle is based on reversible electrochemical reaction. Unlike conventional BESS the system operates with two aqueous electrolytic solutions which are kept in separate tanks. This makes the system better scalable to large capacities than conventional BESS. During the operation of the battery the electrolytic solutions are pumped through a electrochemical cell in which the reaction occurs. In the section ahead three different FBESSs will be described briefly: Vanadium Redox Battery (VRB), Zinc Bromine Battery (ZBB), and Polysulphide Bromide Battery (PSB).

In a VRB energy is stored in two tanks, an anolytic and catholytic reservoir containing sulphuric and acid solutions. The system lifespan is about 15 to 20 years with more than 1,000 charge and discharge cycles at 100% DoD. The system does not need much maintenance but every 5 years the membranes will have to be replaced. The system offers a efficiency of 78%. The cost for the system are 135 euro per kWh but the cost will go down when the energy storage capacity increases. Specific energy and energy density are 25-35 kWh/ton and 20-33 kWh/m^3.

The ZBB system has a relatively high specific energy (75-85 kWh/ton), a high efficiency of 75-85% and a cycle life time of >2,000 cycles at 100% discharge without any damage, and virtually no self-discharge. The materials used to make the batteries can be recycled plastics which allow for low production costs and high recycle-ability.

The PSB system is based on the electrochemical reaction between two salt-based electrolytes. Efficiency and lifetime of the system are in the same range as the other FBESSs, respectively 75% and 15 year. The system has no self-discharge and the chemical elements to build the system are abundant in nature and prices are reasonably low. However, a leak in a tank would expel toxic bromine gas. (Soloveichik [58])

6.5.1. Conclusions on FBESSs

Flow battery energy storage systems are larger storage systems than battery energy storage systems and are less expensive at 135 euro/kWh. The round trip efficiency is high > 75% and they suffer no self-discharge. It can be concluded that the battery storage system is too expensive for the transport concept and the specific energy density is too low with a maximum of 85 kWh/ton for zinc bromine battery systems.

6.6. Thermal storage

Thermal energy storage (TES) uses materials that are kept at high or low temperatures in a insulated container to store energy. The energy can be regenerated by using a heat engine cycle. The round trip efficiency of a TES application is low 30%-60% although the heat cycle efficiency can be high 70%-90%(Chen et al. [16])

6.6.1. Low temperature TES

A system which operates in the temperature range of 0°C to 250°C is considered to be a low temperature TES. These storage systems have a focus on this temperature range due to possible CO_2 reductions in conventional heating and cooling applications in domestic or commercial buildings. The phase change material (PCM) that can be used at higher temperatures up to 250°C offer a higher specific energy density in the range of 150 - 200 kWh/m^3 and 50 - 100 kWh/ton. The capital investment for such systems are in the magnitude of 20 - 25 euro/kWh.(da Cunha and Eames [17])

Conclusions on low temperature TES

Low temperature thermal energy storage systems costs are well within the range which could make the concept feasible but the energy density is too low for the transport concept. This is due to the low operating temperatures. The technique is suitable for heating and cooling applications of buildings but is not suitable for this research topic.

6.6.2. High temperature TES

In the temperature range above 250°C a system is considered to be a high temperature storage system. In industrial applications in use today are salt hydrates the most applied PCMs with a maximum operating temperature of 700°C. Higher temperatures offer a larger storage capacity compared to a low temperature storage system. Storage capacity is in the order of 150 - 165 kWh/ton. The capital cost for this system is in the range of 26 - 32 euro/kWh(Herrmann et al. [32]).

The main cost drivers for a TES are (from biggest to smallest): salt, storage tank, heat exchanger, balance of system, foundation, pumps and insulation material.(Kuravi et al. [43]) Figure 6.1 shows the cost breakdown for a high temperature TES installed on a 50 megawatt concentrated solar plant.

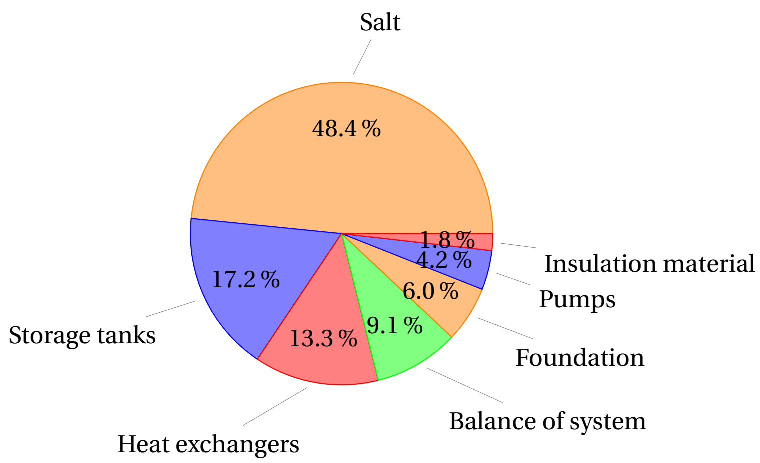


Figure 6.1: TES cost breakdown for 2-tank indirect sensible heat storage(International Renewable Energy Agency (IRENA) [36])

High temperature thermal energy storage is a mature technology which is applied as a storage method at concentrated solar energy plants. The technological readiness level is 9 which means it is being used at an industrial scale. The costs per kilowatt hour of storage capacity are low and the storage capacity is large enough. The round trip efficiency is in the range of 40%-42% this value should ideally be higher but this close to theoretical limit of the system.

Conclusions on high temperature TES

High temperature TES could deliver 150-165 kWh per ton storage capacity for a capital investment in the order of 26 to 32 euro per kWh. These numbers are within the range which is necessary to develop a cost competitive concept. The round trip efficiency is high enough but it is not likely that large improvements are feasible.

6.7. Hydrogen

Most of the energy carriers which are used today are hydrogen carriers as fossil fuels are bounds of hydrogen and carbon. When hydrogen is discussed as a storage medium it can be a hydrogen carrier such as a synthetic fuel or pure hydrogen which is liquefied of compressed.

Hydrogen is a very powerful energy carriers per unit of mass. It can store 39.4 kWh per kg of mass which is three times as much as carbon-based fuels. The energy density of hydrogen per volume metric unit is a four or eight times smaller than carbon-based fuels with high demands on the storage tanks because of low temperatures (-253°C) or high pressures (70 MPa). Table 6.1 shows a short summation of these values.

Table 6.1: Hydrogen general properties

	Temperature in Celsius	Pressure in MPa	Energy density kWh/kg	Energy density kWh/l
Liquid	- 253	1	39.4	2.36
Compressed	15	70	39.4	1.25

The specific energy denisty is very high per kilogram and this density is high enough to be transportable.

The common way to produce hydrogen with electricity is by using electrolysers. At this moment there are two main technologies available on an industrial scale: alkaline and proton exchange membrane (PEM) electrolysers. The efficiency for an alkaline system is up to 70% for large plants. The PEM is a younger technology with a possibly very high efficiency. The theoretical maximum efficiency is 94% but at this moment the efficiency is in the range of 40% to 67%. Due to advances in technology this could increase to 67%-74% by 2030. The cost of a hydrogen based energy storage system is estimated at 2 to 15 euro per kilowatt-hour.(Kaldellis and Zafirakis [39])

The cost of an electrolysers in the current market is 1000 euro per kilowatt of capacity. It is expected market parties that this will decrease to 600 euro per kilowatt in the years ahead. The goal of research institutes is a capital cost as less as 200 euro per kilowatt by 2030.

6.7.1. Liquid hydrogen

Liquid hydrogen can be used to store hydrogen in a concentrated form. For hydrogen to be fully liquid the temperature has to be below 253°C. In a liquid form it contains 2.36 kWh per litre. To store the hydrogen cryogenic storage is necessary which will demand special thermally insulated tanks. It will be difficult to keep hydrogen at these low temperatures, typically 1% leaks away per day. Large storage units can be found with the NASA and US Air Force as they use hydrogen as a fuel in most rocket engines.

The liquefaction of hydrogen consumes a lot of energy. The minimum theoretical needed energy to liquefy one kilogram of hydrogen is 3.3 to 3.9 kWh/kg depending on the process. Actual liquefaction processes consume a lot more energy 10-13 kWh per kg of hydrogen. New methods may reduce the energy which is necessary to liquefy hydrogen; active magnetic regenerative liquefier promise liquefaction at 7 kWh per kilogram of hydrogen. (Gardiner [27])

6.7.2. Compressed hydrogen

Another way of increasing the density per volumeric unit is compression. Hydrogen can be stored in compressed form as long as the pressure exceeds 70 MPa. Compressed hydrogen energy storage is available for small size applications such as fuel tanks for cars. These storage systems cost 15 euro per kWh capacity and are expected to drop to 7 euro per kWh(of Energy Office of Energy Efficiency & Renewable energy [50]). Bulk storage of hydrogen is usually not done compressed but liquified this is due to the lower energy density per volumetric unit for compressed hydrogen storage (1.25 kWh/l).

6.7.3. Hydrogen carriers

Hydrogen can be stored in other chemical combinations which storage and handling less technological challenging. An important factor is the weight fraction of hydrogen in the element.

Ammonia is easy to liquefy and stays liquefied at atmospheric pressure at a temperature below -33°C. The vapor pressure of anhydrous ammonia is 857 kPa at 20°C. The weight fraction of hydrogen in ammonia is 17.65% . This means that ammonia is a easy to handle liquid with a volumetric specific energy density about 35% higher than liquid hydrogen. The specific energy density of ammonia is 5,166 kWh/ton and 3,194 kWh per ton.

6.8. Evaluation of storage options

Many storage options discussed above have an application in a stationary solution which powers small energy grids. As a result many of the storage solutions are not favourable for a transportation solution. This is due to a low specific energy density per kilogram or high cycle lifetime but with a high investment cost. Table 6.2 shows a short summary of the typical values listed in the section above.

Table 6.2: Storage system characteristics

Storage method	Energy density [kWh/ton]	Capacity cost [euro/kWh]	Roundtrip efficiency [%]	Source
Goal values	> 1,000	< 35	> 25	
Pumped hydro	-	75-100	70-85	Barbour et al. [9]
Compressed air energy storage	3.2-5.5	10-70	50-70	Akinyele and Rayudu [7]
Flywheel energy storage system	200	1,000-2,000	>90%	Liu and Jiang [45]
Lead-acid batteries	30-50	60	75-80	Divya and Østergaard [20
Nickel-cadium batteries	45-80	600	75-80	
Sodium-sulphur batteries	151	200-425	85	
Lithium-ion batteries	75-125	150-300	85	Kairies [38]
Flow battery energy storage systems	75-85	150-2,000	75-85	Soloveichik [58]
Low temperature TES	50-100	20-25		Chen et al. [16]
High temperature TES	150-165	26-32	40-42	da Cunha and Eames [17
Liquid hydrogen	39,400	2 - 15	40 - 60	Kaldellis and Zafirakis [3
Hydrogen carrier - ammonia	5,166	2 - 15	25 - 50	

With the blank sheet approach in Chapter 5 the first requirements for the storage characteristics are drawn. In this calculation the parameters: energy denisty, capacity cost and round trip efficiency have proven to be very important. The capital cost to generate hydrogen carriers (chemcical fuels) are important as well but these depend on volumes and power capacity. In Table 6.2 the fist row shows the goal values derived in Chapter 5. In this calculation other factors such as on shore storage cost or port fees have been neglected.

A ship on average can make about 12 - 25 port calls per year in the port of unloading depending on the distance and the voyage speed. If a ship lifetime of 30 years is taken a ship makes a maximum of 750 trips in its economical life. As described in the introduction the maximum difference between the cost to buy and sell electricity is about 6 to 15 cent depending on the carbon cost scenario. If a major part of this difference is reserved for storage cost the maximum which a storage system may cost is 45 to 112.5 euro per kWh if a ship makes a large number of port calls.

Based on this basic approach all battery based systems can be removed from the comparison. The maximum price for a storage system of 100 euro per kWh means that all battery based systems are virtually eliminated either on cost or energy density. The cost of lead-acid batteries for example is low but they to suffer from a very low specific energy density per ton. Although the prices for lithium-ion batteries has decreased dramatically over the last yeas it is not likely that the price for storage will get in the range of 100 euro per kWh or less.(Hensley et al. [31]) As they offer a too expensive storage solution with a density which is small. It is not to be expected that these numbers will increase considerably.

The leading factors with the storage options are the specific energy density, the cost per unit of storage capacity and the efficiency. The storage of energy in hydrogen is a solution with a very high specific energy density but with a lower efficiency than batteries. The hydrogen based energy carriers will be discussed in more detail as they offer most of the desired characteristics and improvements can be expected as much research effort is globally put in to hydrogen research.

The other storage method which is going to be discussed is high temperature thermal energy storage. This method has a much lower storage density than hydrogen carriers but the technique is already available on industrial scale and the financial investments are expected to be smaller than those of hydrogen based solutions.

6.9. Hydrogen carrier - ammonia

In this section the ammonia concept is presented. Energy carriers such as ammonia are energy carriers with a relative high specific energy density. Compared to hydrogen the energy density of ammonia per kilogram is low with only 18.6 MJ/kg compared to 141.86 MJ/kg but the specific energy density is higher with 11.5

MJ/L compared to 8.491 MJ/L. These values would point at hydrogen as a favourable energy carrier but to get this energy density per litre hydrogen has to be cooled to 30K or pressurized at 70 MPa compared to 240K with ammonia at ambient pressure. Ammonia is being considered as a potential replacement for fossil fuels, similar to the Hydrogen Economy. It offers a lot of the benefits of hydrogen but reduces some of the barriers.

Ammonia is a key ingredient for fertilizers used in the agricultural industry. Therefore, it is produced at a large scale globally this industry even consuming 1% of the world's energy production. The well developed technique to produce ammonia is by the Haber-Bosch process. In section 6.9.1 this process is explained in more detail and a transport concept based on this process is presented. A technology which is under development is the solid state ammonia synthesis (SSAS) and this process should be more efficient and more cost effective than the Haber-Bosch process but the technology is not yet available on a commercial scale. Section 7.2 will go in more detail about the SSAS and SSAS based concept.

6.9.1. Haber-Bosch based

Most of the ammonia produced today is made with the Haber-Bosch Process. In this process atmospheric nitrogen is converted in ammonia by a reaction with hydrogen using a metal catalyst under high pressure (20-40 MPa) and high temperature (650-750K). Equation 6.1 shows the reaction, which is reversible and can be used to produce energy from ammonia.

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \tag{6.1}$$

The hydrogen required for the process can be made from various sources in most applications it is mainly derived from natural gas but it could also be produced by electrolysis. For this research the focus is on the production of hydrogen via electrolysis because our energy source for the process is electric energy. The process to make the hydrogen and form the ammonia consumes around 12,000 kWh to produce one ton of ammonia, so the efficiency is about 43%.(Bartels [10])

The installations to produce ammonia are commercially available. The cost of plants using the Haber-Bosch process with an electrical energy input can be split in roughly two parts; the cost for the electrolyser and the other parts. According to a supplier of these installations[1] the electrolyser is half of the total cost for small installations and just over 50% for the larger installation. At this moment a PEM electrolyser costs 1,000 euro/kW and expectations are that these will decrease to 500 euro/kW by mid 2020's.(Bourne [13]). The growing demand for electrolysers, larger systems and growing industrial knowledge about this process is the main driver for the cost reductions for these components. The other parts in the ammonia plant based on the Haber-Bosch process are already well known in the industry and large cost reductions are unlikely. At this moment the cost for an ammonia plant is estimated by supplier at 1,400 to 1,500 euro per kW due to cost reductions in the electrolyser the cost for the system from 2020 to mid 2020's is estimated to be 1,050 to 1,150 euro per kW.

Besided the cost reductions efficiency improvements for the electrolysers are expected as well. The production of the hydrogen takes up about 90% of the total power consumption of the process. Due to improvements it is expected that the energy consumption to produce one ton of ammonia could be reduced to 11,000 kWh.

Storage of ammonia is relative simple and being done on a large scale already. The cost for a storage tank are about 15 to 20 million euro for a 30,000 metric ton tank(Kruse et al. [42]). In this model a relation between the cost for the tank and volume is assumed to have a relation to the power two-third based on the relation of surface area and volume of a sphere. The cost for the storage tanks in the model is defined as below:

$$\begin{aligned} C_{\text{storage}} &= c_1 * c_2 * m^{2/3} \\ c_1 &= \text{uniform distributed between: 15,536 and 20,715} \\ c_2 &= \text{Correction factor of 1.05} \\ m &= \text{storage capacity in ton ammonia} \end{aligned} \tag{6.2}$$

6.9.2. Solid state ammonia synthesis based

The second ammonia based concept is designed around the solid state ammonia synthesis. The technology is driven by the developments in the field of fuel cells.

[1] Proton Ventures BV - Schiedam

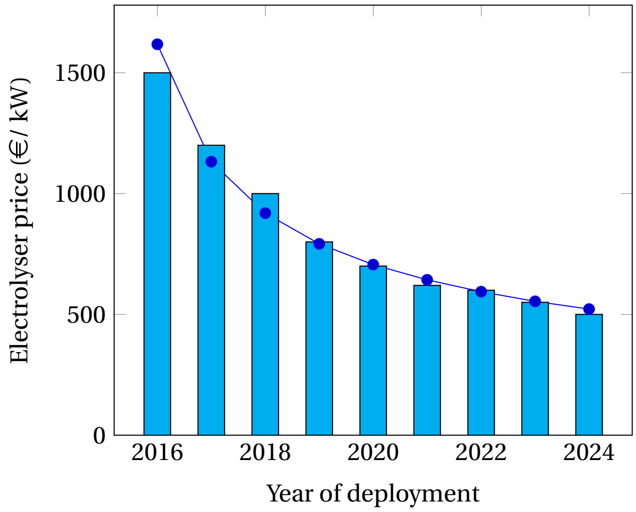


Figure 6.2: System cost considerations by ITM Power(Bourne [13])

A new development in ammonia synthesis is the solid state ammonia synthesis (SSAS). The main advantage of this new technology over the Haber-Bosch Process is the significantly reduced need for energy and economic benefits. The SSAS requires 7,000 - 8,000 kWh/ton NH_3[2], compared to the 12,000 kWh/ton NH_3 for the Haber-Bosch Process, the efficiency of the SASS is therefore in the range of 64% to 74%. The capital cost to produce a ton of NH_3 per day is estimated at 170,000 € for a pilot project.(Leighty [44]).[3]. If the energy which is necessary to produce a ton of ammonia is 7,500 kWh the capital cost of 170.000 euro per ton per day capacity translates to a price of 544 euro per kilowatt.

The cost of the SSAS equipment is assumed to be related to the development of electrolysers. At this moment these cost about 1,000 euro per kilowatt and prices are expected to decrease to 500-600 euro per kilowatt by commercial companies. If the research goals of the ECN institute are met these capital costs can even decrease to 200 euro per kilowatt by 2030.

The chemical process has similarities to the Haber-Bosch process but uses water in stead of pure hydrogen as a supply of hydrogen. Equation 7.2 shows the reaction which describes te process. (Garagounis et al. [26])

$$2N_2 + 6H_2O \rightleftharpoons 4NH_3 + 3O_2 \tag{6.3}$$

Unlike the Haber-Bosch Process the SSAS technology can not be used to produce energy with ammonia but the energy stored in ammonia can also be regenerated by using a fuel cell or burning ammonia as done with traditional carbon fuels in gas turbines or other applications. With solid oxide fuel cells experimental efficiencies of 60% and 70% have already been achieved in 2004.(Dekker and Rietveld [18])(Thomas and Parks [60])

6.9.3. Fuel cells

An ammonia-fed solid oxide fuel cell (SOFC) is a the most efficient method to generate power with ammonia. The ammonia can be used directly in the fuel cell like hydrogen and provides a high power density. In this section the different fuel cells are discussed and the benefits for the ammonia-fed SOFC over the other fuel cells is explained. This section presents the working principle of the fuel cell, application in the concept and advantages and disadvantages of the ammonia-fed fuel cell.

Fuel cells can be categorized in sex major systems according to their operating temperature, efficiency, applications, cost and material.(Kirubakaran et al. [41]). These systems are: alkaline fuel cells, phosphoric acid fuel cells, solid oxide fuel cells (SOFCs), molten carbonate fuel cells, proton exchange membrane fuel cells and direct methanol fuel cells.

Among these different types of fuel cells SOFCs have some advantages over the other fuel cells as these can be directly fed with different types of fuels such as hydrogen, methanol and ammonia, because of the

[2] One ton of liquid NH_3 = 5,166.7 kWh
[3] Conversion rate: 1$ = 0.85 €

operating temperature of 800°C to 1,000°C.

Alkaline fuel cells
Alkaline fuel cells work on the operating principle by the transfer of hydroxide ions through an electrolyte. The fuel cell consists of three main components: cathode, electrode and anode.

The alkaline fuel cell works as followed: oxygen is fed into the cathode to form hydroxide through a reaction with water and an electron (6.4). The ammonia is fed into the anode and reacts with the hydroxide to form nitrogen, water and electrons, in this reaction power is given to an electrical load (6.5). The overall reaction is that ammonia and oxygen are fed into the fuel cell and water and nitrogen are the exhaust products (6.6).

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{6.4}$$

$$2NH_3 + OH^- \rightarrow N_2 + 6H_2O + 6e^- \tag{6.5}$$

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \tag{6.6}$$

Ammonia fuel cells based on the alkaline membrane electrolytes are attractive but they have some disadvantages; the crossover of the ammonia through the membrane can reduce the voltage-circuit and efficiency of the fuel cell, oxidation of the ammonia on the cathode can form toxic nitrous oxide (NO).

Solid oxide fuel cells
Ammonia can be directly fed in a high-temperature solid oxide fuel cells (SOFC). The chemical reaction in the fuel cell is as follows: in the first step ammonia reacts with oxygen to form nitrous oxide, water and electrons (6.7). The nitrous oxide is formed because the diffusion of oxygen through the electrolyte is the limiting factor. In the next step the nitrous oxide which is formed reacts with new ammonia to form nitrogen and water (6.8).

$$2NH_3 + 5O_2^- \rightarrow 2NO + 3H_2O + 10e^- \tag{6.7}$$

$$2NH_3 + 3NO \rightarrow 5/2N_2 + 3H_2O \tag{6.8}$$

The SOFCs working principle can be divided in two systems the SOFC-O and SOFC-H. The difference is that the SOFC-O works with an oxygen-ion-conducting electrolyte and a SOFC-H fuel cell works with a proton-conducting electrolyte. In a SOFC-O some nitrous oxide can be formed and a SOFC-H system only produces water vapour as it only feeds hydrogen and oxygen to the cathode (6.9). This is an advantage because hydrogen is not diluted by water vapour generated in the fuel cell reaction (Afif et al. [3]).

$$2NH_3 + 6e^- \rightarrow N_2 + 6H^+ \tag{6.9}$$

6.10. Thermal energy storage

Industrial scale energy production facilities often use heat as a main working principle. The heat is usually produced by burning fossil fuels. The energy which is released with the process is transferred in steam which powers a turbine to produce mechanical energy which is converted in electrical energy.

The heat which is necessary to power this process could also be generated with solar energy or with electrical energy generated with other renewable energy sources. The production of heat with electricity can be applied if the energy has to be stored over a time interval. Many concentrated solar power plants have a thermal energy storage installation to store energy for a few hours to be able to generate energy after the sun has set.

6.10.1. Production

As mentioned before the heat can be produced by direct conversion of solar light in heat, with a electrical energy source or even fossil fuels. In this research the fossil fuels will not be considered as a source for heat because it is more effective to directly transport fossil fuels to end-consumers because of the higher energy density and a smaller number of conversions. In concentrated solar power plants heat is generated by concentrating solar light on a surface area. This concentrated light beam produces heat which is used transferred directly in molten salt or by using a transferring fluid. This approach is also not considered in this research because it is assumed that the energy is transported to the processing plant as electric energy. The heat is produced with electric heaters, this process is very energy efficient as it can reach conversion efficiencies close to 100%.

The energy stored as heat has to be regenerated to electricity. This process has more limitations than the conversion of electricity to heat. In this concept molten salt is used as a storage material, as this material is mostly used in concentrated solar plant thermal energy storage systems. The operating temperature range is 290-565°C in this range the molten salt suffers no significant decomposition (Gimenez and Fereres [28]). The lower temperature is 60° higher than the melting point this is necessary to keep the molten salt a handleable fluid. The maximum efficiency possible to convert thermal energy in electrical energy is given by the Carnot limit.

$$\eta_C = \frac{T_{hot} - T_{cold}}{T_{hot}} \tag{6.10}$$

where T_{hot} is the maximum temperature of molten salt and T_{cold} is considered to be equal the operating temperature of steam in a steam turbine. For molten salt the associated Carnot limit on efficiency is

$$\eta_C = \frac{838K - 293K}{838K} = 65 \tag{6.11}$$

The round trip efficiency is driven by the efficiency of the steam turbine. Steam turbines which are delivered to the market for these purposes can have an eficiency in the order of 60% %(AG [4]). The round trip efficiency of the thermal energy storage is set at 42% - 45% due to losses in the heat exchanger and other parts of the system.

6.10.2. Storage

In large industrial complexes and concentrated solar plants the heat is stored in molten salt. The molten salt used for this study, solar salt, consists of 60% $NaNO_3$ and 40% KNO_3. This material has a melting point of 494K and a upper heating limit of 870K(Reddy [55]). If the material is acquired in large batches the price per ton averages 627 euro per ton in China.[4] A large industrial supplier[5] made a quote for 775 euro per ton of salt.

Molten salt can be stored in thermally insulated containers. Industrial installations in use today store the heat usually to generate energy during the night or for a few days but not much longer. Although storage for more than a few days is not common it would not give much difficulties. If large volumes are stored in well insulated tanks the heat transfer is much so the losses will be small.

6.10.3. Transport

The transportation of heat is done with a physical connection or by a heat transporting carrier, a ship f.e. An at large scale applied heat transportation concept in the Netherlands is the city heating system, applied in Rotterdam. With this concept heat is transported from industrial complexes to residential areas with pipes. Hot water is pumped through these pipes in order to transport the heat to the users. This system is also applied in various scales in industrial applications.

A different transport method would not be built on pipes, so without a physical connection, but the heat can also be transported with ships, trains or trucks.

During transport and storage the material in the storage tanks looses heat which leads to a reduction of the power generating potential. To minimize the loss the storage tanks can be insulated. Equation 6.12 shows that the heat induction factor (k), contact area (A) and thickness of the insulating material (d) have influence on the insulation characteristics of the tanks.

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d} \tag{6.12}$$

Conventional thermal energy storage units have well insulated tanks. The insulation material costs roughly 4% of the storage facility if the salt is excluded from the cost breakdown. The tanks and heat exchangers are the most expensive units for these installation.(International Renewable Energy Agency (IRENA) [36]) The losses per day are expected to be small due to the large volumes.

[4]This price is based on an average over a inquiry for 30,000 ton molten salt among three Chinese suppliers by the Damen Purchasing Department. The average was 5,000 CNY per ton (1 CNY = 0.13 EUR)

[5]Yara International

For transport with a ship the tanks of the ship have to be insulated to reduce losses during transit but no other special requirements are demanded. The temperature of 565° is high but this is not a critical temperature it is well below any melting point and the salt will cool if a tank ruptures.

6.10.4. Cost

The thermal energy transport can be breakdown in a few big blocks which are the main cost drivers: molten salt, storage tanks, power plant and heat source. The cost for a ton of salt 627 - 775 euro per this range. The cost for storage tanks is estimated at 700 - 850 euro per ton(International Renewable Energy Agency (IRENA) [36]). A steam turbine which can be used to convert thermal energy to electric energy is estimated at 1,000 euro per kilowatt. The units to convert electric energy in thermal energy are assumed to be as expensive as steam turbines and are therefore estimated at 1,000 euro per kilowatt.

7
Concept design

In the previous chapters decisions have been made on the expected cost at which energy can be delivered in the port of loading. The reference value at which energy can be supplied in the port of unloading is set and the first choices in the storage method have been made. In this chapter two concepts will be assessed: a concept based on the transport of ammonia and a thermal energy storage and transport concept.

The energy delivered to the ports has to be stored if there is no ship available to transport it or if the energy can not directly be used in an industrial process. The cost of storage tanks is related in this model to the volume. The cost for a 30,000 ton storage tank is approximately 17 million euro (Protopapas et al. [53]). The expression used for the cost of a storage tank on shore is given:

$$C_S = c_1 * (m/\rho)^{2/3} \tag{7.1}$$

where: c_1 = constant depending on stored material
m = mass of cargo delivered
ρ = denisty of stored material

7.1. Ammonia based concept

In this section the ammonia based concept is discussed. It is chosen to work with ammonia as a light chemical over methanol or ethanol. These chemicals are suitable for the concept as well but ammonia is selected as energy carrier because it does not contain carbon bonds and will therefore not result in the emission of CO_2.

The specific energy densities of the three chemicals are roughly comparable as can be seen in Table 7.1. The chemicals with carbon bonds do offer higher specific energy densities but in Chapter 5 the calculation showed that if the energy density was well over 2,500 kilowatt-hour per ton the specific energy density did not have much extra influence.

Table 7.1: Specific energy density light chemicals

Storage type	Specific energy kWh/ton	Energy density kWh/m^3
Ethanol	8,333	6,667
Methanol	5,472	4,333
Ammonia	5,166	3,195

7.1.1. Ship dimensions ammonia concept

With the non-lineair model described in Chapter 5 the main dimensions of the ship are calculated. As expected are the result of the model is defined by one of the set boundaries, in this case the limiting factor is the length of the ship. The main dimension given by the model are given in Table 7.2.

The main dimensions calculated with the model are used to calculate the levelised cost for electricity for different concepts. For the ammonia based concept a 2018 and 2030 design are made. The concepts use

Table 7.2: Main dimension ship for the ammonia concept

Parameter	dimension	unit
Length oa	152.4	meter
Beam	17.93	meter
Depth	12.20	meter
Draugth	7.84	meter
Block coefficient	0.66	-
Speed	14.6	knots
Deadweight	10.815	tons
Installed power	4,762	kW

different methods to produce ammonia (resp. Haber Bosch and SSAS) and convert the energy stored in the ammonia back to electrical energy by using fuel cells but different input values for the cost of these fuel cells are taken.

7.1.2. Ammonia model with the Haber Bosch production process

Most of the ammonia produced worldwide is made with natural gas. The gas is used to produce hydrogen which is bound to nitrogen to form ammonia (NH_3). The hydrogen can also be produced with electrolysers. In that case the hydrogen is produced from water. In section 6.9.1 the cost of electrolysers are given. In the year 2018 the cost for an electrolyser is estimated at 1,000 euro per kilowatt (Bourne [13]).

The concept design for 2018 works with the Haber Bosch process to produce the ammonia. The cost of these installation have a relation to the cost of the electrolyser and components to bound the hydrogen to the nitrogen. The cost for a total installation are estimated at 1,400 to 1,500 euro per kW in 2018[1] and 1,050 to 1,150 euro per kW in the mid 2020's.

The production of a ton of ammonia with the Haber Bosch process is very energy consuming. It costs 11,000 to 12,000 kWh to produce one ton of ammonia which can be rewritten as an conversion efficiency between 43% and 47%.

The input for the model for the Haber Bosch process is given in Table 7.3.

Table 7.3: Input paramters Haber-Bosch process

Year		Low value	High value	Distribution
2018	Capital cost (euro/kW)	1,400	1,500	Uniform
2018	Conversion efficiency	43%	47%	Uniform
2025	Capital cost (euro/kW)	1,050	1,150	Uniform
2025	Conversion efficiency	43%	47%	Uniform

The energy stored in the ammonia can be regenerated by using fuel cells. The energy efficiency is higher than a gas turbine and is in the range of 50% to 60%(Mekhilef et al. [49]). The capital cost per kilowatt were 2,000 euro (in 2012) and are expected to decrease to 600 euro by 2030 due to technological improvements and ageing of the technology. In the model a range of 1,500 to 2,000 euro per kilowatt for the capital cost of the fuel cell is taken to include systems to support the fuel cell and the cost to install the fuel cell.

In this model the energy which is stored in the ammonia is regenerated with a fuel cell. The input parameters of this fuel cell can be seen in table 7.4

Table 7.4: Input paramters fuel cell Haber Bosch concept

Year	Parameter	Low value	High value	Distribution
2018	Capital cost (euro/kW)	1,500	2,000	Uniform
2018	Conversion efficiency	50%	60%	Uniform
2025	Capital cost (euro/kW)	1,000	1,100	Uniform
2025	Conversion efficiency	50%	60%	Uniform

[1] Proton Ventures BV - Schiedam

Table 7.5: Result for LCOE for the Haber Bosch concept in 2018 for discount rates 5%, 7% and 10%

Discount rate	5%	7%	10%
Distance (nm)	LCOE (cent/kWh)	LCOE (cent/kWh)	1LCOE (cent/kWh)
500	19.70	21.25	23.78
1,000	19.98	21.54	24.1
1,500	20.26	21.84	24.42
2,000	20.54	22.13	24.74
2,500	20.82	22.43	25.06
3,000	21.09	22.72	25.38
3,500	21.37	23.01	25.70
4,000	21.64	23.3	26.02
4,500	21.92	23.6	26.34
5,000	22.19	23.89	26.65
5,500	22.49	24.20	27.00

Results for the 2018 concept
The calculation for the concept have been performed 10,000 times to get an answer with a small variation. The result for the levelised cost of electricity is presented in Table 7.5. The standard deviation on these results is 1 to 1.1 cent on the result of the 2018 concept for the calculation with a discount rate of 7%. The influence of a higher or lower discount rate (5% and 10%) can be seen in Table 7.5 as well. The different discount rates result in a slightly higher and lower LCOE. The influence of the discount rate is substantial, because the investment is made in year '0' and no investments during the duration of the project only expenses such as maintenance.

The goal value of 7.89 cent per kilowatt-hour is not possible with this concept this can be explained by to the low round trip efficiency of 27% but is also a result of the capital investment for the project. Figure 7.1 shows the power capacity of the project on the right axis and also the capital investment in relation to the power capacity. The figure shows that the investment is well over 8,500 euro per kilowatt and it increases with the distance to 8,800 euro per kilowatt for the longest distance. The investment necessary per kilowatt of power capacity is much larger than a conventional energy plant.(Ray and Lee [54])[2]

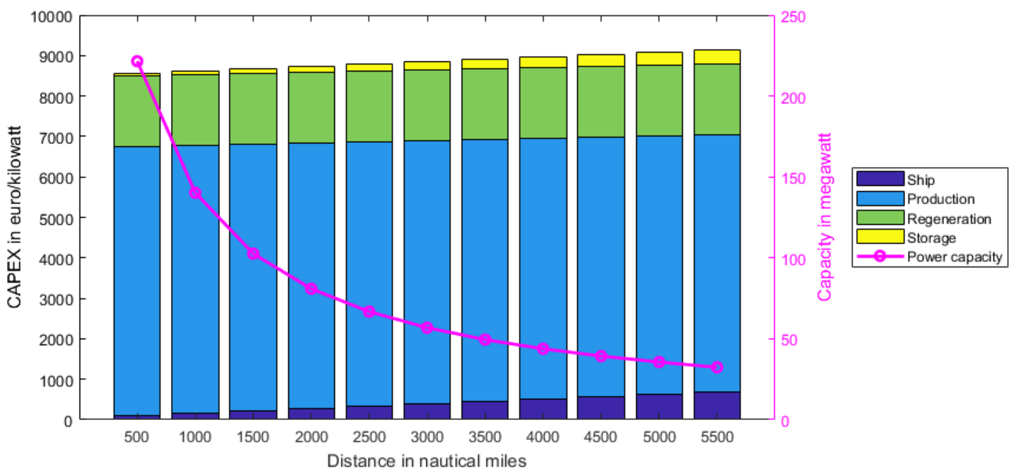


Figure 7.1: Invested capital per major component as a function of the power capacity versus energy capacity of the Haber-Bosch 2018 concept

Results for the 2025 concept
The main difference, or actually only difference, between the 2018 and 2025 concept is the lower capital cost for the concepts. Due to developments in the field of electrolysers and fuel cells it is expected that the cost for

[2]The cost of a conventional natural gas power plant is 820 euro per kilowatt (Ray and Lee [54])

Table 7.6: Result for LCOE for the Haber Bosch concept in 2025 for discount rates 5%, 7% and 10%

Discount rate	5%	7%	10%
Distance (nm)	LCOE (cent/kWh)	LCOE (cent/kWh)	1LCOE (cent/kWh)
500	16.68	17.76	19.62
1,000	16.97	18.07	19.96
1,500	17.26	18.37	20.29
2,000	17.55	18.67	20.62
2,500	17.83	18.98	20.96
3,000	18.12	19.27	21.90
3,500	18.41	19.57	21.62
4,000	18.69	19.88	21.95
4,500	18.98	20.19	22.28
5,000	19.26	20.49	22.61
5,500	19.57	20.81	22.98

these components is less. As could already be seen in the 2018 concept these two components are the largest cost drivers of the concept. Hence the LCOE for the 2025 concept is noticeably less than the 2018 concept. The results for this concept are shown in Table 7.6. Again the results are the average of 10,000 calculations over the set input boundaries (Table 7.3 and 7.4). The standard deviation of the results is between 0.9 and 0.95 cent per kilowatt-hour.

As mentioned before it is expected that the capital investment for this concept is less. Figure 7.2 shows the relation between the power capacity of the concept and the capital cost. The CAPEX per kilowatt is 6,100 for a distance of 500 nm and increases to about 6,500 euro per kilowatt for the distance of 5,500 nm. This is already less than the 2018 concept but still large. This concept does not meet the goal value either. The lowest calculated LCOE with a discount rate of 7% is 17.43 cent per kilowatt-hour at a distance of 500 nm and this increases to 18.72 cent per kilowatt-hour for the longest distance.

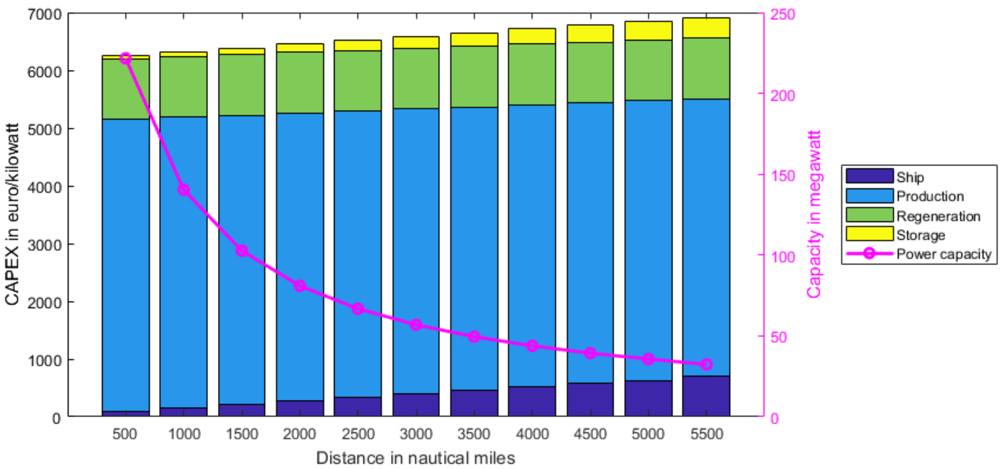
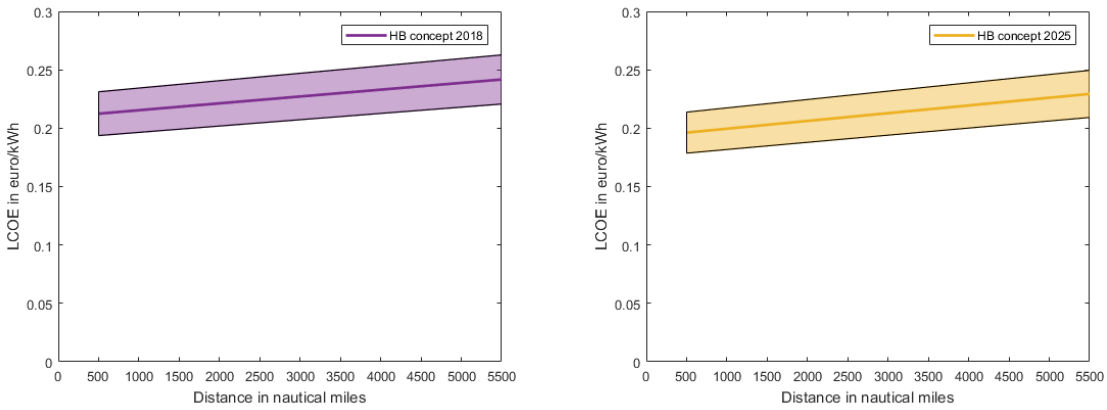


Figure 7.2: Invested capital per major component versus energy capacity of the Haber-Bosch 2025 concept

Summation Haber Bosch concepts

The concepts based on the Haber Bosch process do not meet the goal value set in Chapter 3 of 7.89 cent per kilowatt-hour. The results for the LCOE are visualised in Figure 7.3a and Figure 7.3b these figures show the average values plus a band in which 95% of the results were found and none of the concepts came in the range of the goal value.



(a) LCOE for Haber Bosch concept in 2018 (n = 10,000) (b) LCOE for Haber Bosch concept in 2025 (n = 10,000)

Figure 7.3: Results for the Haber Bosch concept

7.1.3. Ammonia concept based on Solis State Ammonia Synthesis

The second ammonia based concept is designed around the solid state ammonia synthesis. The technology is driven by the developments in the field of fuel cells.

A new development in ammonia synthesis is the solid state ammonia synthesis (SSAS). The main advantage of this new technology over the Haber-Bosch Process is the significantly reduced need for energy and economic benefits. The SSAS requires 7,000 - 8,000 kWh/ton NH_3[3], compared to the 12,000 kWh/ton NH_3 for the Haber-Bosch Process, the efficiency of the SASS is therefore in the range of 64% to 74%. The capital cost to produce a ton of NH_3 per day is estimated at 170,000 € for a test project.(Leighty [44]).[4]. If the energy which is necessary to produce a ton of ammonia is 7,500 kWh the capital cost of 170.000 euro per ton per day capacity translates to a price of 544 euro per kilowatt.

The cost of the SSAS equipment is assumed to be related to the development of electrolysers. At this moment these cost about 1,000 euro per kilowatt and prices are expected to decrease to 500-600 euro per kilowatt by commercial companies. If the research goals of the ECN institute are met these capital costs can even decrease to 200 euro per kilowatt by 2030.

The chemical process has similarities to the Haber-Bosch process but uses water in stead of pure hydrogen as a supply of hydrogen. Equation 7.2 shows the reaction which describes te process. (Garagounis et al. [26])

$$2N_2 + 6H_2O \rightleftharpoons 4NH_3 + 3O_2 \tag{7.2}$$

Unlike the Haber-Bosch Process the SSAS technology can not be used to produce energy with ammonia but the energy stored in ammonia can also be regenerated by using a fuel cell or burning ammonia as done with traditional carbon fuels in gas turbines or other applications. With solid oxide fuel cells experminental efficiencies of 60% and 70% have already been achieved in 2004.(Dekker and Rietveld [18])(Thomas and Parks [60])

Model design

The most important input parameters for the SSAS concept are the costs and conversion efficiencies of the SSAS system and the fuel cell. The capital cost of the SSAS unit are expected to be below 500 euro per kW or even drop to 200 euro per kW. Due to other installations and the building of power plant the capital costs are set at a lower value of 600 euro per kW and a upper value of 1,000 euro per kilowatt and a uniform distribution is applied. The energy consumption to produce one ton of ammonia is set at 7,500 to 8,000 kilowatt-hour per ton which translates to a conversion efficiency of 64.5% to 69%. The energy efficiency of the SSAS is better than that of the Haber-Bosch concept and the technology has to potential to be more cost effective, which allows for a more competitive concept. These values are summarized in Table 7.7.

The results for the LCOE are shown in Table 7.8. The calculations for all three discount rates do not get below the 10 cent per kilowatt-hour mark but the results are a lot better than those of the Haber-Bosch based

[3]One ton of liquid NH_3 = 5,166.7 kWh

[4]Conversion rate: 1$ = 0.85 €

Table 7.7: Input paramters SSAS

	Low value	High value	Distribution
Capital cost (euro/kW)	600	1,000	Uniform
Conversion efficiency	64.5%	69.0%	Uniform

Table 7.8: Results for the SSAS concept

Discount rate	5%	7%	10%
Distance (nm)	LCOE (cent/kWh)	LCOE (cent/kWh)	1LCOE (cent/kWh)
500	10.59	11.35	12.44
1,000	10.89	11.68	12.80
1,500	11.20	12.00	13.16
2,000	11.50	12.32	13.51
2,500	11.80	12.64	13.86
3,000	12.10	12.97	14.22
3,500	12.40	13.26	14.57
4,000	12.70	13.61	14.92
4,500	13.00	13.93	15.27
5,000	13.30	14.25	15.63
5,500	13.63	14.59	16.01

concepts. This better performance is the result of two factors. At first the round trip efficiency is higher (average 36.7%) because of the higher efficiency less energy is lost in the conversion processes from electricity to ammonia and back. The second important factor is the much lower capital cost. The components have a lower expected cost price per kilowatt installed power and less installed power is necessary due to the higher efficiencies. Figure 7.5 shows the relation between the capital cost and the installed power. The cost per kilowatt of power are almost half those of the Haber-Bosch concept with 3,600 euro per kilowatt at 500 nm and 3,950 euro per kilowatt at 5,500 nm.

The power capacity is the same because a transport concept with one ship with the same size is considered. The ship is the same for all ammonia concepts. This limits the volume of ammonia which can be shipped in a year and therefore limits the energy generation capacity.

7.1.4. Conclusions on the ammonia concept

In the ammonia concept three different concepts are analysed a concept for 2018, 2025 and 2030. The 2018 and 2025 concept use the Haber Bosch process to produce the ammonia in the port of loading and the 2030 concept uses Solid State Ammonia Synthesis (SSAS) to produce the ammonia. The production of ammonia by SSAS promises to have better results for the energy input necessary to produce ammonia. This also explains the reason why the 2030 concept outperforms the other two concepts. Figure 7.6 shows the results for the three concepts against the goal values for the four carbon cost scenario's.

Scenario 1 and 2 are the cost to generate electricity if the cost of carbon emission stay low, it can clearly be seen that the transport of energy with the ammonia concept does not outperform the power plants at these scenario's. If the other two scenario's are analysed the SSAS-based concept can outperform fossil fired power plants if these have to pay more for their carbon emissions. For the third scenario the average SSAS result meets the goal value at a distance of 2,000 nm and 95% of the results are better at 4,000 nm. The fourth scenario is always more expensive than the SSAS-based concept. The Haber-Bosch based concepts are not able to meet the goal values for any of the scenario's.

Although the SSAS concept does not meet all goal values it is the most promising concept of the three ammonia concepts. At the end of this chapter the concept will be compared to the thermal energy storage and transport concept.

7.2. Thermal energy storage concept

The transport model for the thermal energy storage is based on the model described in Chapter 5 and is altered for this concept.

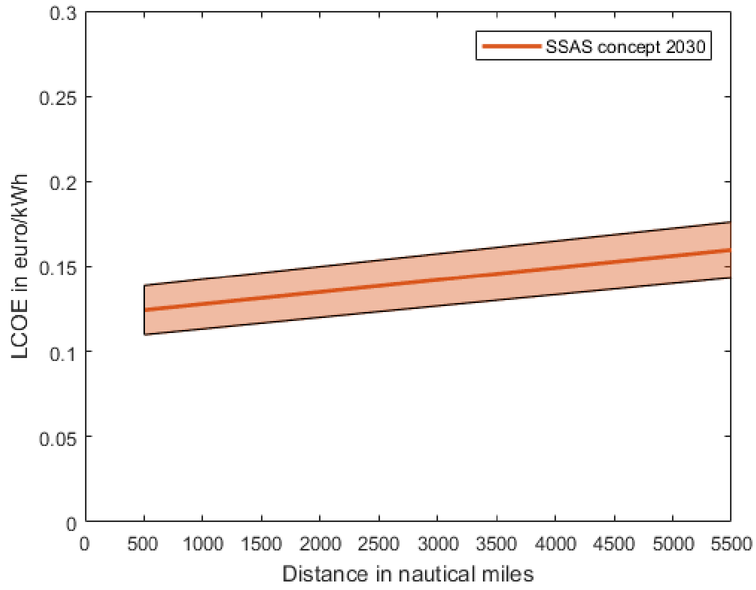


Figure 7.4: LCOE for SSAS concept in 2030 (n = 10,000)

Table 7.9: Results for the ammonia concepts (Discount rate = 7%)

Distance (nm)	Haber Bosch 2018 concept (cent/kWh)	Haber Bosch 2025 concept (cent/kWh)	SSAS concept 2030 (cent/kWh)
500	21.25	17.76	11.35
1,000	21.54	18.07	11.68
1,500	21.84	18.37	12.00
2,000	22.13	18.67	12.32
2,500	22.43	18.98	12.64
3,000	22.72	19.27	12.97
3,500	23.01	19.57	13.26
4,000	23.30	19.88	13.61
4,500	23.60	20.19	13.93
5,000	23.89	20.49	14.25
5,500	24.20	20.81	14.59

The cargo on board which is transported is kept either at high temperatures $\geq 500°C$. Therefore, insulation of the tanks reduces the loss of the cargo during transport. The cost of storage on board is assumed to be 5% of the cost of the steel cost of the ship. In this calculation only insulation is assumed to be necessary as all the other facilities such as foundations and tanks are already included in the ship model.

$$C_{insulation} = 0.1175 * 2000 * W_S^{0.85} \tag{7.3}$$

If the molten salt is stored in tanks on shore all costs are included so tanks, pumps, heat exchangers, foundations and insulation. The cost are set at a range of 700-850 euro as mentioned in Subsection 6.10.4.

The conversion efficiency of electric energy in thermal heat is assumed to be 95-98% energy efficient and back to electricity 42-45%. The losses during transport will be low for large volumes and are therefore taken in a range of 0.3 - 0.5% per day.

The energy which is delivered every year is calculated by the equation 7.4. In this equation the loss of energy during the transport is taken in account as a function of the voyage days.

$$E_{\text{delivered}} = DWT_{\text{cargo}} * RTPY * U * eta_C * \left(1 - \frac{distance}{24V_k} * \eta_L\right) \tag{7.4}$$

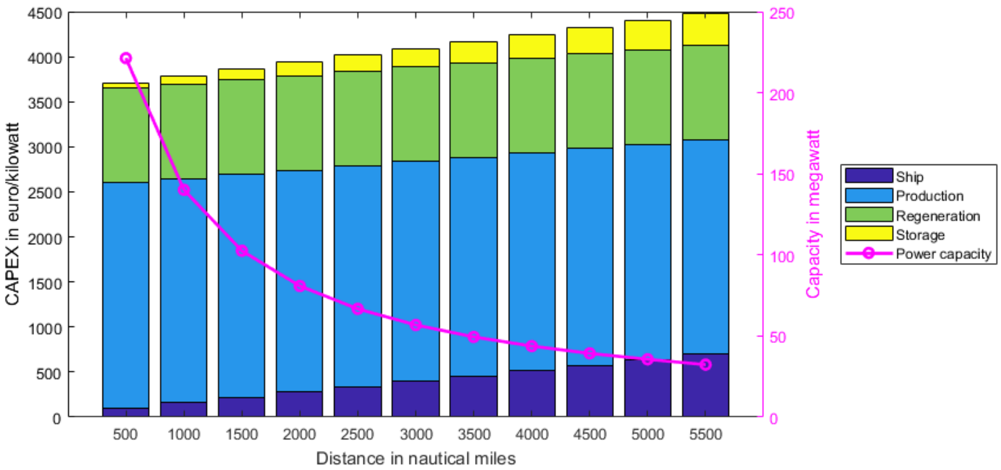


Figure 7.5: Invested capital per major component versus energy capacity of the SSAS 2030 concept

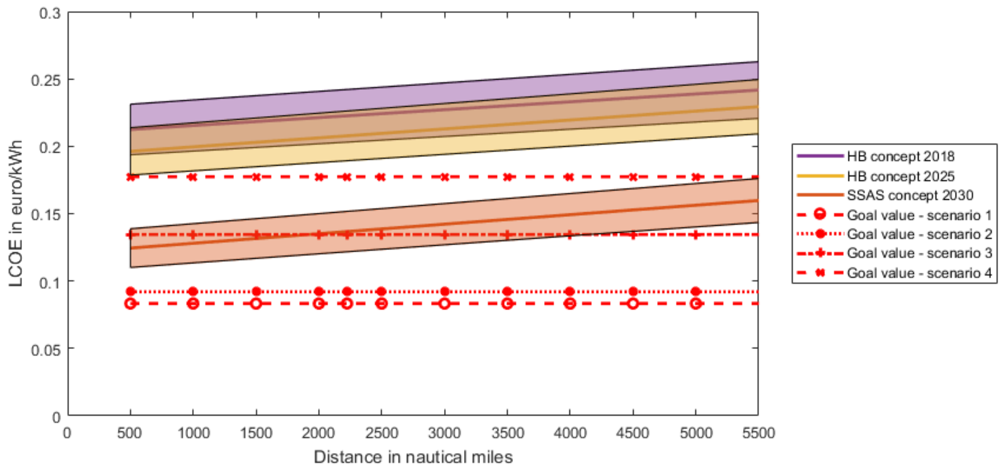


Figure 7.6: LCOE for the three different ammonia concepts (n = 10,000, discount rate = 7%)

where: DWT_{cargo} = mass of the cargo

$RTPY$ = Round trips per year

U = Specific energy denisty cargo

eta_C = Conversion efficiency

$distance$ = single voyage distance

V_k = Speed in knots

η_L = Loss of energy per day

The energy carrier in the thermal energy storage concept is molten salt. This salt has to be placed on board of the ship and in this design it is also placed in the port of loading and unloading. This allows for a constant production of heat in the port of loading and electricity in the port of unloading. The amount of salt necessary is calculated by:

$$m_{\text{salt}} = 2 * V_{\text{storage}} * \rho_{\text{sea}} + DWT_{\text{cargo}} \tag{7.5}$$

where: V_{storage} = Volume of the storage tanks in the ports

DWT_{cargo} = mass of the cargo

For the ammonia concepts an input range was applied to get a result which shows a range of results. This Monte Carlo like approach is used because there is uncertainty on the input values because in this stadium it can not be said what the exact numbers are. Table 7.10 shows the input parameters for the thermal concept. The cost for the heater to heat the salt to the storage temperature is taken at an interval of 900 to 1,000 euro per kilowatt and the efficiency is set at 95-98%(IRENA [37]). The steam turbine which is used to regenerate the heat is set at 900 to 1,000 per kilowatt and the efficiency is assumed to be 42 - 45%.

Table 7.10: Input paramters thermal energy concept

Parameter	Low value	High value	Distribution
Capital cost heater (euro/kW)	900	1,000	Uniform
Conversion efficiency heater	95%	98%	Uniform
Captial cost steam turbine (euro/kW)	900	1,000	Uniform
Conversion efficiency steam turbine	42%	45%	Uniform
Thermal loss per day storage	0.3%	0.5%	Uniform
Salt (euro/ton)	627	775	Uniform

7.2.1. Main dimension ship thermal storage concept

The built-in solver 'fmincon' has been used to define the optimal main dimension for the ship according to the model presented in Chapter 5. The dimensions used for the thermal concept ship can be seen in Table 7.11. The length and depth of the ship are not constrained as the ammonia concept is. This is chosen because the thermal concept depends on bulk transport because the cargo has a much lower specific energy density per ton.

Table 7.11: Main dimension ship for the thermal energy storage concept

Parameter	dimension	unit
Length oa	345.8	meter
Beam	46.3	meter
Depth	25.9	meter
Draugth	17.3	meter
Block coefficient	0.75	-
Speed	15.5	knots
Deadweight	176,730	tons
Installed power	25,837	kW

7.2.2. Results for the thermal concept

In this section the results for the thermal concept will be discussed. Just like the other concept the input parameter for the cost of energy at the port of loading is set at 2 cent but the thermal concept does not reach the goal values of 8.33 to 17.74 cent per kilowatt-hour and it does not outperform the ammonia concepts either. As can be seen in Table 7.12. These results are visualised in Figure 7.7 the concept has a high levelised cost of electricity compared to the ammonia concepts.

Two things are striking in Figure 7.9: the power capacity in the port of unloading is low (<70 MW) and the cost per kilowatt installed power are large (>10,000 euro/kW).

The main reason of these numbers is the small energy density compared to the ammonia concepts. Figure 7.9 shows the power rating of the concept in the port of unloading and this decreases rapidly form 70 megawatt to 10 megawatt at 5,500 nm. This lower power rating is a result of the low energy density of the energy stored in the molten salt (129 kWh/ton). Due to this low power rating in the port of unloading the cost per kilowatt of installed power increase because the total investment cost are divided by the power capacity in the port of unloading.

This low energy density also means that at larger distances the transport of the energy costs more energy than then energy which is stored in the ship. This leads obviously to a higher LCOE because of relative higher transport costs per kilowatt-hour. For the smallest distance (500 nm) this is already 10,000 euro per kilowatt and this increases to 50,000 euro per kilowatt for a distance of 5,500 nm.

Table 7.12: Result for the thermal energy storage concept

Discount rate	5%	7%	10%
Distance (nm)	LCOE (cent/kWh)	LCOE (cent/kWh)	1LCOE (cent/kWh)
500	18.76	20.67	23.78
1000	25.70	28.49	33.02
1500	32.69	36.37	42.35
2000	39.75	44.32	51.75
2500	46.86	52.33	61.23
3000	54.05	60.43	70.81
3500	61.34	68.64	80.51
4000	68.66	76.89	90.26
4500	76.05	85.21	100.10
5000	83.51	93.61	110.03
5500	91.04	102.09	120.05

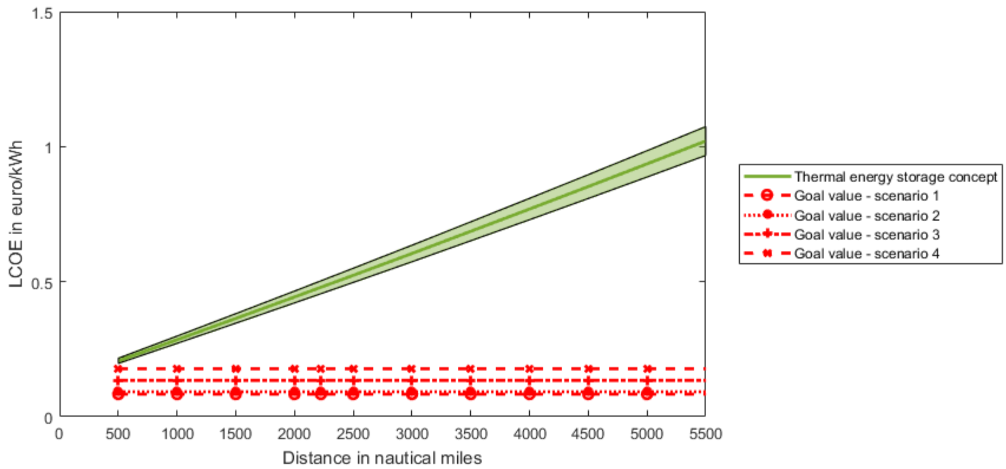


Figure 7.7: LCOE thermal energy storage concept (n = 10,000)

A quick calculation shows that with a deadweight of 150,000 ton, specific energy density of 129 kWh/ton and a 85% MCR of 17,000 kW the ship can sail a round trip distance of 17.600 nm. This would mean that for a round trip of 9,000 nm (distance between ports 4,500 nm) more than half of the stored energy is used to move the ship. This explains the 85.21 cent per kilowatt-hour LCOE which is shown in Table 7.12.

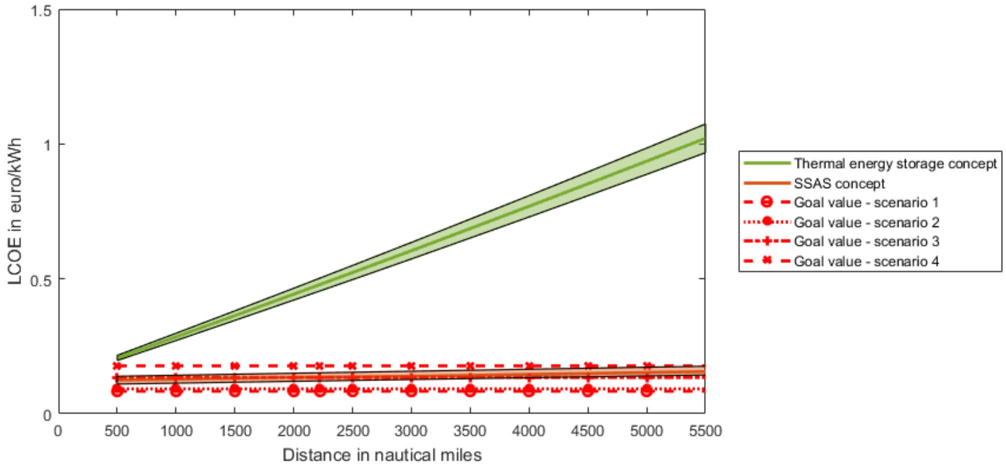


Figure 7.8: LCOE thermal energy storage concept compared to the LCOE of the SSAS concept (n = 10,000)

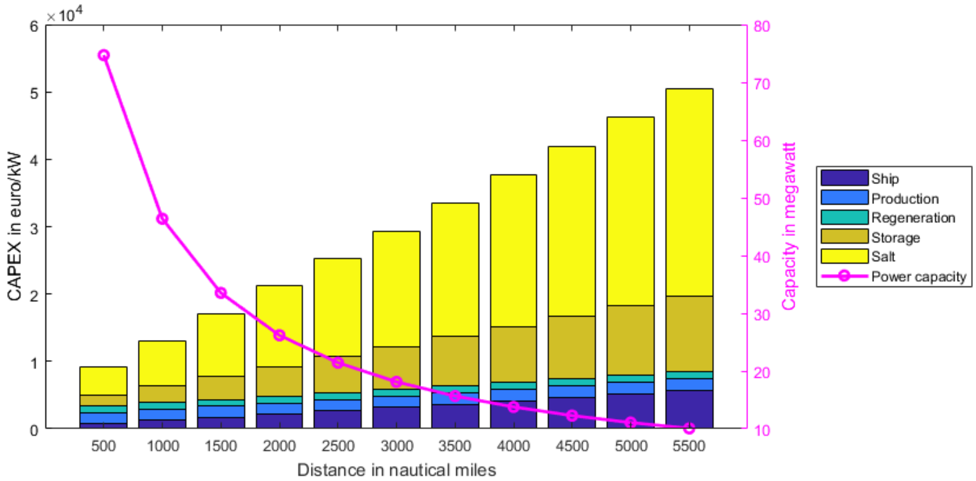


Figure 7.9: Capital investment per kilowatt power capacity versus power capacity in megawatt

If the thermal concept is compared to the best performing ammonia concept, SSAS, it is clearly visible that the ammonia concept offers a better LCOE (Figure 7.8). This can be explained by the higher specific energy density of ammonia, which results in the shipping of much more energy in one voyage. Furthermore, the ammonia concept suffers almost no loss of energy during transport as the product does not degrade. Another driving factor can be seen in Figure 7.9: the relative capital investment which is necessary for the thermal concept is large.

7.3. Conclusion on the transport concepts

The transport concepts presented in this chapter do not meet the goal value set in Chapter 3 but if the results for the concepts are compared the ammonia concept is favourable over the thermal energy storage and transport concepts.

The ammonia concept has a better LCOE and is not as much depending on distance as the thermal concept. The ammonia concepts transports a cargo with a higher energy density and can be seen as more valuable cargo. Less energy is lost in transport because the energy density is 40 times as high (5,166 kWh/ton vs 129 kWh/ton). Therefore it costs less energy to ship one unit of energy (kWh).

The best performing ammonia concept is based on the Solid State Ammonia Synthesis (SSAS). The goal value is not reached for all scenario's but the concept could deliver electrical energy for 11 to 12.4 cent per kilowatt-hour depending on the distance, which is the best concept calculated in this study. The SSAS-technique is still under development and the first real projects are still in their test phase (Leighty [44]). Future developments can reduce cost and improve efficiencies of the SSAS process which could make the concept more cost competitive and might reach the goal value.

8

Conclusion and recommendations

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

8.1. Conclusions

The transport of energy over long distances with ships is a trade with a long history. In the decades ahead the focus of transporting oil and gas could shift towards the transport of renewable generated energy. This trade can be developed along a north-south axis. Renewable energy will play a key role in the decades ahead as the goal of the Dutch government is to reduce the emission of carbon dioxide by 40%-50% by 2030 to comply to the Paris Climate Agreement.

There is be another driver for this change because renewable energy is getting more cost competitive compared to the big energy plants mostly fuelled by coal and gas. New offshore wind farms are being developed almost without subsidy and deliver energy for 5.45 cent per kilowatt hour. If the cost to connect the wind park to energy grid are included the price are higher well over 10 cent per kilowatt hour. According to Bloomberg this price can drop to 8.5 cent per kilowatt hour by 2035 in northern Europe. Other renewable energy such as solar energy are already a cost competitive. Bids as low as 2.0 cent per kilowatt hour have been placed in Dubai and solar energy plants delivering energy for 3.5 cent per kilowatt hour are under development but with solar the costs to generate energy are strongly linked to the place where the solar panel are placed. Locations in the band between 20° to 30° north and south of the equator have a much higher solar irradiance which leads to a higher production per solar panel which lowers the cost per unit of energy. This together with the huge demand for energy in northern regions is reason to develop a transport concept which transport energy along a north-south axis.

In this research a transport concept to transport electric energy between locations is developed. On board the energy is stored in a chemical form. Direct storage of electric energy in electro-chemical storage units is too expensive. The round trip efficiency of a battery storage system is >85% but due to the high capital cost for the storage capacity it is not a suitable solution. This is due to the low number of cycles a battery system would make if it is used for long range transport. When electric energy is converted in another energy carrier and in the port of unloading regenerated to electric energy conversion losses are inevitable.

For the selection of a suitable energy carrier: specific energy density, round trip efficiency and the capital investment are driving parameters. The model showed that an energy density larger than 2,500 kWh per ton is favourable from this follows that hydrogen carriers are the most suitable solutions. Most hydrogen energy carriers are still under development and are either being tested on a small scale or being prepared for laboratory research (TRL 3-5). Pure hydrogen or ammonia are being used on a industrial scale already and offer the high specific energy density.

Ammonia (NH_3) is selected as a energy carrier in this research. Ammonia offers a higher energy density per volume than hydrogen and can be stored on -33°C at atmospheric pressure. Hydrogen has to be stored at -253°C or 700 bar. To liquefy one hydrogen costs 10kWh of energy which is roughly 25% of the energy content in a kilogram. The same order of energy does it cost to transfer a kilogram hydrogen into ammonia.

If the energy is produced using the well known Haber-Bosch process in 2018 the levelised cost of energy is 21.2 to 24.2 cent per kilowatt hour depending on the distance. Developments in the field of electrolysers will reduce the capital investment which can reduce the price to 17.8 to 20.8 cent per kilowatt hour by 2025 if

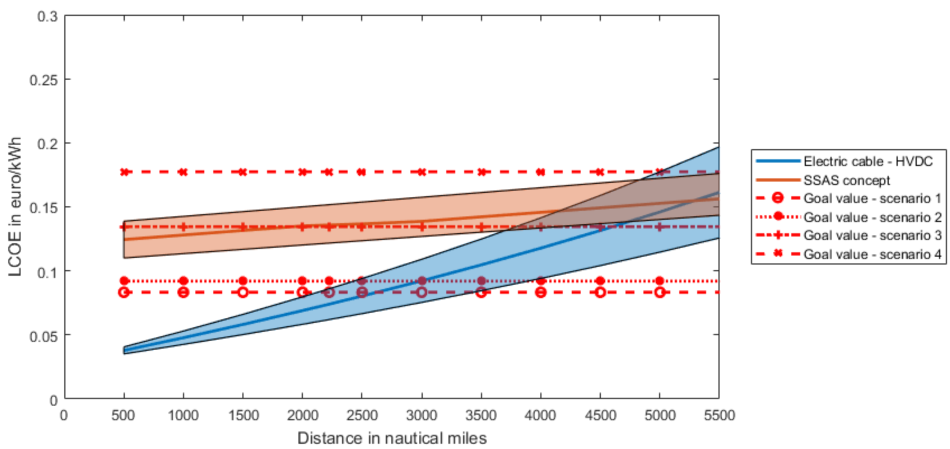


Figure 8.1: SSAS plotted against the cable and the goal value

the energy is supplied at 2 cent per kilowatt hour to the ammonia production facility.

New developments such as the Solid State Ammonia Synthesis (SSAS) have a much larger impact. The cost of this production method is related to the developments in the cost of electrolysers and this method would increase the round trip efficiency to 50% which is double the round trip efficiency of the Haber-Bosch process. If the energy is supplied at 2 cent per kilowatt hour a LCOE of 11.4 to 14.6 cent per kWh is possible. This concept does not meet the goal value.

Compared to an electric cable connection the ammonia based concept can compete if the distance gets larger than 4,000 nautical miles. If only competition based on distance and LCOE is considered. This is visualised in Figure 8.1 A second storage concept which was tested in this research was energy transport in the form of heat. Heat can easily be stored in molten salt and regenerated with a steam turbine. This technique is already mature and available on an industrial scale. The lower specific energy density (129 kWh/ton) and maximum theoretical round trip efficiency of 42% make this concept more expensive than ammonia and large improvements are not likely. The LCOE is 28.5 cents at 1,000 nautical miles and gets larger if the distance increases. The thermal energy storage concept is not suitable for this application.

The cable is one reference case but the system also has to deliver a better cost performance in the market where the energy is supplied to. To make this comparisson four different scenario's are defined based on different carbon emission cost. The first two scenario's assume carbon emission cost comparable to the values most countries apply at this moment, the third and fourth scenario apply much larger emission cost which are equal to the highest carbon price calculated by Sweden and the fourth scenario is the carbon cost scenario according to some environmental scientists. The SSAS concept is not able to be competitive at the low cost carbon scenario's but if the price of emission increase the concept can be competitive. At a distance smaller than 2,500 nm the SSAS concept is more cost efficient than a fossil fired power plant in the home market for the third scenario. The concept always outperforms the highest cost carbon scenario power plant.

The main conclusion of this research would be that the sea transport of bulk electric energy is possible but the market would have to charge high carbon emission costs in the order of magnitude equal to scenario 3 or more (100 euro/tCO_2 and 5% increase per year). Upto distance of 5,000 nm the cable can be more cost competitive but it has to be taken in mind that there have never been laid such large electrical subsea connections and a fixed cable solution implies some complicated technical problems with grid stability

8.2. Recommendations

In this research assumptions according the efficiencies and investment costs are made based on literature and interviews with companies. For the next step more accurate figures about the efficiencies and capital investments of the SSAS are necessary. The capital investments can be divided in the cost for the SSAS units, fuel cells or gas turbines to regenerate the energy and cost to develop the production sites.

The developments in the shore based facilities are most important. Higher TRL levels for the SSAS process are critical when this reaches levels of 7 or more the concept could be worked out in more detail. Cooperation with other parties could be used to share risks and to speed up development processes.

Pure hydrogen is not considered to be an energy carrier due to the extreme conditions in which it has to be stored. More research into large scale pure hydrogen storage is needed.

One of the strong aspects of the ammonia based concept is the flexibility of the storage method. Ammonia could easily be stored for long times in (underground) caverns or tanks. It is expected that seasonal storage is going to be a large market in the decades ahead but this has not been researched in this report.

A

Port tariffs

Every time a ship makes a port call it has to pay the port authority seaport dues and dues to third parties for assistance by tug boats, mooring, unmooring and shifting of the ship, piloting and other services.

The total seaport dues to be paid in the port of Rotterdam are related to the Gross Tonnage, draught, deadweight tonnage, length and number of port calls per year.

A.1. Port dues

The calculation of the port dues is based on the Gross tonnage (GT) of a ship. The GT is a measure for the internal enclosed volumes of a ship. The GT is defined in the *International Convention on Tonnage Measurement of Ships, 1969* in Regulation 3 of Annex 1.

The GT of the ship is defined by the formula:

$$GT = K_1 V \tag{A.1}$$

Where V is the volume of enclosed spaces of the ship expressed in cubic meters and $K = 0.2 + 0.02 log_{10} V$. The total volume of the ship is not known in the concept phase. Therefore, the enclosed volume is approximated by:

$$V = LBDC_B \tag{A.2}$$

The port dues for the port of Rotterdam are defined in *GENERAL TERMS AND CONDITIONS* Annex 1 published by HAVENBEDRIJF ROTTERDAM N.V. The switch percentage applicable for the ship is 133.7%, an GT tariff of 0.300 and a cargo tariff of 0.488 as defined in schedule 1 'Port dues gross tonnage' and schedule 2 'Port dues cargo volume'. No discounts on the port dues for the are applicable. The port dues are can be calculated by the formula:

$$\text{Port dues} = GT * 0.300 + min(GT * 1.337 * 0.488; DWT * 0.488) \tag{A.3}$$

A.2. Piloting

Pilotage is mandatory for almost all sea going ships when they enter a port. Coastal waters are shaped by rivers, currents and wind, and are subject to constant and unpredictable change. In order to enter a port safely a pilot is required. The tariff for the pilot in the model is based on the *Pilotage tariffs 2016 - region Rotterdam-Rijnmond.* The cost of the pilotage are the start tariff and entering of the 1^{th} Maasvlakte. The tariff given by the Loodswezen is given in a table and are based on the draught of the ship. The values in the table can be approximated by a linear function:

$$\text{Pilot tariff} = 1,251.9 * T - 3,585.6 \tag{A.4}$$

The coefficient of determination is 0.9961 which is a good indication for the fit of the function on the data in the table.

A.2.1. Quantity discount on piloting

A ship or group of sister ship's which make frequent port calls can get a discount on the pilotage tariff. The discount is based on the number of port calls and the length of the ship. Table A.1 shows the discount applied by the Loodswezen for the port of Rotterdam.

Table A.1: Quantity discount on piloting

Ship's length over all (m)	81-120,99	121-160,99	161-200,99	201-240,99	241-280,99	281-320,99	321-360,99	>361
Number of calls on a yearly basis								
0-17	0%	0%	0%	0%	0%	0%	0%	0%
18-36	0%	0%	0%	10%	19%	20%	20%	20%
37-48	0%	0%	0%	13%	21%	22%	22%	22%
49-60	0%	0%	8%	15%	23%	24%	24%	24%
61-72	0%	6%	10%	17%	26%	27%	27%	27%
73-84	6%	6%	13%	20%	29%	31%	31%	31%
85-96	6%	8%	15%	22%	31%	34%	34%	34%
97-108	8%	10%	17%	24%	34%	36%	36%	36%
109-120	10%	13%	20%	28%	36%	38%	38%	38%
121-132	13%	15%	22%	30%	38%	41%	41%	41%
133-144	15%	17%	24%	33%	42%	44%	44%	44%
145-156	17%	20%	27%	33%	42%	44%	44%	44%
157-168	20%	22%	29%	33%	42%	44%	44%	44%
169-180	22%	24%	29%	33%	42%	44%	44%	44%
181-365	23%	26%	29%	33%	42%	44%	44%	44%

A.3. Harbour towage

The cost of assistance by tugs for sea-going ships is calculated based on the overall length as defined by the classification societies. In the port of Rotterdam three companies provide assistance to sea-going ships. In the model cost for tugboat assistance is calculated based on these three suppliers and the tariffs are shown in Table A.2. The script selects the cost for assistance based on the lowest price available in the port of Rotterdam. This is assumed to be the same as in other ports.

Table A.2: Assistance to sea-going vessels

Vessel's length overall in meters	Fairplay towage Assistance in euro	Vessel's length overall in meters	Smit Harbour Towage Rotterdam B.V. Assistance in euro	Vessel's length overall in meters	Kotug Assistance in euro
0 - 130	1,200	up to - 138	1,200	up to - 138	1,170
131 - 160	1,400	139 - 150	1,345	139 - 150	1,310
161 - 190	1,800	151 - 163	1,510	151 - 163	1,475
191 - 220	2,325	164 - 175	1,715	164 - 175	1,670
221 - 250	2,625	176 - 187	1,920	176 - 187	1,870
251 - 280	3,050	188 - 212	2,280	188 - 212	2,215
281 - 310	3,375	213 - 236	2,655	213 - 236	2,580
311 - 340	3,825	237 - 260	3,010	237 - 260	2,910
341 - 370	3,975	261 - 285	3,335	261 - 285	3,230
371 - 500	4,200	286 - 309	3,570	286 - 309	3,500
		310 - 334	3,805	310 - 334	3,740
		335 - 358	4,040	335 - 358	3,960
		359 - 383	4,285	359 - 383	4,200
		384 - 425	4,490	384 - 425	4,420

A.4. Mooring and unmooring

A ship needs assistance with the mooring and unmooring of the ship, this assistance is provided with tugs from the water and from the shore by boatman.

The cost for boatman is given in data table based on the ship's length and is approximated with a polynomial function with a coefficient of determination of 0.9972. Equation A.5 shows the formula used in the model to calculate the cost.

$$\text{Mooring and unmooring tariff} = 0.0778 * L^2 - 13.997 * L + 824.89 \tag{A.5}$$

A.5. Monitoring, visit reporting and VTS

Small other third party services are provided to a port entering ship such as monitoring, visit reporting and VTS. The dues for these services are provided by the port of Rotterdam and applied in the model. Tables A.3, A.4 and A.5 show the tariffs for these services.

Table A.3: Port visit monitoring - Reporting tariff

DWT up to	Tariff
1,500	55
3,000	75
4,500	105
7,500	135
12,000	170
17,500	195
22,500	225
30,000	250
37,500	280
50,000	315
62,500	345
>62,500	375

Table A.4: Visit reporting service Rotterdam - Reporting tariff

DWT up to	Tariff
4,500	30
17,500	60
37,500	90
75,000	120
125,000	150
250,000	180
400,000	210
>400,000	240

Table A.5: VTS - Reporting tariff

Overall length in meters	Tariff
< - 40	free of charge
41 - 99	113.45
100 - 249	113.45 + 7.71 * (length - 100)
250 - >	1,269.95

B
Propulsive power prediction

The power demand for the ship is calculated in this model based on the parameters for length, beam, draught, block coefficient and speed. These are the same as for the levelised cost of electricity optimisation tool.

For this calculation the approach described by J. Holtrop and G.G.J. Mennen is used[34] [35]

C

Ship model

Table C.1: Constraint definition

Constraint	Equation/definition	Explanation
c(1)	$8.5 - L/B \leq 0$	Constraint on the length-to-beam ratio
c(2)	$L/B - 14.9 \leq 0$	Constraint on the length-to-beam ratio
c(3)	$L/D - 15 \leq 0$	Constraint on the length-to-depth ratio
c(4)	$L/T - 19 \leq 0$	Constraint on the length-to-draft ratio
c(5)	$T - 0.45\ DWT^{0.31} \leq 0$	Empirical constraint on the relationship between deadweight and draft
c(6)	$T - 0.7\ D + 0.7 \leq 0$	Empirical constraint on relationship between depth and draft.
c(7)	$DWT - 500{,}000 \leq 0$	Upper constraint on deadweight.
c(8)	$25{,}000 - DWT \leq 0$	Lower constraint on deadweight.
c(9)	$F_n - 0.32 \leq 0$	Constraint on Froude number.
c(10)	$0.07\ B - KB - BM_T + KG \leq 0$	Empirical constraint on relationship between beam, vertical location of centres of buoyancy and gravity, and metric radius.
c(11,12)	$50 \leq L \leq 375$	Upper and lower bounds of ship length.
c(13,14)	$20 \leq B \leq 60$	Upper and lower bounds of beam.
c(15,16)	$13 \leq D \leq 30$	Upper and lower bounds of depth.
c(17,18)	$6 \leq T \leq 20.1$	Upper and lower bounds of draft.
c(19,20)	$0.50 \leq C_B \leq 0.82$	Upper and lower bounds of block coefficient.
c(21,22)	$11 \leq v_k \leq 20$	Upper and lower bounds of speed (in knots).

Bibliography

[1] Netherlands: Coal impots, May 2017. URL www.theglobaleconomy.com/Netherlands/coal_imports.

[2] ABB. Abb wins orders over $ 300 milion for world's first 1,100 kV UHVDC power link in China.

[3] Ahmed Afif, Nikdalila Radenahmad, Quentin Cheok, Shahriar Shams, Jung H. Kim, and Abul K. Azad. Ammonia-fed fuel cells: a comprehensive review. *Renewable and Sustainable Energy Reviews*, 60:822 – 835, 2016. ISSN 1364-0321. doi: http://dx.doi.org/10.1016/j.rser.2016.01.120. URL http://www.sciencedirect.com/science/article/pii/S1364032116001611.

[4] Siemens AG. Efficiency turns less into more - Siemens steam turbine portfolio, 2017. URL https://www.energy.siemens.com/mx/pool/hq/power-generation/steam-turbines/downloads/new/siemens-steam-turbines-product-overview-EN-updated.pdf.

[5] International Energy Agency. *Projected Costs of Generating Electricity*. 2010.

[6] International Energy Agency. Energy Technology Perspectives 2014 - Harnessing Electricity's Potential, May 2014.

[7] Daniel Akinyele and Ramesh Rayudu. Review of energy storage technologies for sustainable power networks. 8:74–91, 12 2014.

[8] Greg Albright, Jake Edie, and Said Al-Hallaj. A comparison of lead acid to lithium-ion in stationary storage applications. *AllCell Technologies LLC*, Mar 2012.

[9] Edward Barbour, I.A. Grant Wilson, Jonathan Radcliffe, Yulong Ding, and Yongliang Li. A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, 61(Supplement C):421 – 432, 2016. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2016.04.019. URL http://www.sciencedirect.com/science/article/pii/S1364032116300363.

[10] Jeffrey Ralph Bartels. A feasibility study of implementing an ammonia economy, 2008.

[11] V. Bertram and H. Schneekluth. *Ship Design for Efficiency and Economy*. Elsevier Science, 1998. ISBN 9780080517100. URL https://books.google.nl/books?id=Uq07g98n0TAC.

[12] Bloomberg. Falling costs has U.K. headed for subsidy-Free offshore wind power, June 2017.

[13] Simon Bourne. Scaling PEM electrolysis to 100MW. In *Hannover messe 2017*, April 2017.

[14] Business Insider. CO2 EUROPEAN EMISSION ALLOWANCES, January 2018. URL http://markets.businessinsider.com/commodities/co2-emissionsrechte.

[15] Centraal Bureau voor de Statistiek. Aandeel hernieuwbare energie 5,9 procent in 2016, May 2017. URL https://www.cbs.nl/nl-nl/nieuws/2017/22/aandeel-hernieuwbare-energie-5-9-procent-in-2016.

[16] Haisheng Chen, Thong Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, and Yulong Ding. Progress in electical enery strorage system: A critical review. *Progress in Natural Science*, 19:291–312, July 2008.

[17] Jose Pereira da Cunha and Philip Eames. Thermal energy storage for low and medium temperature applications using phase change materials – a review. *Applied Energy*, 177(Supplement C):227 – 238, 2016. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2016.05.097. URL http://www.sciencedirect.com/science/article/pii/S0306261916306948.

[18] Nico Dekker and Bert Rietveld. Highly efficicent conversion of ammonia in electricity by solid oxide fuel cells. *6^{th} European Solid Oxide Fuel Cell Forum*, page 1524, June 2004.

[19] Francisco Díaz-Gonzaález, Andreas Sumper, Oriol Gomis-Bellmunt, and Roberto Villafáfila-Robles. A review of energy storage applications for wind power applications. *Renewable and Sustainable Energy Reviews*, December 2012.

[20] K.C. Divya and Jacob Østergaard. Battery energy storage technology for power systems—an overview. *Electric Power Systems Research*, 79(4):511 – 520, 2009. ISSN 0378-7796. doi: https://doi.org/10.1016/j.epsr.2008.09.017. URL http://www.sciencedirect.com/science/article/pii/S0378779608002642.

[21] Wind Europe. The European offshore wind industry – key trends and statistics 2016, January 2017. URL https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-and-statistics-2016/.

[22] Eurostat Statistics Explained. Energy price statistics. URL http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Electricity_prices_for_industrial_consumers.

[23] Katie Fehrenbacher. A jaw-dropping world record solar price was just bid in Abu Dhabi. *Fortune*, September 2016.

[24] Financieel Dagblad. Stekker uit rotterdams project voor opvang CO_2, June 2017.

[25] Fraunhofer ISE. Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. *Study on behalf of Agora Energiewende*, 2015.

[26] Ioannis Garagounis, Vasileios Kyriakou, Aglaia Skodra, Eirini Vasileiou, and Michael Stoukides. Electrochemical synthesis of ammonia in solid electrolyte cells. *Frontiers in Energy Research*, 2:1, 2014. ISSN 2296-598X. doi: 10.3389/fenrg.2014.00001. URL http://journal.frontiersin.org/article/10.3389/fenrg.2014.00001.

[27] Monterey Gardiner. Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs. *DOE Hydrogen and Fuel Cells Program Record*, July 2009.

[28] P. Gimenez and S. Fereres. Effect of heating rates and composition on the thermal decomposition of nitrate based molten salts. *Energy Procedia*, 69(Supplement C):654 – 662, 2015. ISSN 1876-6102. doi: https://doi.org/10.1016/j.egypro.2015.03.075. URL http://www.sciencedirect.com/science/article/pii/S1876610215003811. International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014.

[29] Ioannis Hadjipaschalis, Andreas Poullikkas, and Venizelos Efthimiou. Overview of current and future energy storage technologies for electric power applications. *Renewable and Sustainable Energy Reviews*, 13(6):1513 – 1522, 2009. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2008.09.028.

[30] Christopher G. Hart and Nickolas Vlahopoulos. An integrated multidisciplinary particle swarm optimization approach to conceptual ship design. *Structural and Multidisciplinary Optimization*, 41(3): 481–494, Apr 2010. ISSN 1615-1488. doi: 10.1007/s00158-009-0414-0. URL https://doi.org/10.1007/s00158-009-0414-0.

[31] Russell Hensley, John Newman, and Matt Rogers. Battery technology charges ahead. *McKinsey Quarterly*, July 2012.

[32] Ulf Herrmann, Bruce Kelly, and Henry Price. Two-tank molten salt storage for parabolic trough solar power plants. *Energy*, 29(5):883 – 893, 2004. ISSN 0360-5442. doi: https://doi.org/10.1016/S0360-5442(03)00193-2. URL http://www.sciencedirect.com/science/article/pii/S0360544203001932. SolarPACES 2002.

[33] ABB's high voltage cable unit in Sweden. Submarine power cables, May 2008.

[34] J. Holtrop and G.G.J. Mennen. Statistical power prediction method. 25:253–256, October 1978.

[35] J. Holtrop and G.G.J. Mennen. An approximate power prediction method. 29(335):166–170, July 1982.

[36] International Renewable Energy Agency (IRENA). Renewable energy technologies: cost analysis series – concentrating solar power, June 2012.

[37] IRENA. Concentrating solar power. *RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES*, 1, June 2012.

[38] Kai-Philipp Kairies. Battery storage technology improvements and cost reductions to 2030: A deep dive, March 2017. URL https://costing.irena.org/media/11341/2017_Kairies_Battery_Cost_and_Performance_01.pdf.

[39] J.K. Kaldellis and D. Zafirakis. Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency. *Energy*, 32(12):2295 – 2305, 2007. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2007.07.009. URL http://www.sciencedirect.com/science/article/pii/S0360544207001302.

[40] Kotaro Kawajiri, Takashi Oozeki, and Yutaka Genchi. Effect of temperature on pv potential in the world. *Environmental Science & Technology*, 45(20):9030–9035, 2011. doi: 10.1021/es200635x. URL http://dx.doi.org/10.1021/es200635x. PMID: 21851102.

[41] A. Kirubakaran, Shailendra Jain, and R.K. Nema. A review on fuel cell technologies and power electronic interface. *Renewable and Sustainable Energy Reviews*, 13(9):2430 – 2440, 2009. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2009.04.004. URL http://www.sciencedirect.com/science/article/pii/S1364032109000872.

[42] C.J. Kruse, National Research Council (U.S.). Transportation Research Board, National Cooperative Freight Research Program, United States. Department of Transportation. Research, Innovative Technology Administration, Texas Transportation Institute, and Cambridge Systematics. *Marine Highway Transport of Toxic Inhalation Hazard Materials*. NCFRP report. Transportation Research Board, 2012. ISBN 9780309258418.

[43] Sarada Kuravi, Jamie Trahan, D. Yogi Goswami, Muhammad M. Rahman, and Elias K. Stefanakos. Thermal energy storage technologies and systems for concentrating solar power plants. *Progress in Energy and Combustion Science*, 39(4):285 – 319, 2013. ISSN 0360-1285. doi: https://doi.org/10.1016/j.pecs.2013.02.001. URL http://www.sciencedirect.com/science/article/pii/S0360128513000026.

[44] William C. Leighty. Solid state ammonia synthesis (SSAS) pilot plant demonstration system for renewable energy (RE) firming storage, transmission, and export, June 2013.

[45] Haichang Liu and Jihai Jiang. Flywheel energy storage—an upswing technology for energy sustainability. *Energy and Buildings*, 39(5):599 – 604, 2007. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2006.10.001. URL http://www.sciencedirect.com/science/article/pii/S0378778806002350.

[46] Patrick Luckow, Elizabeth A. Stanton, Spencer Fields, Bruce Biewald, Sarah Jackson, Jeremy Fisher, and Rachel Wilson. 2015 Carbon Dioxide Price Forecast. *Synapse Energy Economics, Inc.*, March 2015.

[47] MAN Diesel & Turbo. *MAN B&W ME-B-Engines*, September 2012.

[48] R. McKenna, S. Hollnaicher, P. Ostman v. d. Leye, and W. Fichtner. Cost-potentials for large onshore wind turbines in europe. *Energy*, 83:217 – 229, 2015. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2015.02.016. URL http://www.sciencedirect.com/science/article/pii/S0360544215001681.

[49] S. Mekhilef, R. Saidur, and A. Safari. Comparative study of different fuel cell technologies. *Renewable and Sustainable Energy Reviews*, 16(1):981 – 989, 2012. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2011.09.020. URL http://www.sciencedirect.com/science/article/pii/S1364032111004709.

[50] U.S. Department of Energy Office of Energy Efficiency & Renewable energy. Physical hydrogen storage. URL https://energy.gov/eere/fuelcells/physical-hydrogen-storage.

[51] Michael G. Parsons and Randall L. Scott. Formulation of multicriterion design optimization problems for solution with scalar numerical optimization methods. *Journal of Ship Research*, 48(1):61–76, March 2004.

[52] BP p.l.c. Bp energy outlook 2017 edition, July 2017.

[53] Annie Protopapas, C. James Kruse, Leslie E. Olson, Michael B. Donelan, and Nathan Hutson. Marine highway transport of toxic inhalation hazard materials. *Transportation Research Record: Journal of the Transportation Research Board*, 2012.

[54] Suparna Ray and April Lee. Eia publishes construction cost information for electric power generators. *U.S. Energy Information Administration*, June 2016.

[55] Ramana G. Reddy. Molten salts: Thermal energy storage and heat transfer media. *Journal of Phase Equilibria and Diffusion*, 32(4):269, July 2011. ISSN 1863-7345. doi: 10.1007/s11669-011-9904-z. URL https://doi.org/10.1007/s11669-011-9904-z.

[56] Siemens. High-voltage direct current transmission (HVDC), May 2014.

[57] Solargis. Solargismaps. URL http://solargis.com/assets/graphic/free-map/DNI/Solargis-World-DNI-solar-resource-map-en.png.

[58] Grigorii L. Soloveichik. Battery technologies for large-scale stationary energy storage. *Annual Review of Chemical and Biomolecular Engineering*, 2(1):503–527, 2011. doi: 10.1146/annurev-chembioeng-061010-114116. URL https://doi.org/10.1146/annurev-chembioeng-061010-114116. PMID: 22432629.

[59] M. Stopford. *Maritime Economics*. Routledge, 1997. ISBN 9780415153102. URL https://books.google.nl/books?id=_R-YB70kly8C.

[60] George Thomas and George Parks. Potential roles of ammonia in a hydrogen economy, February 2006.

[61] Centraal Bureau voor de Statistiek. Wind steeds belangrijker voor productie van hernieuwbare elektriciteit, July 2017. URL https://www.cbs.nl/nl-nl/nieuws/2016/09/wind-steeds-belangrijker-voor-productie-van-hernieuwbare-elektriciteit.

[62] VVD and CDA and D66 and ChristenUnie. Regeerakoord 2017 - Vertrouwen in de toekomst, October 2017. URL https://www.tweedekamer.nl/sites/default/files/atoms/files/regeerakkoord20172021.pdf.

[63] D.G.M. Watson. *Practical Ship Design*. Elsevier ocean engineering book series. Elsevier, 1998. ISBN 9780080429991.

[64] World Bank; Ecofys. Carbon pricing watch 2017. *Washington, DC: World Bank*, 2017. URL https://openknowledge.worldbank.org/handle/10986/26565.

[65] X. Xiang, M. M. C. Merlin, and T. C. Green. Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection. In *12th IET International Conference on AC and DC Power Transmission (ACDC 2016)*, pages 1–6, May 2016. doi: 10.1049/cp.2016.0386.