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ABSTRACT

In MoVe IT! Task 6.6 was investigated if existing inland vessels can be adapted to the potential market of CO_2-transport.

Assessment of a candidate solution leads to the conclusion, that transport of liquefied CO_2 in independent tanks can be considered as technically feasible in general and is applicable to existing inland vessels.

A business case study showed however that IWW transport of CO_2 is economically not feasible, even if a rather large ship type (110m Rhine vessel) is considered: The transport costs for the shipment of liquefied CO_2 over a distance of 600 km are approximately three times as high as the current prices of futures (2013 and 2020) on Carbon Credits (CERs). Secondly, additional costs incur if liquefaction and offshore transport to a storage field with sea-going ships are considered. Finally, inland shipping has to compete with pipeline transport, which has roughly 25% lower costs per tonne of CO_2 transported over the same distance.

Transport of CO_2 with inland ships may become an economically feasible alternative if the price of carbon credits rises to its introductory level or even further increases

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TABLE OF CONTENTS

1. Executive Summary

1.1. Problem Definition

Transportation of CO_2 is considered as a potential market for inland shipping, for which so far no suitable capacity exists, nor specific rules are in place.

For the amounts of CO_2 that would result if Carbon Capture and Storage (CCS) are applied to large power plants, ships and transport systems need to be developed.

In MoVe IT! adaptation of existing inland vessels to CO_2 transport is addressed as a candidate solution. New technical requirements then arise with respect to safe transport and efficiently storing CO_2. Furthermore logistical issues emerge around door-to-door transport of CO_2. Finally, the envisaged transport solution has to be economically feasible.

1.2. Technical Approach

The aim of task 6.6 is to investigate in how far existing vessels can be adapted to new markets, in this case to transport CO_2. Technical solutions to safely transport CO_2 exist, however, they are not yet applied to inland vessels. The feasibility of adjusting existing inland vessels to CO_2 transport is therefore assessed in technical and economic sense.

A three step research approach is followed to investigate the feasibility and practicality of adaptation to CO_2 transport as retrofit options for existing vessels:

1. Market analysis to identify the potential markets for CO_2 transport, relevant transport relations and its place in a multi-modal transport chain;
2. Investigation of technical and logistical requirements regarding CO_2 storage on board of and transport with inland ships;
3. Economic feasibility study comprising a cost break-down for CCS, cost estimation for CO_2 transport with adapted inland ships and a comparison with the price development of Certified Emission Reduction units (CERs).

1.3. Results and Achievements

Transport of CO_2 in the context of CCS has been identified as a potential market for inland shipping. Technologies to safely and effectively store and transport CO_2 with inland ships are available.

In the context of MoVe IT!, looking at retrofit options for existing ships, an approach comprising transport of liquefied CO_2 in independent pressure tanks has been analysed and considered as technically feasible in general sense.

The economic feasibility of this solution has been assessed by means of a cost calculation for an adapted 110m Large Rhine Vessel sailing on a 1200 km roundtrip between a power plant and a seaport. This choice depends on the assumption that presumably a minimum payload is necessary to approve a transport solution as feasible. If the assessed solution isn't feasible, transport with smaller vessels also proves to be not efficient. Relatively high investment costs together with lower payload would increase the total transport costs per unit [€/t] of smaller vessels (e.g. Johan Welker type) by 50% compared to the Large Rhine Vessel.

The 110m Large Rhine vessel, with an estimated investment of 4.5 million € for tank equipment and conversion, would result in average transport costs of approx. 20 € per tonne CO_2. The case was found to be economically not feasible as the transport costs for IWT already exceed the current (Apr. 2013) price of CO_2 certificates. Moreover, the considered transport costs only cover the transport of CO_2 from a power plant to a sea port with inland ships. Additional costs for CCS like CO_2 capturing, liquefaction, buffer storage, offshore transport and disposal further reduce the economic feasibility of CO_2 transport by inland vessels in general.

1.4. Contribution to MoVe IT! Objectives

The aim of WP6 was to assess how inland ships can be adapted to changing conditions or new markets, and task 6.6 focuses on CO_2 transport. Technical solutions are identified in this task and considered as feasible. However, CO_2 transport with inland ships is to be considered as economically unfeasible, as the price of CO_2 certificates has developed to a level that is much lower than the transport costs.

1.5. Exploitation and Implementation

In this task, an assessment is made particularly for adaptation to CO_2 transport for one selected vessel type: a 110m Large Rhine Vessel. The results can be used directly for existing ships of the same characteristics. For smaller units (e.g. L < 86m) generally yields, that the transport costs per unit cargo are higher, which results in an even lower economic feasibility.

2. Introduction

2.1. Background

In the MoVe IT! project, measures to modernise existing vessels are investigated, with the aim to raise their economic or environmental performance, and to contribute to an improved competitive performance compared to other modes of transport.

Whereas other Work Packages of MoVe IT! investigate technical options to retrofit existing inland waterway vessels with the aim to continue serving their current markets, WP6 looks at modifications aiming to allow the existing vessels to serve new markets. In this context, task 6.6 addresses adaptations required to serve CO_2 transport.

2.2. Aim of the Task

The aim of task 6.6 is to investigate if existing vessels can be modified into CO_2-tankers.
An approach, comprising transport of liquefied CO_2 in independent pressure tanks, is analysed and assessed with regards to its technical and economic feasibility. This is worked out in a business case for a 110m Large Rhine Vessel sailing on a 1200 km roundtrip between a power plant and a sea port.

2.3. Structure of the Report

In chapter 3, an elaboration of the envisaged problem is presented. Use is made of the findings from previous studies on this matter.
In chapter 4, the potential market for CO_2 transport is analysed, as well as relevant transport relations that could be served by inland shipping.
Chapter 5 deals with technical and logistical requirements regarding CO_2 transport and storage on board of inland ships.
A solution is proposed to adapt existing inland vessels to the requirements regarding CO_2 transport. The solution, which is considered as technically feasible, is accordingly assessed on its economic feasibility in chapter 6.
The economic feasibility study comprises cost estimations for CO_2 transport with adapted inland ships; a cost break-down for CCS and a cost comparison with the current market price of Certified Emission Reduction units (CERs).
The report closes with overall findings and recommendations in chapter 7.

3. Problem Analysis

3.1. Introduction

The development of Carbon Capture and Storage (CCS) in Europe and, as a consequence, the demand for CO_2 transport is largely driven by the EU ETS system: the Emission Trading Scheme. Industry sectors that have a high energy consumption or high amounts of CO_2 emissions are required to deliver certificates for every tonne of CO_2 emitted in a particular year. The amount of certificates given to a company is reduced over time, incentivising the company to reduce its CO_2 emissions. Certificates can be traded so that investment in CO_2 emission reduction has a benefit, and companies short of certificates can purchase additional ones from parties having excess certificates. Through this process a market price of certificates is achieved, which gives companies a reference to decide for investing in emission reduction technology vis-à-vis selling or purchasing CO_2 emission rights.

One of the means to reduce emissions is Carbon Capture and Storage (CCS). The CO_2 produced by power plants, large steel mills as well as other energy intensive industries (covered under the EU ETS regime) can be captured, compressed and then transported and injected into a storage field, say an empty oil field, to reduce the net emission of greenhouse gases.

In the FP-7 project CO_2Europipe it was indicated that within Germany and the Netherlands there is a large potential for CO_2 transport, particularly for inland CO_2 barging between energy consuming industries and German and Dutch seaports [CO_2Europipe, 2011]. Sea ports are then transhipment points for onward transport to offshore empty oil fields where the CO_2 can be stored. This is driven e.g. by the fact that ample throughput capacity exists on the considered waterways, and a number of large CO_2 emitters are located near these waterways. Inland shipping could be advantageous as it is capable to circumvent the complexities and lengthy permit application procedures for pipeline transportation.

3.2. Problem Definition

The transportation of CO_2 is a new market segment for shipping in general, and in particular for inland shipping for which so far no suitable capacity exists, nor specific rules. So far there are only a few examples for the transport of CO_2 with a ship, e.g. the coaster MV “Coral Carbonic” with a net capacity of 547 tonne

CO_2. [Anthony Veder]. For the amounts of CO_2 that would result from large power plants aiming for CCS, transport systems need to be developed [Umweltbundesamt, 2006]. Further, low-cost solutions can be beneficial to timely and cost-effectively realize emission reduction targets [CO_2Europipe, 2011].

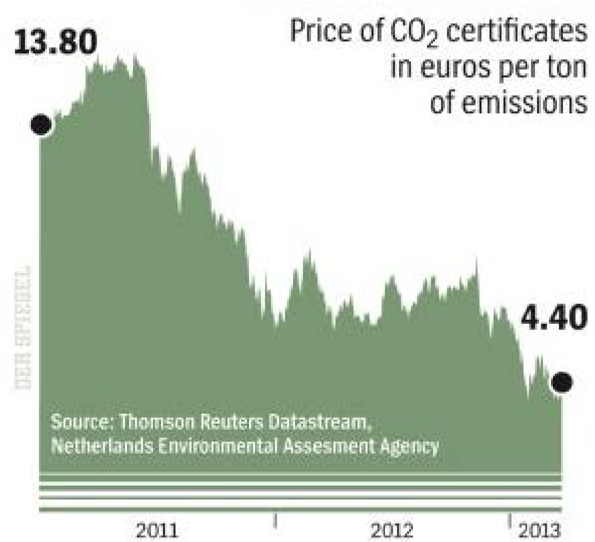
3.3. Applicability to MoVe IT!

In the framework of MoVe IT! the adaptation of existing inland vessels to transport CO_2 was addressed as a candidate retrofit option that would serve as a new market raising demand for inland water transport. To implement this option, however, technical requirements need to be met with respect to safely and efficiently storing CO_2 on board ships. Furthermore the logistical chain of transport of CO_2 from emitting plant to storage site needs to be developed.

3.4. Difficult Conditions: Price Development of CERs

Since their introduction the price of CO_2 certificates (CERs) has lowered rather than risen, which causes the incentive to invest in reduction or in CCS to be much lower than policy makers had hoped for. Figure 1 gives the price development of CO_2 certificates over time: from around EUR 15 per tonne two years ago to less than EUR 5 mid 2013.

Figure 1 – CO_2 price over time



Source: Thomson Reuters, taken from NEAA

As a consequence the advantage of reducing emission is very limited as often investments into emission reduction are costlier than simply purchasing additional certificates. With regard to CCS, and the associated CO_2 transport technology, transport chain operating costs are an important factor.

3.5. Research Approach

A three step research approach is followed to investigate the feasibility and practicality of adaptation to CO_2 transport as retrofit options for existing vessels:

1. Market analysis to identify the potential market of CO_2 transport, relevant transport relations and the place of inland waterways transport in a multi-modal transport chain;
2. Investigation of technical and logistical requirements regarding CO_2 transport by inland ships;
3. Economic feasibility study comprising a cost break-down for the CCS logistics chain, a cost estimation of CO_2 transport using adapted inland ships and a comparison with the price development of Certified Emission Reduction units (CERs).

4. Market Analysis CO_2 Transport

4.1. Description of Potential Markets for CO_2 Transport

Two main markets can be distinguished for CO_2 transport. The first market is the transport of CO_2 from a production site to a storage field (the so called Carbon Capture and Storage; CCS). The second market is the use of CO_2 in industrial processes.

4.1.1. Carbon Capture and Storage (CCS)

The largest potential market is the CCS market. It must be noted that currently this market is rather small, but its potential is being investigated and pilots are being prepared, with a view on climate change policies (reduce CO_2 emissions) in general, and carbon trading market development in particular (the EU ETS system already in place for a number of energy intensive sectors).

The CO_2 produced by large steel mills, other energy intensive industries (covered under the EU ETS regime) as well as coal power plants (also covered under EU ETS) can be captured, compressed and then transported to a storage field. This storage field can be located onshore or offshore. Typically empty oil fields and gas fields can be used to store CO_2; these fields used are located deep under the ground and after filling can be closed permanently.

It is understood that 90% of all CO_2 produced by coal power plants can be captured, transported and stored. Three techniques exist to capture CO_2. The first method is pre-combustion capture in which the CO_2 is partially combusted. End products are hydrogen and still some CO_2. Main by-product of this technology is water vapour. The second method is post-combustion in which the CO_2 is captured after combusting the fossil fuels. CO_2 can be captured from exhaust gases and other large emitting points. The technique is applicable to both new and existing power plants. Main challenge is to apply the technique at a wider scale than is currently done. The third method is Oxy-firing capture which involves burning fuel in pure oxygen instead of air. The exhaust gas obtained consists of water and CO_2 and is ready to be dried and compressed[1].

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[1] http://www.co2captureproject.org/co2_capture.html

After capturing, the CO_2 can then be transport (described in more detail in the following paragraphs) and stored. To store the CO_2 in empty oil or gas fields, the CO_2 is injected under high pressure in these storage rooms. The rooms were able to store oil and gas for millions of years and are therefore considered able to store CO_2 gas as well. The fields absorb the CO_2 and trap it. Impermeable cap rock acts as a final seal to ensure safe CO_2 storage for millions of years.

In the FP7 project "CO_2Europipe" the potential European CO_2 market is estimated for the years 2020, 2030 and 2050. The overall volumes of captured CO_2 are estimated to be 45 Mt / year in 2020, 358 Mt / year in 2030 and 1,222 MT / year in 2050. Most of these emissions will be stored somewhere instead of used in other sectors, like the food-processing industry. Main driver for the increase in carbon dioxide capture over this period are the CO_2 goals set forth in the Kyoto Treaty and other climate change policies which aim to reduce CO_2 emissions and are assumed to become more stringent over time.

4.1.2. Use of CO_2 in Industrial Processes

A second market is the transport of CO_2 which is used in industrial processes, i.e. from producers (same as above) to industries consuming CO_2. Three industrial processes can be distinguished in which CO_2 is often used:

1. The food processing industry: e.g. for producing soft drinks and beer.
2. In green houses: CO_2 is used in greenhouses to stimulate the growth of crops (Plants grow stronger and will be of higher quality once clean CO_2 is used to nourish them and high CO_2 concentrations are offered).
3. For enhanced oil recovery: By pumping CO_2 into oil fields still in use, the pressure in these fields can be raised and more oil can be extracted (30 to 60% can then be extracted) than by using procedures without CO_2 (when only about 20-40% can be extracted).

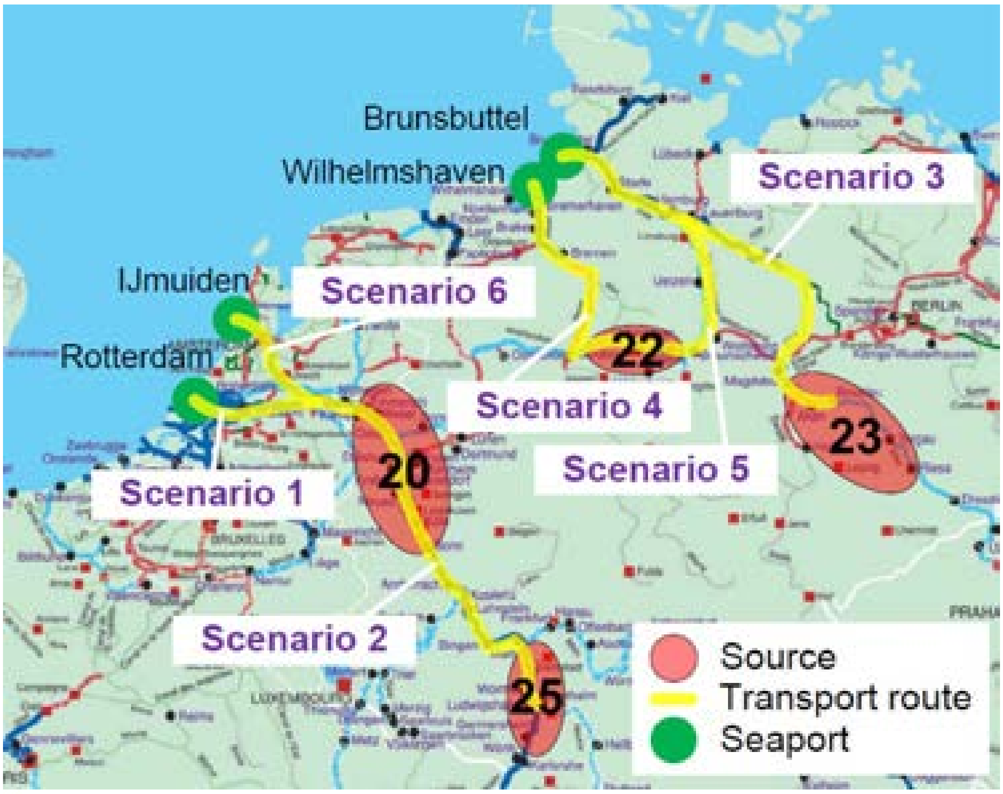
Although CO_2 can be used in many industrial processes, it is unlikely that the transport of CO_2 for this purpose is likely to grow extensively during the coming years, as the volumes of production of these sectors will not increase much and as already through regional channels these sectors are provided with CO_2 (example: CO_2 from refineries in the Port of Rotterdam is transferred to greenhouses in the nearby Westland by pipeline).

The largest potential for CO_2 transport will therefore relate to the storage of CO_2 both in offshore oil fields.

4.2. Transport Relations for CO_2

In the CO_2Europipe project, multiple transport scenarios were investigated for CO_2 inland barging in combination with CCS. These scenarios based on transport relations between the four largest CO_2 source clusters in North West Europe and the seaports Rotterdam; IJmuiden; Wilhelmshaven and Brunsbüttel which were envisaged as CO_2 hubs. The resulting transport relations are shown in Figure 2.

Figure 2 – CO_2 source clusters and transport relations for inland barging



Source: CO_2Europipe (2011)

Coal burning power plants are indicated as large CO_2 sources [PRTR 2010], which are prevalently built along rivers or canals because of their cooling needs as well as for logistic reasons (coal supply). Table 1 gives an overview of large coal burning power plants that are connected to the inland waterway network. As in MoVe IT! retrofit options for existing ships are subject, the daily CO_2

production of these power plants are expressed in cargo capacity of typical inland vessels.

Table 1: Overview of IW connected, large coal burning power plants

Origin: Power plant	Annual CO_2 production [x1,000t]	River or Canal	Typical ship size	Cargo capacity [t]	Daily production [ship units]	Destination:
Mannheim	6,510	Rhine	110 x 11.4m	2,500	7	Rotterdam
Voerde/Wesel	6,240	Rhine	110 x 11.4m	2,500	7	Rotterdam
Grosskrotzenburg	4,480	Main	110 x 11.4m	2,500	5	Rotterdam
Perterhagen	3,870	Weser	85 x 11.4m	1,750	7	Bremerhaven
Heilbronn	3,240	Neckar	90 x 11.4m	1,750	4	Rotterdam
Bergkamen	3,020	DHK	110 x 11.4m	2,500	3	Rotterdam
Herne	2,480	RHK	110 x 11.4m	2,500	3	Rotterdam
Altbach	2,220	Neckar	90 x 11.4m	1,750	3	Rotterdam
Karlsruhe	2,170	Rhine	110 x 11.4m	2,500	2	Rotterdam
Veltheim	1,740	Weser	85 x 11.4m	1,750	3	Bremerhaven

Source: Own work, based on data of [PRTR 2010]

The daily CO_2 production of the investigated power plants corresponds to a cargo capacity need of 2 to 7 inland vessels for each plant. The number of vessels that is needed to transport the annual CO_2 production depends amongst others on the voyage length, sailing speed of the vessels and cargo handling times.

A rough estimate of the potential market can be made if four days are assumed for a complete roundtrip including cargo handling. As the daily production corresponds to a cargo capacity need of 2 vessels and a roundtrip takes 4 days, at least a fleet of 2x4 = 8 vessels is needed per individual power plant. Considering all ten mentioned power plants, a market potential of approx. 175 inland vessels would exist.

4.3. Conclusions on Market Analysis CO_2 Transport

It can be concluded that:

- CO_2 transport in the context of Carbon Capture and Storage is a small market at the moment, but could have a large growth potential in the next decades, based on emission reduction targets in place and assuming CCS is the preferred option chosen.
- Within Germany and the Netherlands there is a large potential for inland CO_2 barging as CO_2 source clusters are located along the River Rhine or along waterways that connect to German sea ports, which are envisaged as CO_2 hubs;
- The annual CO_2 production of a typical large coal-fired power plant is estimated at 2 to 6.5 million tons. Based on the typical cargo capacity of a CO_2 carrying ship, 8 to 28 inland vessels would be needed for each power plant to serve its annual transport need. Considering the 10 largest IW network connected power plants, a market potential of approx. 175 inland vessels would exist.

5. Technical and Logistical Requirements

5.1. States of Aggregation for CO_2

CO_2 can be transported in three different states: gas, liquid and solid. The state chosen will influence the mode of transport used.

Gaseous state

Bulk cargo as gas is voluminous and therefore is often transported by onshore and offshore pipelines. To reduce the volume of the gas and make it better transportable, the gas has to be compressed before it enters the pipeline. This compression brings additional costs in addition to the transport itself.

Currently compressed gas is only transported by pipeline and not by any other mode of transport. The compressed gas is still too voluminous to be transported cost effectively by any other mode of transport than pipeline. To enable the transport of gas in ships (and other modes) the volume can be further reduced through liquefaction.

Liquefied gas

The transport of liquefied gases in ships is already common practise. For many decades gases like LPG and LNG are transported by ships all over the world. The existing technology and experiences with these gases can be transferred to the transportation of liquid CO_2.

Also CO_2 transport by vessels, mainly maritime vessels, is already common practise. An advantage of ship transport compared to pipeline transport is the high flexibility of vessels. In the CCS market the CO_2 is transported from a production site to an empty oil or gas field. Once the field is full, the field is closed and the transport of CO_2 will be moved to another empty field. As pipelines usually are connected to only one field, they become idle once that field is full. It is very costly and technically complicated to relocate the pipelines to another field. It should also be noted that the pipelines already in place might have a reduced quality as they might have been idle already for many years. Vessels can be re-used and switch between fields. Besides the higher flexibility of vessels, the use of vessels rather than pipelines is considered more economically viable once the distance travelled between the site and the field is larger than 1,000 – 1,500 kilometres which would imply high costs of constructing (dedicated) pipelines. Note that these figures hold for sea going vessels. Transport of CO_2 by IWT vessels is not common until date and hardly happens.

Solidified gas

The third and last state, in which CO_2 can be transported, is through solidification. The volume is further reduced than the liquefied state and much more CO_2 could be transported at once. However the solidification of the gas is a very energy intensive and costly procedure and therefore is an inferior option both from a cost and energy perspective, compared to the other two options. This state is hardly used and therefore it will not further be explored.

5.2. Multi-modal Transport Chain of Carbon Capture and Storage

Figure 3 shows the CCS transport chain and the different possibilities of multi-modal transport. The chain starts at the power plant (or alternative CO_2 producing entity). The CO_2 can have two destinations: the industrial processing industry or storage. If the destination is the industrial processing, it is very likely that the CO_2 will be transported by truck.

To transport large quantities of CO_2, trucks and trains are not considered as favourable options as due to their relatively small carrying capacity the costs of CO_2 transportation by these modes are considerable[2]. Several sources indicate that the role of truck and train will remain insignificant for CO_2 bulk transport (e.g. Global CCS Institute; Intergovernmental Panel on Climate Change). According to their analyses, trucks may be used for the transport of small quantities on short distances at best.

If the destination is a storage field, then pipeline transport; shipping or a combination of both (bi/multi-modal transport) remain.

However, the aggregation state chosen at the beginning of the transport chain (pressurised gas versus liquefied state) mainly determines the preferred transport mode throughout the complete chain, as explained in the following section.

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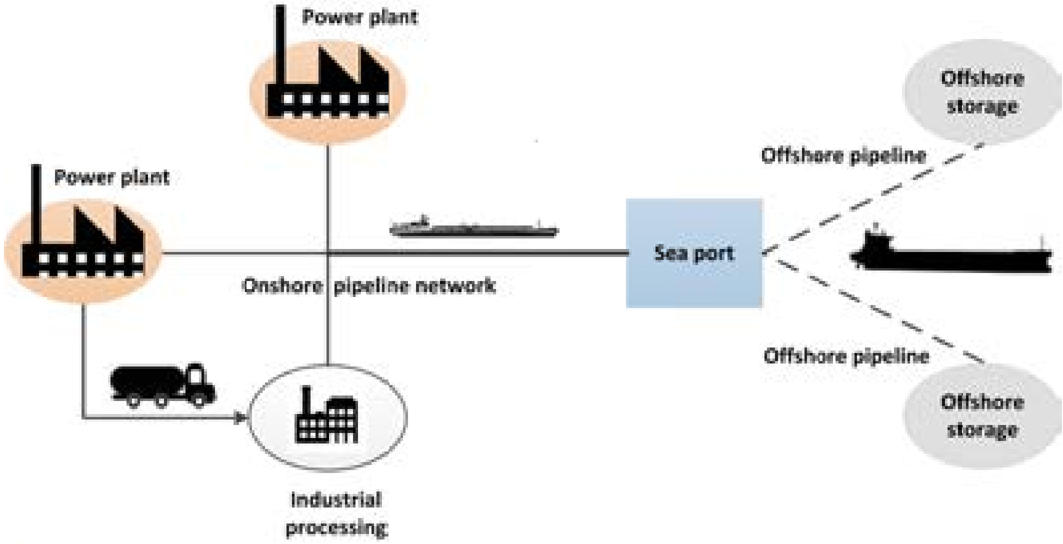
[2] During the design phase for the Canyon Reef project in the USA, several transport options were evaluated extensively. The evaluation showed that the use of trucks and / or trains was more than twice as expensive as the usage of pipeline transport.

Figure 3 – Overview of the CCS transport chain



Source: Ecorys (2013)

5.2.1. Disadvantage of Multi-modal Transport

A multi-modal option is theoretically possible: e.g. CO_2 is transported from the power plant to the seaport by pipeline and then transferred onto a sea-going vessel. This transport option is however not often used in practise, as the highly pressurized gas transported by pipeline has to be relieved (in the port) to a lower pressure and then liquefied in order to be loaded onto a ship. This double treatment is energy consuming, so cost increasing, and therefore economically not attractive. The same yields for a transport chain starting with inland barging (so: liquefied CO_2) and then transhipped into an offshore pipeline (so: pressurized gas). Also in this case the aggregation state has to be changed and the option is therefore economically not attractive.

As multi-modal transports are economically not attractive, single-modal transport chains remain if CCS is considered: pipelines or shipping solutions, where we assume that a combination of inland shipping to a seaport and transhipment onto a seagoing vessel does not require a change of state.

5.2.2. Single-modal Transport of CO_2

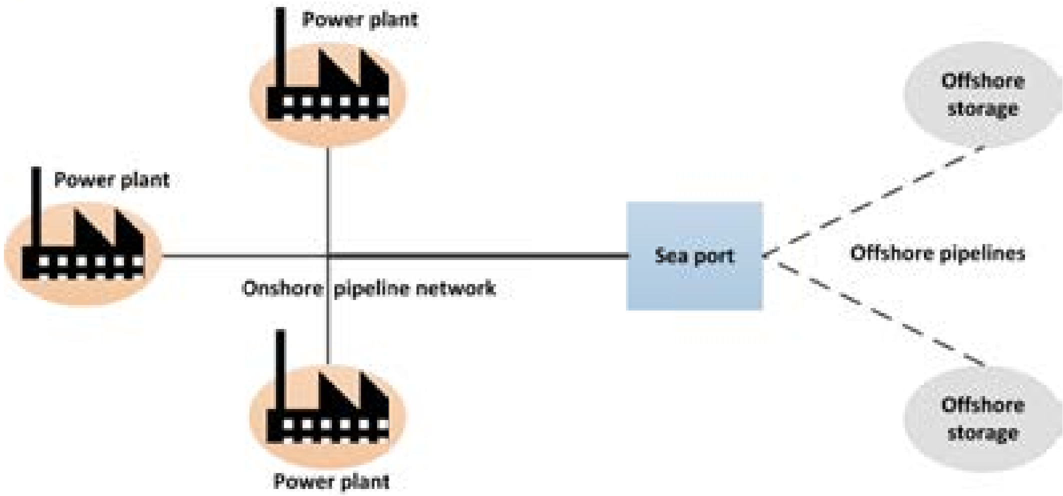
As mentioned above, CO_2 is preferably transported in one aggregation state, resulting in two single-modal transport chains: pipelines or shipping solutions.

Issue to mention here is that these transport solutions are possibly in competition with each other if the same corridors are considered and if both pipeline and waterway infrastructure is in place.

Pipeline Transport

As mentioned above CO_2 in the state of gas is often transported by pipelines due to its volume. Pipeline transport will start with the onshore pipeline branch. Economically most viable is the use of a hub and spoke network. The pipeline originating from the power plant is connected to a main pipeline which runs between inland industry centres and the nearest seaport. In the sea port the onshore pipeline is connected with offshore pipelines and this offshore pipeline is connected with the offshore storage field, as shown in Figure 4.

Figure 4 – Transport chain Pipeline



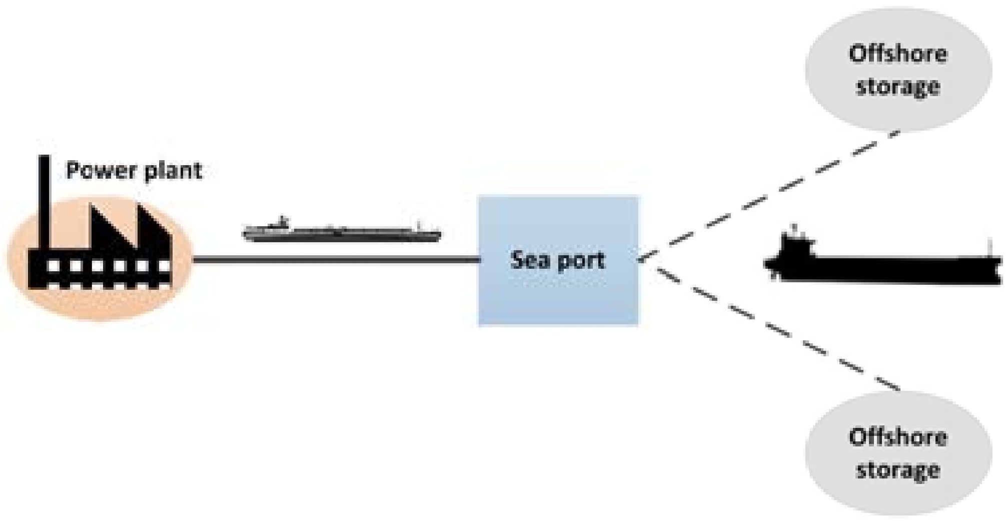
Source: DST/Ecorys (2013)

Shipping

To transport CO_2 by other modes, like ships, trucks or trains, the volume has to be reduced which mostly is done through liquefaction, which reduces the volume by a factor 85 (1m^3 liquefied gas equals 85 m^3 gaseous CO_2).

If the shipping option is chosen the CO_2 is – after being liquefied – loaded on-board a barge and then transported to the seaport. Main condition is that the power plant is closely located near a waterway; otherwise an additional transport mode has to be interposed, resulting in higher transport costs due to transhipment. Once the barge reaches the seaport the CO_2 has to be transferred from the barge to a seagoing vessel that will ship the CO_2 to the offshore storage field, as shown in Figure 5.

Figure 5 – Transport chain Shipping



Source: DST/Ecorys (2013)

The operation cycle of CO_2 transport using ships is more complex than using pipeline transport. The cycle for shipping consists of four phases:

Phase 1: Loading
During the loading phase the ship needs to be pressurized and filled with gaseous CO_2 before the liquid gas can be loaded. This procedure prevents contamination by humid air and formation of dry ice.

Phase 2: Transport to site
Due to heat transfer the CO_2 will be boiled. Some CO_2 will be released together with the exhaust gas of the ship engines. During short trips this process is unlikely to happen. To avoid this on longer trips, a refrigeration unit can be used to capture and re-liquefy the CO_2. This however raises the overall transport costs.

Phase 3: Unloading
During the unloading phase dry gaseous CO_2 will fill the space previously occupied by the liquid gas. This CO_2 used can be reused and re-liquefied once the tank is refilled.

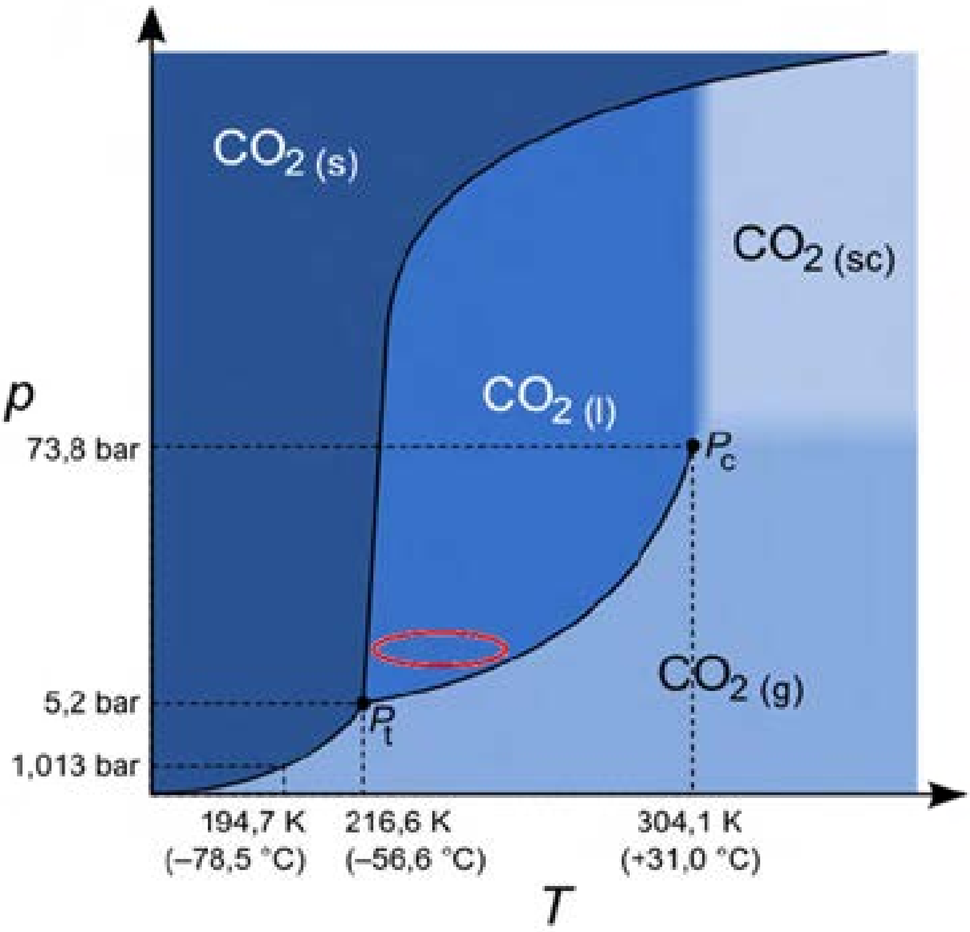
Phase 4: Return Journey and maintenance
Often the ship will return empty. Ballast water is then needed to stabilize the vessel. During any dock works the tank should be filled with CO_2 purged with air to ensure safe working. Once the vessel leaves dry dock the tanks should be fully dried, purged and filled with CO_2 gas to ensure safe proceedings.

5.3. Effective Transport in Liquid Phase

Analogous to LPG and LNG, CO_2 must be liquefied for transport by ship, because otherwise the transport capacity would be too low. The following phase diagram shows the different states (gaseous, liquid or solid) of CO_2 in respective conditions.
Carbon dioxide has no liquid state at pressures below 5.2 bar. At these pressures the gas deposits directly to a solid (dry ice) at temperatures below -78.5°C and the solid sublimes directly into a gas above that temperature.
Liquid carbon dioxide forms at pressures above the triple point (5.18 bar at -56.6°C, see figure below), however at temperatures lower than 31°, which correspond to the critical temperature. At that temperature a pressure of 73.8 bar is required to keep CO_2 liquid. To avoid heavily constructed tanks, operating pressures are to be between 6 and 20 bar. So a suitable transport condition is achieved closely above the triple point: 6 bar at -46°C, as marked in the figure. At this condition the density of the gas is between 1.0 ton/m^3 and 1.2 ton/m^3.

The typical loading condition of the gas is however 8 bar at -46°C. The 2 bar pressure margin is applied to compensate the pressure loss during loading. Vaporisation and adiabatic expansion of a small portion of gas at the initial phase of the tank filling, provides cooling down of the cargo tanks.

Figure 6 – Phase diagram of carbon dioxide.



Source: Wikipedia.org

5.4. Dangerous Goods and Regulations

CO_2 is a colourless, non-flammable, taste- and odourless gas. Because it is heavier than air, it has the property to collect on the ground. A particular danger of the gas is that high concentrations, if not detected in time, can cause suffocation. This potential risk is high when CO_2 is spreading in confined areas. Industrial applications however have shown that it can be safely stored and transported, if appropriate precautions are taken.

As bulk cargo the following legal requirements for dangerous goods are to be met.

At seaports (e.g. Rotterdam):

- International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC-Code by IMO)
  The technical requirements concerning the tank system are primarily given by this code. This rule applies for all ships that sail in the seaport area.

On the River Rhine:

- RheinSchUO/ROSR (CCR-ZKR)
- ADN 2011 und ADNR 2009

General regulations:

- DIN EN ISO 28460 (Cargo-handling of liquefied gas)
- DVGW G652(A) (Compendium on liquefied gas equipment)

5.5. *Further Technical Requirements*

To prevent gas leakage or pressure build-up, the low temperature needs to be maintained and for that reason it is advised to equip the vessels with:
1. a redundant cooling system. Without an onboard cooling system, both steel tank and cargo will warm up during transport, despite insulation. Depending on the duration of the transport, tank and cargo can be heated up to ambient conditions beyond this maximum.

2. Thermal insulation for cargo tanks to:

– Minimize heat flow
– Protect tank structure from effects of low temperature

3. Insulation material should possess following characteristics:

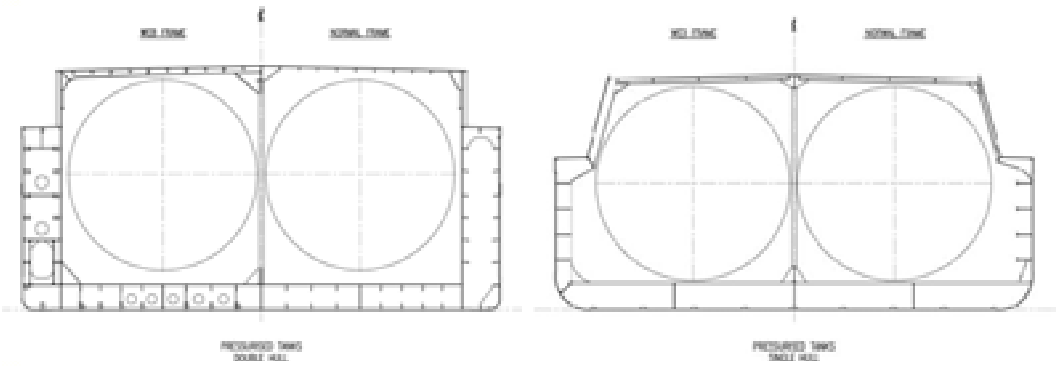
– Low thermal conductivity
– Ability to bear loads
– Ability to withstand mechanical damage
– Light weight
– Unaffected by cargo liquid or vapour

A cargo containment system that meets the legal requirements and is applicable to existing inland vessels is given in the following section.

5.6. Proposed Solution

As CO_2 can only be liquefied by pressurization (as explained above), application of independent tanks of type C is currently the only realistic containment system for transportation [DNV, 2013].
Independent tanks of Type C are normally spherical or cylindrical pressure vessels having a design pressure higher than 4 bar and designed and built to conventional pressure vessel codes [CCNR, 2010].

Figure 7 – Intersection of inland gas-tanker with independent tanks of type C



Source: [CCNR, 2010]

The cylindrical tanks may be vertically or horizontally mounted. Horizontal tanks supported by saddles should preferably be supported by two saddle supports only. In this case, the effect of hull interaction is normally small and may not need to be considered [DNV, 2013].

Independent Tanks (Type C) further have the following characteristics:

- Provide required secondary barrier layer at hold
- Pressure tank (low danger in case of leakage)
- Are completely self-supporting
- Are applicable to existing ships
- Thermal insulation available
- Enable active cooling

5.7. Conclusion on Technical and Logistical Requirements

It can be concluded that:

- Inland CO_2 barging is to be considered as a part of a multi-modal transport chain, involving transhipment onto a sea going vessel for delivery at offshore Carbon Storage fields;
- The liquid state is considered as the most practical aggregation state to transport CO_2 with inland ships;
- Transport of liquefied CO_2 in independent tanks is indicated as technically feasible in general and applicable to existing inland vessels;
- The following regulations yield for CO_2 transport with inland ships:
  - International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO IGC-Code)
  - RheinSchUO/ROSR (CCR-ZKR)
  - ADN 2011 und ADNR 2009
  - DIN EN ISO 28460 (Cargo-handling of liquefied gas)
  - DVGW G652(A) (Compendium on liquefied gas equipment)

The economic feasibility of CO_2 transport with inland vessels on which independent tanks are applied will be investigated in the following chapter.

6. Economic Feasibility IWT

In the context of MoVe IT!, looking at retrofit possibilities for existing ships, the cost component introduced by inland waterway transport with adapted existing vessels is investigated in this chapter.

6.1. Methodology

The economic feasibility of CO_2 transport with adapted vessels is assessed as follows:

Cost calculations have been made for a 110m Large Rhine Vessel (CEMT Va). The assumption is that an existing vessel of this size will be upgraded to a CO_2 tanker by application of independent pressure tanks of type C, as proposed in section 5.5.

Cost Model

The cost of inland waterway transport can be aggregated to three main components:

- investment and insurance costs,
- labour costs,
- fuel and lubrication costs.

Hereby, a distinction can be made between fixed and variable costs: Investment, insurance and labour costs are costs components which can be addressed to time charter, so fixed costs. Fuel and lubrication costs are cost components due to sailing with the purpose of transporting cargo, so variable ones.

General Assumptions

For the calculation of transport costs, it is assumed that the ships sail 350 days a year, to be used exclusively in shuttle service on a relation between power plant and seaport. The waiting times at the port are considered to be 12 hours for loading and offloading.

The capital costs are treated by means of a linear depreciation of the total investment. The period of deprecation is based on the whole economic life of the vessel and the CO_2 tanks, which is defined in this study to be 12.5 years. In addition, interest costs on capital have been accounted with 5% of the investment. The annual repair and maintenance costs are accounted with 30 €/t cargo carried. The insurance costs per year are based on a fixed component of € 55,000 per ship. A yearly fee of € 25,000 has been accounted for survey. These are expert values, which are estimated in good accordance to PLANCO & BfG (2007), NEA (2011) and BdB.

The labour costs are determined in accordance to the manning crew regulations that apply to the Rhine (RheinSchUO), considering 18-hour operation. Additional costs due to social insurance contributions and allowances are included[3]. The ship is assumed to be operated by a shipping company. The option skipper/owner was not considered.

6.2. Business Case: 110m Large River Vessel

In this business case a 110m Large Rhine Vessel is considered. Main dimensions of the vessel can be found in the following table 2. Figure 8 gives an impression of the tank arrangement on board of the ship.

	GMS-110 (CEMT class Va)
Length	110 m
Beam	11.40 m
Draught (max)	3.50 m
Payload (max)	2520 t

Table 2 – Main dimensions 110m Large Rhine Vessel

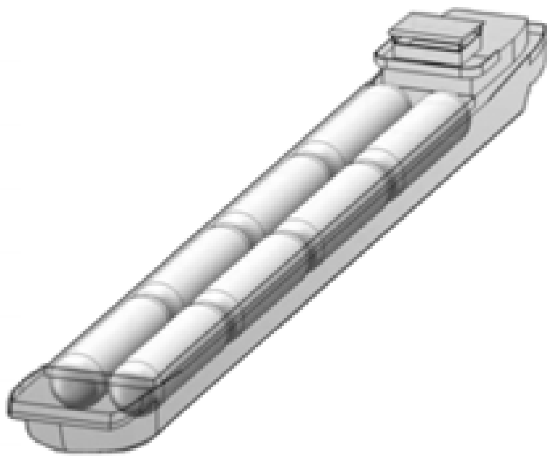


Figure 8 – Impression of an adapted inland vessel for CO_2 transport

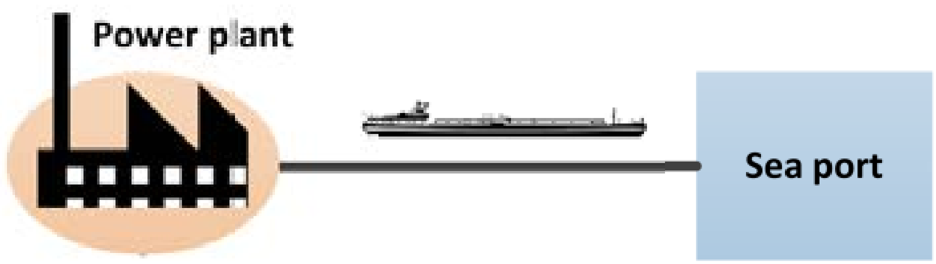
Source: DST (2013)

[3] The appropriate information on the individual parameters bases on interviews with experts as well as own calculations and investigations or are taken from literature (PLANCO & BfG (2007) referring to personnel cost structures).

Transport Relation

A fictive transport relation with a length of 600 km has been assumed. This leads to a 1200 km roundtrip. To keep in mind is that cargo is transported in only one direction. In case of a free-flowing river, the ship sails loaded in downstream direction and in ballasted condition upstream.

Figure 9 – Transport chain for IWW



Source: DST/Ecorys (2013)

Analysis Results

The results for a 110m inland ship that is converted to a CO_2 tanker with independent tanks are given in Table 3.

Table 3: Estimated transport costs per tonne CO_2 for a CEMT Va class vessel on a 1200 km roundtrip

	Base case	Higher investment cost
Residual value ship	€ 1,500,000	€ 1,500,000
Tank equipment	€ 3,000,000	€ 3,600,000
Conversion costs	€1,500,000	€ 1,800,000
Total investment	€ 6,000,000	€ 6,900,000
Depreciation per year	8% (lifetime of 12.5 yrs)	
Other operating costs	X	
Annually transported volume	Y	
Costs per tonne CO_2	**€ 19.04**	**€ 20.20**

Costs per tonne include operational variable costs and fixed costs divided by the transported amount over the depreciation time. The resulting transport costs for a distance of 600 km (using the costs model presented above) are approximately 20 EUR/tonne CO_2.

For smaller units (e.g. < 86m), the transport costs per unit are expected to be higher as their cargo capacity is lower and the investment in tank equipment and conversion are relatively larger than for larger ship types.

6.3. Additional Costs for CCS

The above calculated transport costs only cover transport from the power plant to the CO_2 transhipment hub at the seaport with inland ships. Additional costs that accrue are to be accounted for. The following cost components are to be considered at the beginning of the transport chain:

- CO_2 capturing and gas treatment at the power plant
- Liquefaction and buffer storage at the inland port
- Loading onto inland vessel

Further costs component accrue at the end of the transport chain:

- Port dues at the sea port
- Transhipment to buffer storage or to sea-going vessel
- Offshore transport with sea-going vessels
- Disposal at depleted oil field.

In the 2011 study of ZEP cost estimations for CO_2 transport by ships were made. Although the cost estimates focused on maritime transport rather than inland waterway transport, they can give an indication of the relevant costs of seaborne CO_2 transport and its structure. In the said study it was assumed that maritime transport ships have a carrying capacity between 10,000 and 40,000 m^3. Further it was indicated that the investment costs of a CO_2 ship are probably higher than investment costs for LNG and LPG vessels. It should be noted that these estimates are based on newly constructed CO_2 vessels rather than retrofitted ships as is the focus of MoVe IT!.

Table 4 and Table 5 give cost estimates for CCS demonstration projects in which ships are applied for the transport of CO_2 to offshore disposal fields. The costs include amongst others costs due to liquefaction of CO_2.

Table 4: Cost estimates (€/t CO_2) for commercial natural gas-fired power plants with CCS or coal-based CCS demonstration projects with a transported volume of 2.5 million t/pa

Length of network (in km)	180	500	750	1500
Ship	8.2	9.5	10.6	14.5
Liquefaction (for ship transport)	5.3	5.3	5.3	5.3
Total	13.5	14.8	15.9	19.8

Source: The costs of CO_2 Capture, Transport and Storage, ZEP (2011)

Table 5: Cost estimates for large-scale networks of 20 million t/pa (€/ t CO_2)

Length of network (in km)	180	500	750	1500
Ship (including liquefaction)	11.1	12.2	13.2	16.1

Source: The costs of CO_2 Capture, Transport and Storage, ZEP (2011)

Two conclusions can be derived from the tables:

- The costs of transportation increase less than proportionally to distance, which is different from the pipeline transport concept, indicating shipping provides a competitive advantage over longer distances. However CO_2 transport by vessel has higher step-in costs and liquefaction always needs to take place, keeping the total transport costs higher than for pipelines up to distances of 1500 km.
- Also ship transport benefits of scale. The more CO_2 is transported per year the lower the unit costs will be.

Analysis Results

Depending on the transport distance and the transported volume, the transport costs for offshore transport of CO_2 with ships (incl. liquefaction) amount to approx. 11 EUR per tonne (for large volumes over relatively short distances) up to 20 EUR per tonne CO_2 (for relatively small quantities over a large distance).

If the costs for inland transport over a distance of 600 km (or a roundtrip of 1200 km) are considered, the total transport costs (incl. liquefaction) are estimated at 30 to 40 EUR per tonne CO_2.

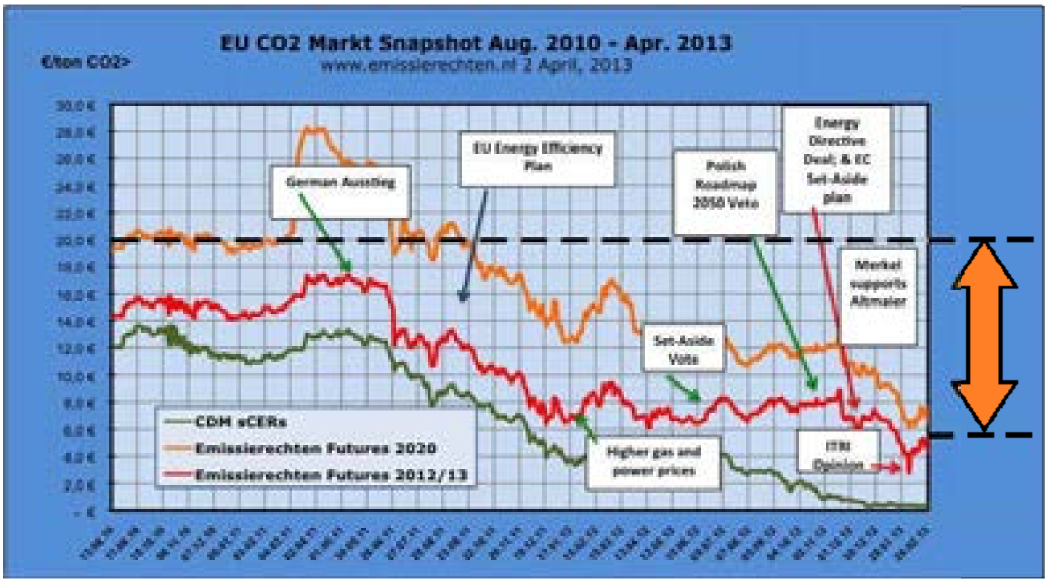
In the following section the feasibility of CO_2 transport with inland ships is assessed by comparing the accrued transport costs with the current price of CO_2 certificates.

6.4. Comparison with Certified Emission Reduction Units

The transport costs for CO_2 with inland ships for the investigated relation and ship type amount to approximately 20 € per ton. Figure 10 shows the cost level of inland CO_2 transport in relation to the price development of CO_2 certificates (CERs) and futures (for 2013 and 2020) over time.

The current prices (April 2013) of futures on CERs are approximately 7 EUR per ton.
If we compare the transport costs with the prices for CERs, it is obvious that the transport of CO_2 with the investigated 110m inland ship from a power plant to a seaport over a distance of 600 km is, at the time, economically not feasible.

Figure 10 – Price development of CO_2 certificates and futures



Source: www.emissierechten.nl

If the price of carbon credits rises to its initial level or even further increases to levels above 20 EURO/ton, the transport of CO_2 with inland ships may become economically feasible. The real threshold must be higher considering additional costs of bunkering, liquefying, etc. Investments are expected if the real price of certificates is higher than 30/40 EURO/tonne over a longer period. In that case inland shipping has to compete with pipeline transport. For that reason a cost comparison is made in the following section.

6.5. Cost Comparison with Pipeline Transport

In 2011 the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) published a report containing cost estimates for CO_2 capture, transport and storage.

The following tables are taken from this report and show the pipelines transportation costs for both onshore and offshore pipelines. The costs depend on the volume of CO_2 transported per annum (million t/p.a.).

Table 6: Cost estimates (€/t CO_2) for commercial natural gas-fired power plants with CCS or coal-based CCS demonstration projects with a transported volume of 2.5 million t/pa

Length of network (in km)	180	500	750	1500
Onshore pipeline	5.4	n.a.	n.a.	n.a.
Offshore pipeline	9.3	20.4	28.7	51.7

Source: The costs of CO_2 Capture, Transport and Storage, ZEP (2011)

Table 7: Cost estimates for large-scale networks of 20 million t/pa (€/ t CO_2)

Length of network (in km)	180	500	750	1500
Onshore pipeline	1.5	3.7	5.3	n.a.
Offshore pipeline	3.4	6.0	8.2	16.3

Source: The costs of CO_2 Capture, Transport and Storage, ZEP (2011)

Two main conclusions can be derived from the tables:

- The costs for CO_2 transported by pipelines (both onshore and offshore) increase almost proportionally with the transport distance.
- Pipelines benefit from the economies of scale. The more CO_2 is transported per year the lower the transportation costs per unit will be.

Further can be derived that:

- A transport relation consisting of a 600 km large-scale onshore pipeline and a 750 km offshore pipeline is estimated with 13 to 15 EU per ton. These costs are lower than for ship-based transport.

6.6. Conclusions on Economic Feasibility

As regards the economic feasibility it can be concluded that:

- Resulting from the applied cost model for inland ships, the transport costs for an adapted 110m inland vessel, sailing between a power plant and a seaport over a distance of 600 km, are approximately 20 EUR/tonne CO_2.
- The transport costs rise to approximately 30 to 40 EUR per tonne if liquefaction and offshore transport with ships are considered.
- Compared with the current prices of futures (2013 and 2020) on CERs it is obvious that the transport of CO_2 with inland ships is, at present, economically not feasible (nor is pipeline transport).
- If the price of carbon credits rises to its initial level or even further increases, the transport of CO_2 with inland ships may become economically feasible. However, still in that case inland shipping has to compete with pipeline transport.

7. Overall Findings and Conclusions

7.1. Overall Findings

The transport of CO_2 is considered as a potential market segment for inland shipping, for which so far no suitable capacity exists, nor specific rules.
In previous studies it was indicated that for the quantities of CO_2 that would result if Carbon Capture and Storage (CCS) are applied to large power plants, ships and transport systems need to be developed.
In MoVe IT! adaptation of existing inland vessels to CO_2 transport was addressed as a candidate solution.

Regarding the potential market of CO_2 transport it can be concluded that:

- CO_2 transport in the context of Carbon Capture and Storage is a small market at the moment, but could have a large growth potential in the next decades.
- Within Germany and the Netherlands there is a large potential for inland CO_2 barging as CO_2 source clusters are located along the River Rhine or along waterways that are linked to German sea ports;
- Indicated relevant transport relations are: from large coal-fired power plant along the Rhine corridor to the Port of Rotterdam or German sea ports, which are envisaged as CO_2 hubs;
- The annual CO_2 production of typical large coal-fired power plants is estimated at 2 to 6.5 million ton. Based on a typical cargo capacity, 8 to 28 inland vessels would be needed per power plant to serve its CO_2 transport need on an annual basis. Considering the 10 largest IW network connected power plants, a market potential of approximately 175 inland vessels exists.

Technical and logistical requirements are:

- Inland CO_2 barging is to be considered as a part of a multi-modal transport chain;
- The liquid state is considered as most practical aggregations state to transport CO_2 with inland ships;
- Transport of liquefied CO_2 in independent tanks is indicated as technically feasible in general and applicable to existing inland vessels;
- The following regulations yield for CO_2 transport with inland ships:
  - International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO IGC-Code)
  - RheinSchUO/ROSR (CCR-ZKR)
  - ADN 2011 und ADNR 2009
  - DIN EN ISO 28460 (Cargo-handling of liquefied gas)
  - DVGW G652(A) (Compendium on liquefied gas equipment)

From the economic feasibility study it follows that:

- Resulting from the applied cost model for inland ships, the transport costs for an adapted 110m inland vessel, sailing between a power plant and a seaport over distance of 600 km, are approximately 20 EUR/tonne CO_2;
- These transport costs rise to approximately 30 to 40 EUR per tonne CO_2 if liquefaction and offshore transport to a storage field with sea-going ships are considered;
- Compared with the current prices of futures (2013 and 2020) on CERs, it is clear that the transport of CO_2 with inland ships is, at the time, economically not feasible.
- If the price of carbon credits rises to its initial level or even further increases, the transport of CO_2 with inland ships may become economically feasible. However, inland shipping has to compete with pipeline transport, which has estimated costs of around EUR 13-15 per tonne of CO_2 transported over the same distance.

7.2. Conclusions

The analysis of task 6.6 has shown that while the transport of CO_2 by barge is considered technically feasible, the resulting costs per tonne of CO_2 arrive at around EUR 20/ton, still excluding the transhipment, liquefaction and maritime leg of the transport chain. When this is compared with the current market price of CERs of around EUR 7/ton, the shipment of CO_2 by barge is economically not feasible.

8. Bibliography and References

- BdB, Kalkulationshilfe
- CCNR (2010), Central Commission for the Navigation of the Rhine, Strasbourg and Oil Companies International Marine Forum: International Safety Guide for Inland Navigation Tank-barges and Terminals
- CO_2Europipe (2011) Development of a large-scale CO_2 transport infrastructure in Europe: matching captured volumes and storage availability
- DNV (2013), Strength Analysis of Independent Type C Tanks, Classification Notes No. 31.13, Det Norske Veritas AS, July 2013
- Gasunie (2010), CO_2 transport en opslagstrategie
- Global CCS Institute (2013), Transport of CO_2
- Intergovernmental Panel on Climate Change (IPPC) (2005), IPCC special report on carbon dioxide capture and storage, Chapter 4 Transport of CO_2
- NEA/Panteia, Cost Structure for inland tanker navigation 2010 and forecast 2011, Zoetermeer, 2011
- PLANCO Consulting GmbH und Bundesanstalt für Gewässerkunde BfG (2007), Verkehrswirtschaftlicher und ökologischer Vergleich der Verkehrsträger Straße, Schiene und Wasserstraße, Essen/Koblenz
- TNO (2011) CO_2 capture, transport storage and utilization
- Zero emissions platform (ZEP) (2011), The costs of CO_2 Capture, Transport and Storage

Websites

- http://www.co2captureproject.org/co2_storage.html
- www.ft.com/intl/cms/s/0/a5cd18e8-1037-11de-a8ae-0000779fd2ac.html
- www.maersk.com/Press/NewsAndPressReleases/Pages/MT130309.aspx
- www.newgencoal.com.au/carbon-capture-a-storage/transport/html
- www.zeroco2.no/transport/ship-1
- whttp://encyclopedia.airliquide.com/encyclopedia.asp?LanguageID=7&CountryID=1&Formula=&GasID=26&UNNumber=&EquivGasID=26&PressionBox=&VolLiquideBox=&MasseLiquideBox=&VolGasBox=1&MasseGasBox=&btnGasToLiquid=Berekenen&RD20=29&RD9=8&RD6=64&RD4=2&RD3=22&RD8=27&RD2=20&RD18=41&RD7=18&RD13=71&RD16=35&RD12=31&RD19=34&RD24=62&RD25=77&RD26=78&RD28=81&RD29=82

9. Indexes

9.1. Index of Figures

9.2. Index of Tables

9.3. List of Abbreviations

CCS	–	Carbon Capture and Storage
CDM	–	Clean Development Mechanism
CEMT	–	Classification of European Inland Waterways; Conférence européenne des ministres des Transports
CER	–	Certified Emission Reduction Unit
CO_2	–	Carbon dioxide
DHK		Datteln-Hamm Canal
DST	–	Development Centre for Ship Technology and Transport Systems
ETS	–	Emission Trading Scheme
EU	–	European Union
FP7	–	Seventh Framework Program
IMO	–	International Maritime Organisation
IWT	–	Inland Waterway Transport
LNG	–	Liquefied Natural Gas
LPG	–	Liquefied Petroleum Gas
RHK	–	Rhine – Herne Canal

10. Annexes

10.1. Public summary

In MoVe IT! Task 6.6 was investigated if existing inland vessels can be adapted to the potential market of CO_2-transport.

Assessment of a candidate solution leads to the conclusion, that transport of liquefied CO_2 in independent tanks can be considered as technically feasible in general and is applicable to existing inland vessels.

A business case study showed however that IWW transport of CO_2 is economically not feasible, even if a rather large ship type (110m Rhine vessel) is considered: The transport costs for the shipment of liquefied CO_2 over a distance of 600 km are approximately three times as high as the current prices of futures (2013 and 2020) on Carbon Credits (CERs). Secondly, additional costs incur if liquefaction and offshore transport to a storage field with sea-going ships are considered. Finally, inland shipping has to compete with pipeline transport, which has roughly 25% lower costs per tonne of CO_2 transported over the same distance.

Transport of CO_2 with inland ships may become an economically feasible alternative if the price of carbon credits rises to its introductory level or even further increases