Closing Carbon Cycles on the High Seas

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ABSTRACT

In this paper, a concept for energy-efficient carbon dioxide (CO_2) capture and storage on board a ship is presented and techno-economically assessed. The captured CO_2 can be offloaded at ports and used again for the production of synthetic hydrocarbons. During the production of these renewable PtX-fuels, large amounts of oxygen are emitted, which so far have no substantial use in future energy systems. This oxygen is cryogenized and taken on board the ship to feed a closed-cycle engine. In addition, the oxygen expansion heat sink is utilized to efficiently liquefy the captured CO_2. Since this concept closes the carbon cycle, we call it Power to Cycle Engine.

Keywords: carbon supply, ptx-fuels, closed cycle engine, maritime propulsion, power to cycle engine

NONMENCLATURE

P2CE	Power to Cycle Engine
CO_2	Carbon Dioxide
O_2	Oxygen
IMO	International Maritime Organization
GHG	Greenhouse Gases
FT	Fischer-Tropsch
lq	liquid
g	gaseous

1. INTRODUCTION

In order to counteract the climate catastrophe, the United Nations has set the goal to limit global warming to well below 2, preferably to 1.5 degrees Celsius, by reducing greenhouse gas emissions. Maritime transport is responsible for about 3% of global GHG emissions, which is equivalent to the emissions from the 100 countries with the lowest GHG emissions [1]. Therefore, the International Maritime Organization (IMO) has committed in its Initial GHG strategy that total maritime annual emissions should be reduced by at least 50% by 2050 compared to 2008. The European Commission's proposal to extend the European emissions trading system to the maritime sector sets a clearly more ambitious target for climate-neutral shipping by 2045 [2]. To meet these goals, international shipping faces a fundamental technology transformation in the upcoming decades. In addition to numerous efficiency strategies [3], four energy carriers as pathways to complete climate neutrality are in the focus of attention. These include renewable hydrogen, ammonia, methanol and hydrocarbons from Fischer-Tropsch synthesis or methanation [4,5]. FT-Diesel is the only drop-in capable fuel that does not require installation of a completely new propulsion system [6]. At the same time, it depends heavily on the direct-air-capture (DAC) technology, for which the cost and efficiency development is associated with high uncertainties [6,7]. The energy-intensive DAC process is supposed to provide the CO_2 (carbon) needed to produce FT-Diesel or other hydrocarbons. The propulsion concept presented in this paper replaces this type of CO_2 source with CO_2 taken directly from the ship's exhaust gas stream, where it is present in much higher concentrations than in the ambient air and can therefore be captured much more efficiently.

2. POWER TO CYCLE ENGINE

2.1 The Concept

The propulsion concept envisaged is described here for the application case in shipping, but can also be used for propulsion machines on land. The core aspect is the energy-efficient system-integrated concept of carbon supply for the production of synthetic hydrocarbons.

The concept which is displayed in Figure 1 can be best explained starting from the separation of CO_2 from the engine exhaust gas stream by water condensation. The CO_2 is then compressed and liquefied in a heat exchanger. The heat exchanger transfers the heat to the cryogenic O_2, which must be heated to be fed to the engine as part of the intake air. The other, much larger part (~80%) of the intake air consists of recirculated CO_2.

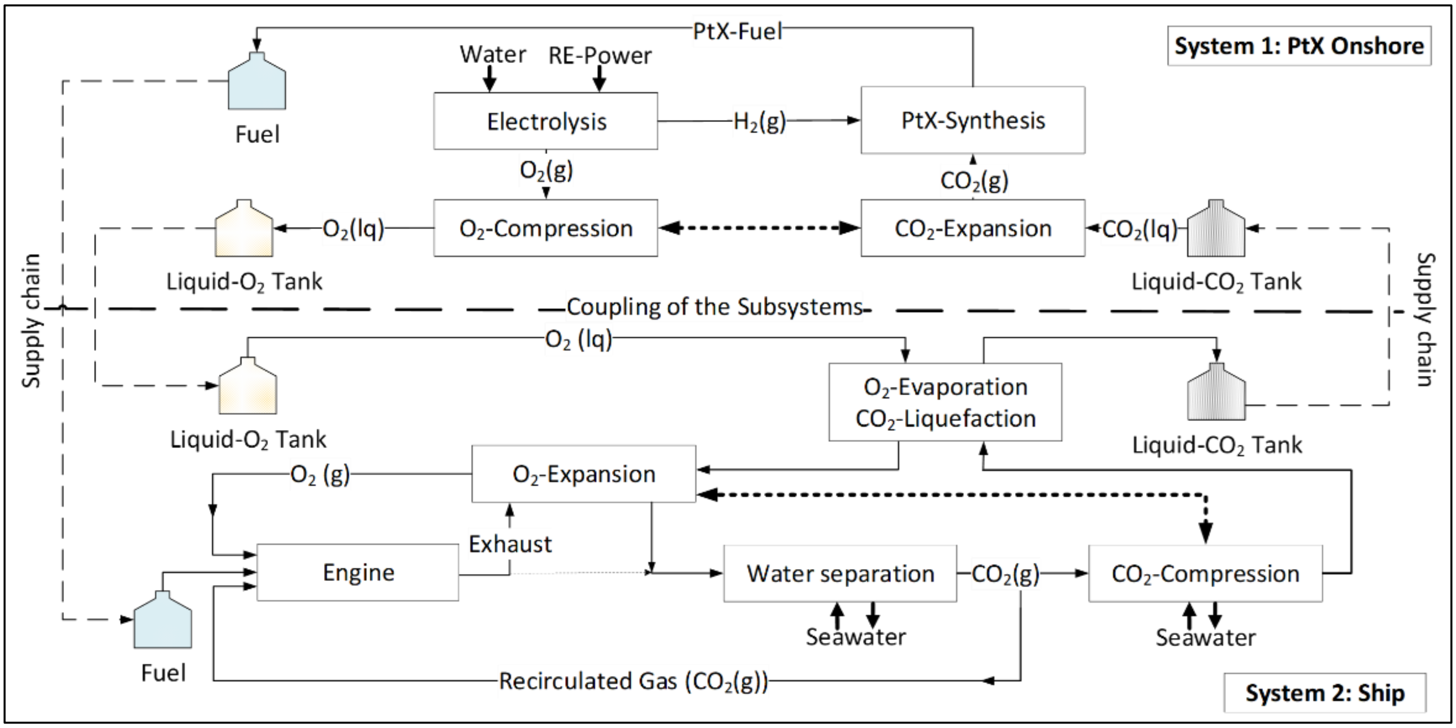

Figure 1: Overview of the Power to Cycle Engine concept (own illustration)

In this mode of operation, which is also known as *Kreislaufantrieb* (closed-cycle engine), no nitrogen oxides are produced during combustion due to the lack of nitrogen in the intake gas mixture. This is the essential prerequisite for CO_2 separation at the water condenser.

The electrolysis that takes place on land produces sufficiently large quantities of oxygen, which can be liquefied onshore by exploiting the same synergy effects as on board the ship (heat sink of the CO_2 to be heated). Disadvantages arise due to the loss of capacity on board the ship. However, the CO_2 produced can be stored in the emptying oxygen tanks, so that the additional capacity requirement for the two substances can be halved overall.

2.2 Mass flows within the system

For the basic system design, the following relationship can be established between the mass flows of O_2 and CO_2 as a function of engine power.

$$\dot{m}_{CO2} = P_{Motor} \cdot v_{spez.} \cdot 3.2 \, \frac{m_{CO2}}{m_{Diesel}} \qquad (1)$$

$$\dot{m}_{O2} = \dot{m}_{CO2} \cdot \frac{M_{O2}}{M_{CO2}} \cdot \lambda = \dot{m}_{CO2} \cdot 0.8 \qquad (2)$$

with:

P_{Motor}: *Engine Power*
$v_{spez.}$: *Specific fuel consumption of the engine*
$\dot{m}_{O2}$: *Oxygen mass flow*
$\dot{m}_{CO2}$: *Carbon dioxide mass flow*
M_{O2}: *Molar mass oxygen (31.99 g/mol)*
M_{CO2}: *Molar mass carbon dioxide (44.01 g/mol)*
λ: *Stoichiometric oxygen demand (~1.1)*

For the storage conditions in the additional gas tanks of the ship, it is assumed for the following calculation that these correspond to those of a design commercially available today (O_2: 131 Kelvin und 18 bar; CO_2: 285 Kelvin und 22 bar). The enthalpies of evaporation and condensation of the two gases in the combination with the ratio of the two mass flows to each other can now be used to determine whether the oxygen is in principle a sufficient heat sink for the condensation of the CO_2. For CO_2 condensation, the gas must be cooled down from 300 to 258 Kelvin after compression to 22 bar, which corresponds to an enthalpy difference of 320 kJ/kg. The evaporating oxygen absorbs an enthalpy of 500 kJ/kg at a pressure level of 18 bar and a heating of 131 to 290 Kelvin. Even if the lower oxygen mass flow rate from equation (2) is taken into account, the enthalpy difference can be considered a sufficient heat sink for liquefying the CO_2. Therefore, this conceptual calculation can show the theoretical feasibility of the concept.

2.3 Technoeconomic Assessment

The proposed P2CE technology aims to replace DAC technology as the source of carbon to be used as an input for the synthetic production of hydrocarbons. Therefore, in this part we want to examine the competitiveness against the DAC technology in a cost comparison. We hypothesize that the key tradeoff is between more transport capacity and lower carbon supply costs for the synthesis process compared to the DAC options.

2.3.1 Methodology

Our model is based on the total cost of ownership approach (TCO) for container ships by Schönknecht [8]. We have re-parameterized it with current cost assumption data (annex) and further differentiated the capital costs of the ship to integrate the P2CE technology conversion into the cost accounting (eq. 3). The model year is 2030.

$$C_F = C_S + C_E + C_{P2CE} + C_{FT} + C_{GT} + C_C + C_{OP} \qquad (3)$$

with:
C_F: *Fixed costs of vessel operation [€/a]*
C_S: *Capital costs of the base vessel [€/a]*
C_E: *Capital costs of the engine [€/a]*
C_{P2CE}: *Capital costs of the P2CE system [€/a]*
C_{FT}: *Capital costs of fuel tanks [€/a]*
C_{GT}: *Capital costs of gas tanks O_2/CO_2 [€/a]*
C_C: *Capital costs of containers [€/a]*
C_O: *Other capital costs of operation [€/a]*

The capital costs for the P2CE system include expenses for the turbomachinery and heat exchangers for the expansion and compression of the CO_2 and O_2, as well as the costs for the cycle engine system.

Variable costs, including handling and canal charges and labor and insurance costs, are modeled after Schönknecht (2009), except that Fischer-Tropsch diesel costs are used instead of heavy fuel oil costs. In order to show the influence of the CO_2 costs and thus the dependence on DAC cost development, we have decomposed the FT-Diesel into its cost components. For the sensitivity analysis we varied the CO_2 costs between 20 €/t_{CO2} and 90 €/t_{CO2} (according to [6] and [7] based on the method described in [9])

The fixed and the variable costs are then divided by the transport work of the vessel to calculate estimated cost of transports per tons-kilometers. Since additional gas tanks have to be installed on the vessel with P2CE technology, the transport capacity is reduced here according to equation (4).

$$\mathrm{LOC} = \min\left\{\frac{DWT - M_{GT}}{DWT}; \frac{NTEU \bullet v_{TEU} - V_{GT}}{NTEU \bullet v_{TEU}}\right\} - 1 \qquad (4)$$

with:
DWT: *Deadweigt tonnage of the vesse [t]]*
M_{GT}: *Weight of gas tanks [t]*
$NTEU$: *Nominal TEU-Capactity [n]*
v_{TEU}: *Specific Volume per TEU [m³/TEU]*
V_{GT}: *Volume of gas tanks*

2.3.2 Results

In the reference case of a 20,000 TEU container ship shown in Figure 1, it is clear that the fixed costs of P2CE technology significantly exceed those of the conventional ship powered by renewable FT-Diesel. However, the decisive costs for the container ship service are the fuel costs. Since the CO_2 can be saved by using the P2CE technology, the fuel costs are significantly lower for the P2CE technology.

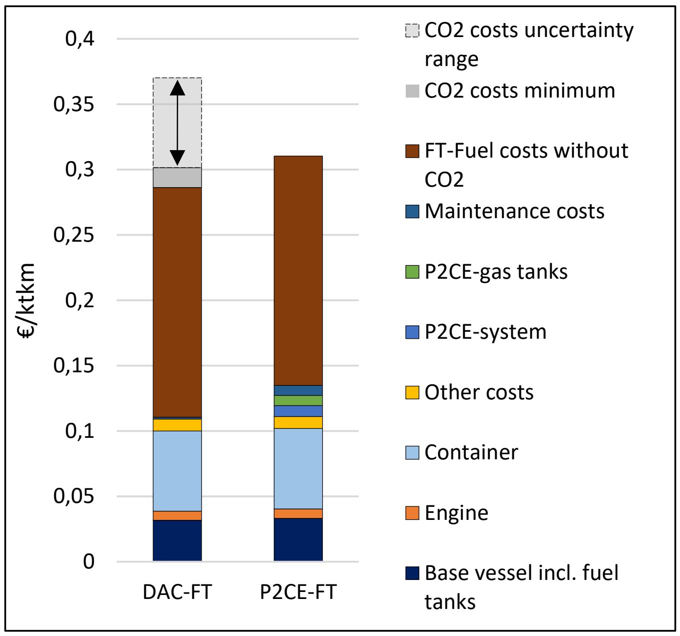

Figure 2: Modelling results for the reference case of a 20,000 TEU container vessel in freight costs per 1000 tons-kilometers (scenario year: 2030)

Depending on the CO_2 cost assumption, the use of P2CE technology is more cost-efficient. At this point, it should be mentioned that the cost assumptions for P2CE technology are also subject to strong uncertainties. With the cost assumptions made, it can be summarized that the CO_2 supply costs of the P2CE technology for the reference case are 31 €/t_{CO2}.

Since the energy requirement of the ship's propulsion system is proportional to the third power of the ship's speed, this has a strong influence on the total costs of container ship transport. However, since a slower speed is also associated with a decrease in transport work, an optimum can be determined for the total costs of transport. For conventional propulsion with heavy fuel oil (HFO), this modeled optimum is 16 knots. This corresponds to the approximate speed that has been observed since the introduction of slow steaming in container shipping.

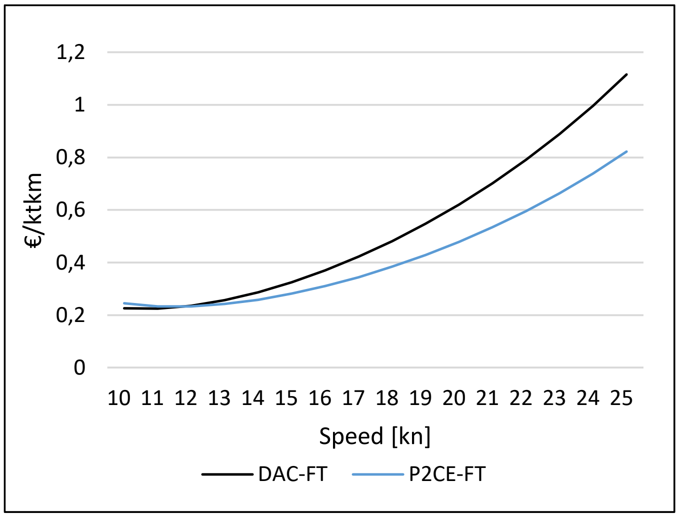

Figure 3: Freight costs per 1,000 tons-kilometers as a function of the vessel speed (scenario year: 2030)

With regard to a variation of the speed, it can be said that at higher speeds the cost comparison is significantly more positive for the P2CE technology. This can be explained by the fact that P2CE technology is comparatively more capital cost intensive. The conventional ship, which is operated with FT-DAC fuel, pays relatively higher fuel costs, which means that the larger energy requirement at greater speeds is reflected more strongly in the freight costs.

2.3.3 Discussion

The modeling results are in the order of magnitude of comparable studies on climate-neutral shipping [4,5,10]. The cost assumptions especially for the DAC and the P2CE technologies are critical parameters for which the uncertainty is currently still particularly high. The use of a so-called bivalent tank in which O_2 and CO_2 can be stored is not guaranteed. If it turns out that bivalent tank use is not possible, the loss of cargo would be twice as high. On the other hand, further space savings could be achieved by optimizing the tank size depending on the routes, which would have a positive impact on the overall cost of P2CE technology. With the practical deployment of P2CE, certain restrictions arise with respect to bunker operations, since the captured CO_2 must also be exchanged with the cryogenic O_2. These additional costs have to be considered in future studies.

2.4 Conclusions

In light of the currently unsolved problem of a reliable source of CO_2, the P2CE technology concept represents a promising opportunity to supply the shipping industry with synthetic hydrocarbons. This paper has shown that the technology can be cost-competitive versus the DAC technology. Moreover, unlike an ammonia or hydrogen fuel cell drive, it can be easily retrofitted. Since P2CE Technology always provides exactly as much CO_2 as is needed for the ship's energy consumption, it is also not dependent on a global CO_2 source market development and does not have an additional need for the expansion of renewable energy sources.

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ANNEX

Technoeconomic Assumptions for scenario 2030

Parameter	**Value**	**Unit**
Transport distance	20,000	*km*
DWT vessel	28,0000	*tons*
Engine Power	68	*MW*
WACC	10	*%*
Lifetime	25	*years*
Base vessel costs	113,000,000	*€*
Engine costs	385	*€/kW*
Container costs	1222.75	*€/a*
Fuel tank costs	0.083	*€/kWh*
P2CE gas tank costs	3,120	$€/m^3$
P2CE compressor costs	3,300	$€/kW_{compressor}$
P2CE expander costs	1,650	$€/kW_{expander}$
P2CE-Engine Modification and Heat Exchanger	193	$€/kW_{engine}$
P2CE-Maintenance Costs	4	*%/Capex*
P2CE-Oxygen Costs	0.01	*€/kg*