Life Cycle Performance Assessment - method and tool for decision makers

Markus Lehne BALance Technology Consulting GmbH;
Christian Norden, BALance Technology Consulting GmbH;
Dr. Stephan Wurst, BALance Technology Consulting GmbH;
Rolf Nagel, Flensburger Schiffbau-Gesellschaft mbH & Co. KG

Summary

Low emission shipping has become a key competitive factor for shipping companies and for European maritime industry based on an increasing public awareness and fiercer environmental legislation.

In order to achieve a significant emission reduction, a number of new technologies are in development. The most suitable technology depends on the specific transport service of a ship and its operational profile and combines low emission shipping with a high profitability. Identifying the most suitable potential technology means to investigate all life cycle phases in a holistic approach.

Life cycle performance assessment combines methods of screening-LCA for environmental impact assessment with economic perspective in terms of net-present value and amortisation for a multi-criteria assessment to support the decision making process.

The paper introduces the methodology of LCPA and how the developed software-tools BAL.LCPA and BAL.CDB enable its utilisation, before the benefit for different stakeholders is demonstrated in 2 model cases.

ABBREVEATIONS

AP	Acidification Potential
CED	Cumulative Energy Demand
CDB	Component database
EC	European Commission
SECA	Sulphur Emission Controlled Area
EEDI	Energy Efficiency Design Index
EP	Eutrophication Potential
EU	European Union
FMI	Functional Mock-up Interface
GWP	Global Warming Potential
IMO	International Maritime Organisation
JOULES	Joint Operation for Ultra Low Emission Shipping
LCA	Life Cycle Assessment [ISO 14040]
LCPA	Life Cycle Performance Assessment
LNG	Liquefied Natural Gas
NPV	Net Present Value
PM	Particulate Matter [2.5 and 10]
SCR	Selective Catalytic Reactor

1 Introduction

The environmental impact of shipping is becoming a key competitive factor for shipping companies worldwide. Fiercer environmental legislation like emission taxes or emission control areas affects the business opportunities and the cost structure of shipping companies. In addition, the increasing public awareness of shipping pollution forces shipping companies to present transparently their environmental impact as well as their measures for environmental impact optimisation to expand future business opportunities.

Moreover, fuel costs have been and will remain a major cost item in shipping resulting in the common practise of slow steaming in order to realise fuel costs savings. Although the corresponding emission reduction is a secondary effect, the economic threat to optimise energy costs is expected to become the main driver for the further development and implementation of low-emission technologies, if they are profitable from a lifecycle perspective.

Under the described conditions, the continuous improvement of today’s technology still offers some potential, but will surely not show the way out. Therefore the development and implementation of alternative propulsion technology that enables the use of alternative energy carriers, like fuel cells or the use methanol from renewable sources could decrease the environmental impact of shipping significantly by consuming a reasonable amount of renewable energy in its production. A successful market introduction of alternative energy carriers depend on the actual technology readiness level, and the profitability of the technology, which is mainly determined by the investment- and maintenance costs as well as the anticipated difference in energy price development throughout the life cycle. In this regard, the market introduction of new technologies could be fostered by fiercer environmental legislation.

In the EU-funded research project JOULES (Grant agreement nr. 605190), energy grids for ultra-low emission shipping are investigated for 11 different application cases, varying from an urban ferry to Ro-Pax ferries or ocean cruiser vessel to container vessels operating in arctic regions. Thereby every application case has elaborated the implementation of alternative propulsion systems taking into account the individual requirements based on the specific operation profile as well as the expected technology readiness level in 2025 and 2050. The results will be at least two new ship designs for each application case.

In order to assess the anticipated performance of the new ship designs, the potential reduction of the environmental impact as well as the profitability has to be assessed. In this analysis, numerous aspects need to be considered and compared to a baseline design - a state of the art ship. With respect to the environmental impact, the footprint of the applied materials as well as the energy used in the ship production process needs to be investigated before comparing the actual differences in emission output during operation. In terms of the economic dimension of the assessment, potentially higher investment costs may pay off by reduced energy consumption or less costly fuel. Different maintenance intervals may also affect the profitability as well as potential payload difference due to required space of the specific energy carrier storage requirements.

As a result, the most promising new ship designs would combine a significantly reduced environmental impact with an overall economic benefit in terms of net present value and amortisation. These new ship designs are supposed to lead to an increased demand for complex, high-tech ships and ship technologies, resulting in new business opportunities for European shipyards and maritime equipment supplier in order to strengthen the employment in the European maritime industry.

In this regard, the research of the JOULES- Project aims towards a sustainable maritime transport in Europe.

2 Life cycle performance assessment

The assessment of the environmental impact and the profitability of the new ship designs for each of the 11 application cases require a comprehensive method that considers the environmental and economic impact of the ship production, the ship operation as well as the end of life. Therefore, the method of lifecycle performance assessment (LCPA) is selected to carry out a comprehensive analysis of new ship designs and to compare with the LCPA of the reference vessels.

Life cycle assessment is defined as compilation and evaluation of in- and outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). In general, LCA can be carried out for product systems, processes or companies. However, the LCPA-approach applied within in the JOULES-project reduces the LCA to a screening-LCA of the product system "ship" due to the sheer size, complexity and its uniqueness and combines it with the economic assessment that considers every cash flow throughout a ship´s lifecycle to calculate the net present value and the amortisation of each ship design. As a result, the Joules-LCPA is considered a holistic approach for the comparative evaluation of alternative transport solutions.

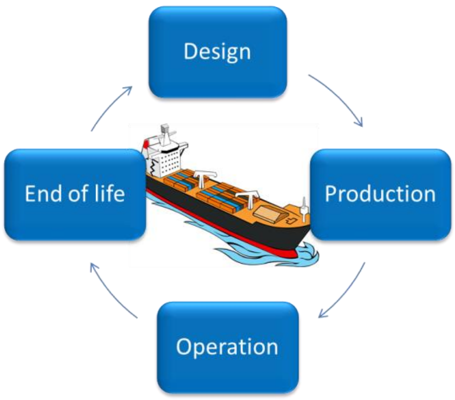

Figure 1: Ship life cycle

As depicted in figure 1, the lifecycle of a vessel consists of the phases: design, production, operation (including refurbishments) and the end of life phase. As basis for a comprehensive LCPA, relevant data for each lifecycle phase needs to be identified, collected and analysed. This step is crucial to achieve a meaningful assessment, which depends on the quality and the level of detail of the collected data. Thus, the data collecting process is essential and challenging.

A set of global values are introduced to the Joules-LCPA methodology in order to reflect different future scenarios. With respect to the economic dimension of the LCPA, the energy price development is the most prominent example (see Figure 2).

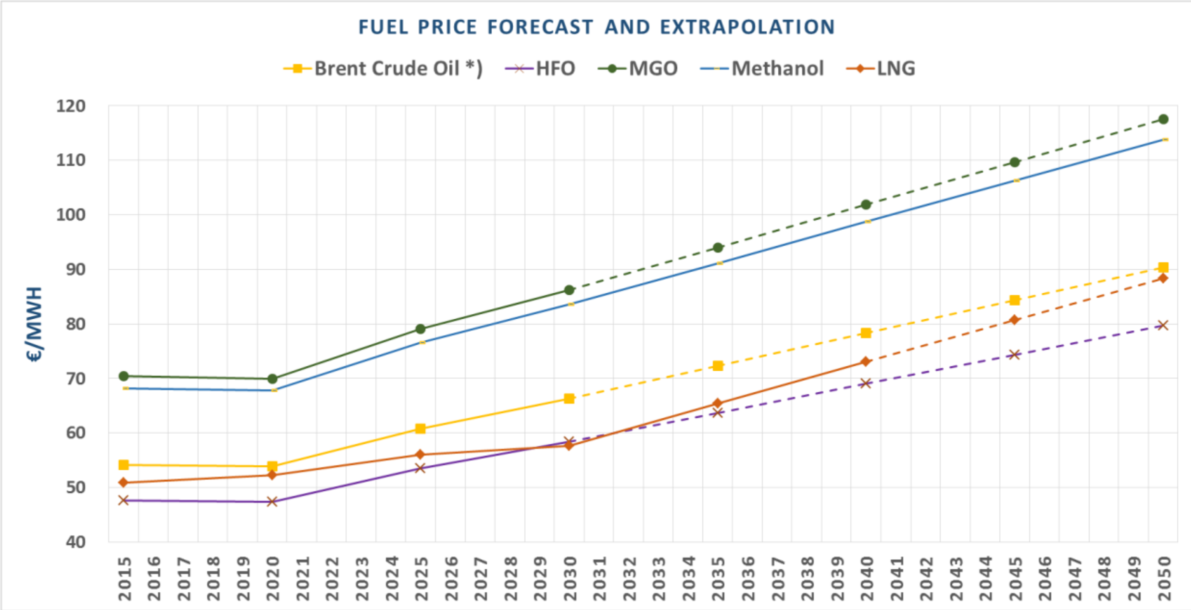

Figure 2: Fuel price forecast

2.1 Economic assessment

The economic perspective is focusing on cash flows associated with the investigated ship. Therefore, accounting systems are the basis to collect relevant data like operation costs of a ship, consisting of cost categories like personnel, energy (fuel)-, maintenance, depreciation, port fees, taxes, etc. However, since LCPA considers a 25 year long lifecycle of a ship, the future development of the cash flows as a time series is important. Cost items like the future development of fuel costs or development of maintenance costs over time, which are typically increase in a non-linear way throughout the lifecycle, need to be predicted (Drewry Shipping Consultants, 2005).

In order to deal with the uncertainty of predicting future cash flow developments affecting the LCPA-results, different scenarios can be created. Therefore a set of global values is introduced to the Joules-LCPA methodology in order to reflect different future scenarios. As an example, figure 2 depicts the fuel price forecast derived and extrapolated within the JOULES-project based on existing forecasts (EIA, 2014). Scenarios may consider alternative energy price development forecasts, which can be part of the assessment to analyse the impact on the LCPA results and to test the robustness of the investigated ship designs.

Different energy price developments underline the importance of the exact point in time of each cash flow throughout the life cycle. Therefore the concept of the Net-Present Value (NPV) is applied in the LCPA. The NPV discounts every cash flow with an interest rate to express every future cash flow in today´s monetary unit, which enables direct comparison of investment with different durations, before every discounted cash flow is aggregated. Thus the NPV represents a strong basis for the decision making process of comparing different ship designs in the early design stage.

Another important indicator in the economic part of the LCPA is the payback period, which is defined as the duration until the aggregated net cash flows after taxes associated with an investment object (like a ship) equals the investment costs. (Kalyevara, et al., 2014) In this respect, the payback period is an indicator for the economic risk associated with the investment and need to be assessed in the evaluation process of the new ship designs.

2.2 Environmental assessment

Gathering the relevant data for the environmental impact is even more complex. The general process to conduct a LCA starts with the collection of environmental life cycle data. Afterwards, a calculation model based on the collected data is set up before a broad range of environmental indicators is used to conclude the assessment. In order to assess the environmental impact of a specific ship design properly, the environmental load of the specific ship design needs to be investigated for every life cycle phase. In case of the production phase, the environmental load of every applied material, component or system including its transport needs to be considered as well as the energy consumption in the production and in the assembling process in the shipyard. Following this example, the amount of relevant data for the operational phase of the investigated ship design increases, since the environmental load of material for maintenance, repair and refurbishment with the corresponding energy consumption for these processes (on-board or in a repair yard) are part of the analysis and, most importantly, the emission of the energy consumption to propel the vessel needs to be investigated in the operational phase. Thereby, emissions of the energy conversion on-board are part of the analysis as well as the energy production and the energy provision.

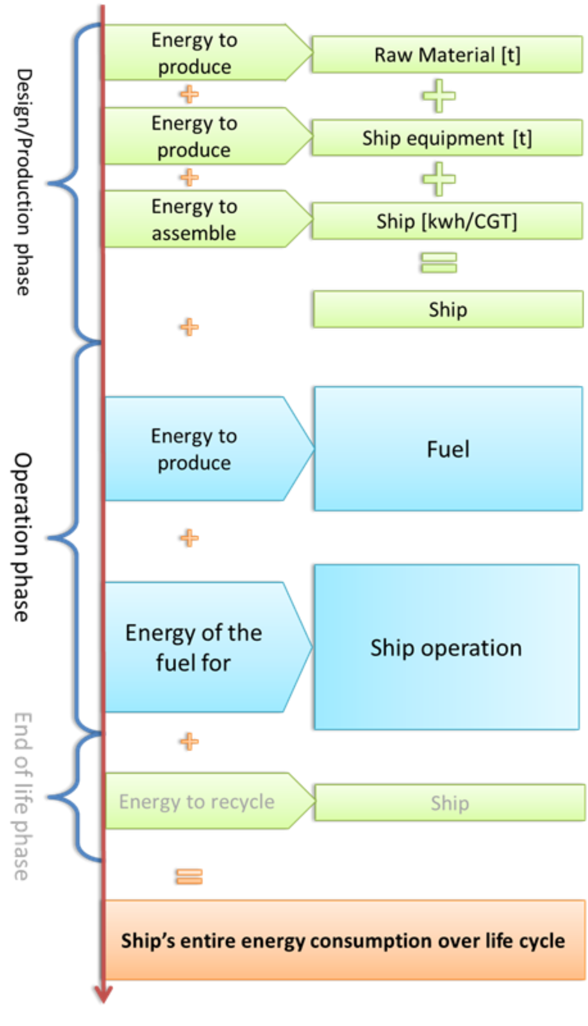

Figure 3: Joules Screening LCA

These two briefly introduced examples underline that performing a complete life cycle assessment is a complex matter. The amount of required data would take an enormous effort to gather or is even not available, especially if the investigates product system is a new design concept. Therefore the alternative method of screening-LCA is introduced to the methodology, which uses a limited set of data and indicators in order to support a quick decision making process and to balance the relation between effort and benefit.

In more detail, the screening LCA-method applied in the Joules-project concentrate on the assessment of the production and operational phase of new ship designs. While the assessment of the production phase focuses on the environmental impact of the energy used to produce the applied materials (from systems or components) and the energy used in production in the shipyard. Whereas the discussed environmental impact assessment of the operational phase focuses on the impact of the energy production, provision and conversion, since they are considered to have the biggest impact on the results.

2.3 Life cycle performance assessment

The introduced holistic approach of life cycle performance assessment combines the ecological and the economic life cycle assessment. Thereby numerous specific results are generated, which complicates the support for quick the decision making. In order to cope with the amount of results, several key performance indicators are selected to summarise the main results in order to present an easy to understand result overview. This approach enables an easy comparison of different ship designs and thereby fosters the decision making process using important sustainability aspects. Thus, the Key Performance Indicators (KPI) of the life cycle performance assessment are:

- Global Warming Potential (GWP): According to the U.S. Environmental protection agency (EPA), the GWP "was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of one ton of a gas will absorb over a given period of time, relative to the emissions of one ton of carbon dioxide. The larger the GWP, the more that a given gas warms the Earth compared to carbon dioxide over that time period." (EPA - United States Environmental Protection Agency).
- Cumulative Energy Demand (CED) assesses the energy used throughout the ship´s life cycle. Starting point is the production phase with the

energy demand for applied materials and the yard production. The CED also considers the energy used in the energy converters during the operational phase and the energy used to produce and provide the energy to the ship. In addition, the energy used for the recycling process is also part of the CED.

- Net Present Value (NPV) adds up all cash flows throughout the life cycle and discounts them with a specific interest rate in order to consider the point in time of cash flows.
- Acidification potential (AP) measures the emissions of SO2 and NOx as mol H+ equivalent or kg SO4 equivalent. Acidification causes damage effects on soils and water.
- Eutrophication potential (EP) is mainly caused by NOx emissions which lead to undesired fertilizing effects of terrestrial ecosystems, which is especially important in coastal areas.
- Particulate matters (PM 10) is also known as particle pollution or PM. And is a mixture of very small particles and liquid droplets. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

The individual results of the introduced KPIs complicate the direct comparison of the investigated ship designs due to different units and the individual importance of each KPI for different stakeholders (Yard, ship owner, ship operator) Therefore, the life cycle performance indicator is calculated to ease the decision making process. In fact, the life cycle performance indicator carries out a use-value analysis, which takes the individual weighting of the KPIs into account according to the focus of the analysis. The result is a single, numeric value, which summarises the weighted KPI results to support the decision making process by ranking the investigated ship designs according to its score.

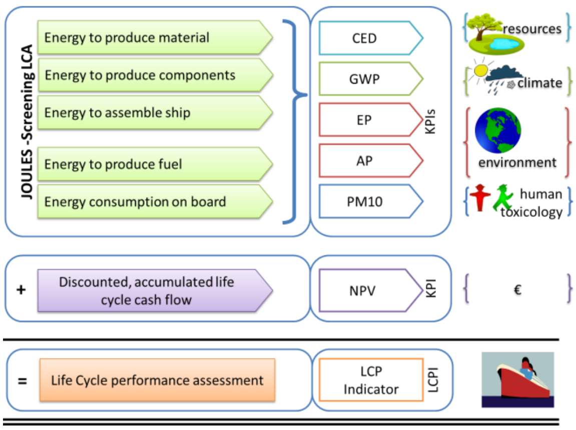

Figure 4: KPIs of the Life cycle performance assessment

The presented methodology also allows comparing the introduced KPIs for specific life cycle phases of alternative ship design. According to the specific interest of the stakeholder, the analysis can focus the comparative analysis of the operational phase for ship operators while shipyards may concentrate on the investigation of the production phase. In this regard, the developed, holistic assessment method complies with the specific analytic needs of different stakeholders.

3 Software-tools for Life cycle performance assessment

The introduced assessment methodology requires a wide range of input data for the complex calculation of the key performance indicators. To assist the assessment process, two software-tools have been developed: In the component data base (CDB) the collected data can be stored and exchanged on component or system level. These components can be imported into the BAL.LCPA-tool, which processes the actual life cycle performance assessment.

The BAL.LCPA software enables an iterative process of modelling, calculation and comparative result presentation to support the decision making process. Besides the actual numeric results, various visualisations are available for each KPI, which allows more in-depth analysis of the result of interest (exemplary KPI visualisation is presented in chapter 4). Thereby it can be shown how the KPIs develop over time and also to what extent the different components influence a certain KPI. For further post processing an export of the raw data is possible. This functionality provides a wide range of analysis opportunities, from a brief overview to an in-depth investigation of details.

However, is has to be kept in mind that the result quality heavily depends on the input data. As already discussed, that amount of required data and the effort to gather reliable data in the necessary level of detail can be challenging. In order to cope with this challenge, the BAL.LCPA tool offers the opportunity to store the collected data on component or system level in an integrated component data base (CDB), from which the components can be imported easily to BAL.LCPA and vice versa.

In case of the JOULES-project, the required data to carry out a LCPA is gathered from different work areas. In terms of LCPA of the propulsion systems, components like engine, propellers and entire systems are used to simulate the energy grid for each individual application case. The relevant LCPA- results of the simulation are stored in the CDB to ensure a high data quality. Moreover, the CDB also contains LCPA related data for each component or system like pricing information and the amount of material that is contained in the device.

The component database is a web based client-server application which runs on every recent browser. The CDB contains the simulation models supporting information for component verification and LCPA data for each component or system. For each component or system, one or more calculation results can be stored for later use. These results can also be accompanied by a description and user comments.

Communication between the LCPA tool and the component database resp. the simulation tools is performed by means of XML files. A JOULES template for such exchange processes has been defined which is also used for the communication between the component database and the simulation software which avoids the maintenance of different formats.

4 Case study

Case study 1
Comparison of four primary energy converters

The modelling of primary energy converters is essential to achieve proper results in the LCPA calculations. Therefore, a simple example with four different types of primary energy converters using various kinds of fuels is discussed in the following model case:

- Diesel Engine using diesel oil
- Lean Gas Engine using LNG
- Dual Fuel Gas Engine using LNG and Diesel oil as pilot fuel
- Fuel Cell using methanol

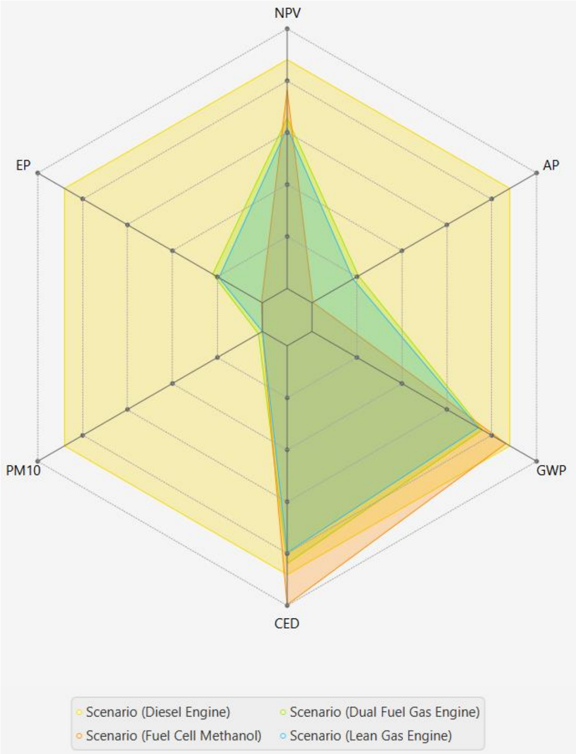

Figure 5: Spider graph of KPI results

For all types of primary energy converter, the same propeller load has been assumed over one year. Depending on actual load the correct SFOC or heat rate - e.g. according to the relevant project guide of engine manufacturers- are used for calculation of the fuel oil consumption.

In the first place, a result overview of all KPIs is displayed by the LCPA-Tool as a spider web. Which already indicates principle performance differences between the primary energy converters.

The diesel engine has been chosen as reference scenario, while better performances of the compared technologies point to the spider web centre. For a more detailed analysis and result interpretation several sub-charts for each KPI are available.

The fuel consumption is the starting point for many other subsequent calculations, in particular CED and GWP for well to tank and NPV calculation (see figure 5).

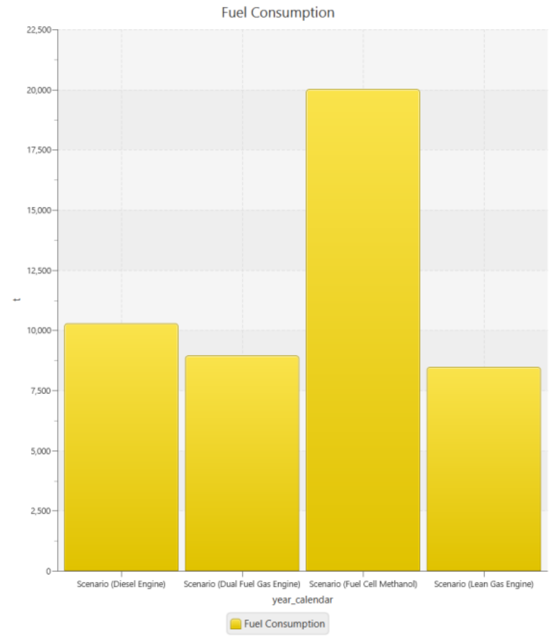

Figure 6: Fuel Consumption of different primary energy converter

According to the results, the lean gas engine has the lowest fuel consumption in terms of mass, whereas the fuel cell has nearly double methanol consumption depending mainly on the lower heat value of the fuel while the same efficiency of the primary energy converter is assumed. Figure 7 depicts typical input parameters of primary energy converters for the example of a propulsion diesel engine.

Propulsion Diesel Engine (MGO)	
Eta (mechanical)	0.980
Eta (electrical)	0.980
Eta (thermal)	1.000
Revolution	750 rev/min
Methan Slip	0.0 %
Load	75 %
SFOC	181.0 .. 208.0 g/...
SC (MGO)	0.10 %
CF (MGO)	3.206
LHV (MGO)	42,700 kJ/kg
SOM (MGO)	2
SPNOx (Tier II)	8.100 .. 14.500 g...
FC (MGO)	1,097 USD/t
FPF EE (MGO)	11,810 kJ/kg
FPF GWP (MGO)	450.5 g/kg

Figure 7: Typical data example for diesel engine

Eta mechanical describes the efficiency between the propeller power and the primary energy converter, e. g. by a gear box. Based on the rpm value, the correct emission factor from the SPNOX curve, which represents the Tier II limits, is taken. CF converts the amount of fuel burnt into CO_2-emissions and this factor is taken from IMO. FPF EE denotes the energy expended to produce one kg of diesel oil and FPF GWP denotes the associated emissions in g CO2 eq. Such values are taken from public available databases (e.g. Ecoinvent) or from Edwards et.al. (2013).

CED and GWP results (both including the well to tank fraction) are presented in figure 8 and 9, which also reveals that the well to tank fraction is generally low for conventional fossil based fuels. However, the expended energy for Methanol production is significantly higher. This tendency is even more pronounced in case of production of all kinds of liquid fuels from renewable energy sources.

Same tendency holds for GWP, but LNG has the advantage of a relative low CF-factor of 2.75. However, the LCPA-tool also considers the methan slip (see figure *8* of course 0 for diesel engines). While 1.5% methan slip is used for the dual fuel gas engine, the lean burn gas engine has a methan slip of 0.5%. The lower value for the lean burn gas engine is due to better optimisation of the ignition of gases in the Otto-cycle for this type of engine (also leading to better heat rate compared to dual fuel engines).

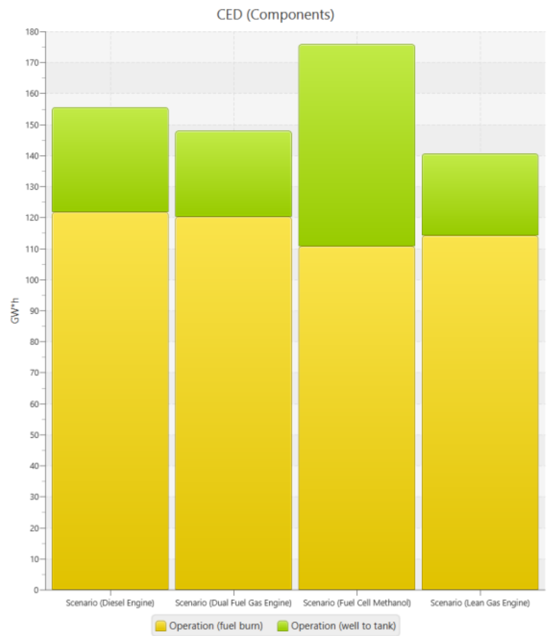

Figure 8: Cumulative Energy Demand (CED) comparison

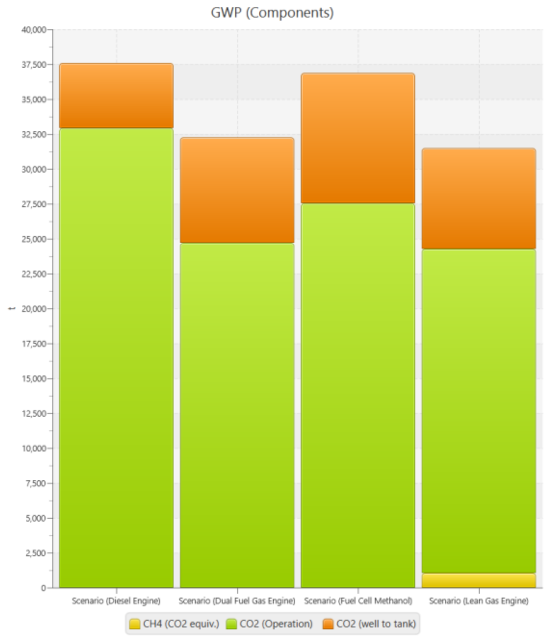

Figure 9: Greenhouse warming potential (GWP) comparison

However, CO_2-emissions can be significantly reduced, if fuels are produced from renewable energy.

As SO_x emissions are more or less eliminated in this comparison example (all scenarios fulfil the SECA requirement with sulfur content below 0, 1%), the NO_x emissions are dominating the graph for acidification potential (AP). NO_x emissions contributes with a characterisation factor of 0.7 to the acidification potential and thus, even the Tier III level as achieved by the Dual Fuel Gas Engine has a relevant impact on this environmental impact category.

NOx emissions of lean burn gas engines are below Tier III requirements and a further improvement can be seen (blue line). Fuel cells emit only very little NOx emissions (orange line), whereas diesel engines without SCR only fulfil Tier II requirements (outer reference line).

PM emissions only play a significant role for diesel engines and for dual fuel gas engines, the pilot fuel contributes to this impact category.

The complex modelling of primary energy converters including fuel properties has been discussed using this example model. The tool allows also the assessment of other fuel types like e. g. a mix of diesel oils blended with synthetic diesel, hydrogen for fuel cells or synthetic fuels from various renewable feedstocks. The modular approach in modelling these primary energy converters allows for any kind of adaptation in the future.

Case study 2
Comparison of three Ro-Pax ship designs

A comparative LCPA on ship level has been modelled for the Ro-Pax application case in the JOULES project. By this example the basic LCPA modelling is explained.

A proper modelled operation profile is crucial for a meaning full LCPA, especially in case of investigating the optimisation of the ship design and its energy grid. In this regard, the LCPA-tool allows to implement any timespan as operation profile, like daily profiles, which are typical for Ro-Pax ferries or weekly profiles, as often used for cruise vessels (e. g. one week Caribbean). Main interruptions in service, like class surveys or dockings, can be implemented as event. This allows for a flexible use of the LCPA-Tool.

The life cycle performance assessment approach compares two future alternative designs against an existing baseline vessel. The future design configurations are assumed to realise a CO_2-emission reduction of 20 % until 2025 and at least 80 % in 2050 according to the objectives of the JOULES project.

The 2025 design uses enhanced energy recovery systems from exhaust gas and cooling water as well as some 2nd generation bio-fuel. NO_x emissions are reduced to Tier III level by applying SCR-technology. The 2050 design is an electric ferry using fuel cells operated with hydrogen from renewable energy sources. Alternatively, the electrical energy can be stored in redox-flow batteries and thus a full electric design could be achieved.

The 2025 design is expected to have a moderate reduction in GWP (CO2 eq.), a more pronounced reduction in AP and EP due to SCR technology at approximately same life cycle costs (see figure 10). However, the energy demand for this holistic approach is increased due to applying the well to tank approach for fuels. In this case the fraction of synthetic fuel from 2nd generation of bio mass from short rotation forestry (SRF) contributes to this higher cumulative energy demand.

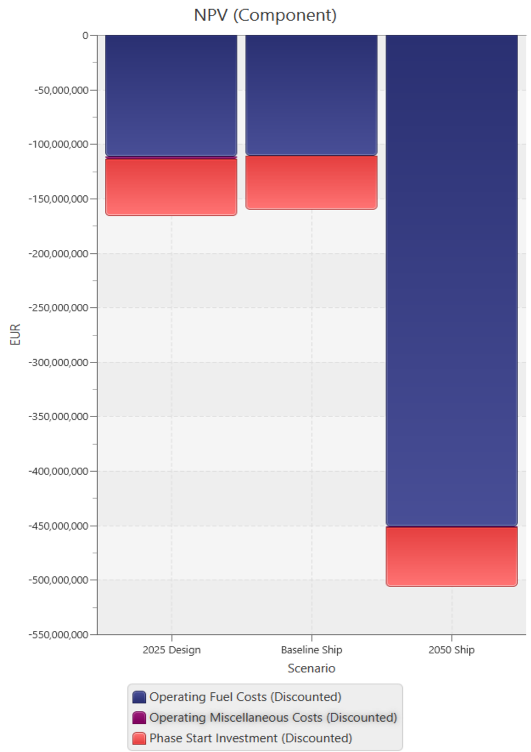

Figure 10: Cost drivers

In contrast, the 2050 design is based on an assumed technology quantum leap using an electric ship with fuel cells converting hydrogen produced from energy from renewable sources. The environmental impact categories (AP, EP, PM 10) and the impact category climate change (GWP) disappeared, but NPV and CED are well pronounced. Although only preliminary results are available at this stage of the project, the general tendency of emission reduced ships will be technically ready but at the trade-off for energy and economy becomes obvious. Figure 10 shows the fuel costs as main driver in this example with hydrogen being actually extremely expensive in terms of €/kWh.

The BAL.LCPA-tool also allows to consider the impact of external cost, which are derived from the EU-project NEEDs and represents the actual state of knowledge. Introducing the internalisation of external costs to the case study, the results doesn´t change dramatically, as presented in the following revised calculation results (see figure 11).

Considering the internalisation of external costs changes the ranking of advantageousness in this assessment. The slightly higher investment costs of the 2025 ship design are compensated by its lower environmental impact expressed in lower external costs compared to the baseline ship design. In fact, life cycle costs are reduced by more than 13%.

In case of the 2050 design, the external costs shrink the life cycle cost gap in the comparison since the 2050 design causes no external costs at all. In fact, the NPV gap of the life cycle costs for the 2050 design compared to the baseline design reduces from 340 mill. € to 241 mill.€ over the course of the lifecycle. However, the main cost driver of the 2050 design is the significantly higher operating fuel costs (see figure 11). Anticipating a different hydrogen price development, caused by different market development or political action, would change the results of the assessment.

Thus internalisation of external costs could be one possible political instrument to close the future gap between environmental/climate change requirements and economic constraints and promote the uptake of new environmental friendly technology.

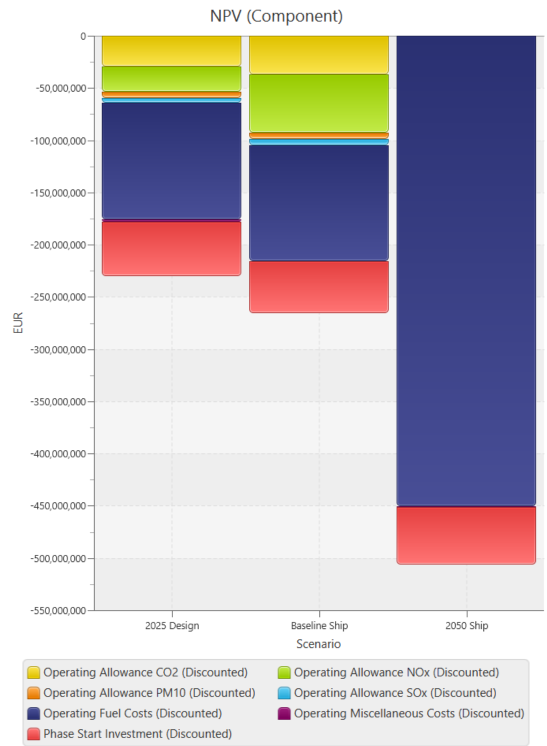

Figure 11: Cost drivers including external costs

5 Conclusions

The identification of suitable new technologies to achieve significant emission reduction while increasing the profitability at an acceptable risk-level requires a comprehensive assessment. The introduced method of life cycle performance assessment allows to compare alternative ship designs in the early design stage for various Key

Performance Indicators covering main ecological and economic aspects, like greenhouse warming potential (GWP), cumulative energy demand (CED) or net present value (NPV). In the end, the LCPA-results are building a strong baseline for the decision making process. Thereby, the flexible approach enables specific stakeholders to tailor the assessment to their needs by focusing the LCPA on the GWP reduction, impact in terms of particulate matters, profitability reflected as net present value for specific phases of a ship´s life cycle.

The challenge in performing holistic life cycle assessments is the identification, collection and storage of relevant and reliable data. The Joules-LCPA approach support the user to handle the data management with the integration of a component data base (CDB), where the data can be stored in component or system level. The easy to use import function to the BAL.LCPA-tool, in which the actual life cycle performance assessment is performed, ensures a data quality level to process meaningful results for the support of the decision making process.

Two case studies demonstrate the capabilities of the holistic LCPA-approach with the software tool support of BAL.LCPA and BAL.CDB. The comparative approach in combination with the descriptively result visualisation allows to identify quickly the essential results and their influencing factors, like major cost drivers or components with a high environmental impact.

The feature to consider different global value-set, like different future fuel price developments, adds the opportunity to compare different future scenarios and thereby test the robustness of the investigated ship designs, systems or components.

The next steps within the Joules-research project include detailed life cycle performance assessments of 11 different ship types. Thereby, every ship type focuses on a different technology to decrease its environmental impact according to the individual operation profile. The gathered data will populate the component data base and thereby increase the opportunities for future comparative life cycle performance assessments. The LCPA results will be used to evaluate the achievements of the research project, in terms of emission reduction and profitability to estimate the potential implementation of certain technologies. Moreover, the results will be the baseline for deriving political recommendations to foster the implementation of ultra-low emission shipping.

6 ACKNOWLEDGEMENTS

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