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Life Cycle Assessment to Determine the Relevance of Including Absorption Cooling Plants in the Curriculum for Marine Engineers

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Abstract: The need for a sustainable transition of energy and shipping industries necessitates a methodological approach to determine the most environmentally relevant content and learning objectives of educational programs within technical engineering. One approach is application of Life Cycle Assessments (LCA); a methodology suitable for evaluating environmental performance of technologies, product systems or practices.

To evaluate this approach, a case study comparing conventional cooling for air conditioning onboard cruise ships with absorption cooling is undertaken by the authors, where a consequential LCA using inventory data from a market supplier and a life cycle inventory database is conducted. Eighteen environmental impact areas are considered in the study, with no external normalization or weighting of results. The results are proven using two types of fuel, marine diesel oil and methanol.

The impact assessment results uniformly identify the absorption cooling plant as having the best environmental performance with potential impacts averaging 20% of the conventional plant in most categories. These results indicate that absorption cooling plants should be included in the curriculum for marine engineers.

A more widespread adoption of the methodology to evaluate or qualify course content will likely require further qualification of teaching staff, due to prerequisite knowledge requirements for conducting LCA's.

Keywords: Environmental Assessment; LCA; Course Content Qualification; Sustainable Transition

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1. Introduction

Marine engineers are at the forefront of technological development and advancements. While not necessarily taking direct ownership in new product development, the ongoing management and assimilation of new technology in operations is a cornerstone of the profession. This is also evident from the title of the bachelor's program in Denmark: "Bachelor's Degree Program in Technology Management and Marine Engineering" (BTME).

The exponential growth in technology, and the urgent need for decarbonization of all sectors requiring novel solutions and optimizations, empathize that educational institutions should remain vigilant in ensuring that curricula are updated to reflect current and future needs (Cassard & Hamel, 2018). The overall content of the BTME is defined in the pertinent law act and the International Convention on Standards of Training, Certification and Watchkeeping (STCW). While STCW lists specific requirements for a number of subjects, the law act stipulates high level requirements and intended learning outcomes in a number of technical and management fields, thus allowing the professional colleges offering the program considerable flexibility in determining the taught subjects and technologies covered.

A frequently utilized data source to determine updates to the curriculum is dialogue with shipping companies and maritime authorities. In this study we propose an alternative methodology, in which suggestions for changes to the curriculum may be qualified via their change to the potential environmental impact for a given use case or service. The methodology proposed is Life Cycle Assessment (LCA), a tool used for comparative assessment of different technologies (Bjørn et al., 2018).

Rather than relying on a reactive, qualitative approach, where new technology must first be adopted by the industry, which in turn requests said technology included in the curriculum, we propose a data-driven method governed by the urgent need for a sustainable transition of the industry to determine if a technology should be included in the bachelor's program.

Energy efficiency improvements have been identified as one of the lowest cost mitigation pathways to limit global warming due to anthropogenic greenhouse gas emissions (GHG) (IPCC, 2022). For ship designs, continual improvements to energy consumption are stipulated by the International Maritime Organization (IMO) via the Energy Efficiency Design Index guidelines (MEPC, 2011). In cruise ships, most of the energy is used for propulsion and HVAC purposes (Barone et al., 2020). In both areas, energy consumption may be optimized via new and more efficient technology, or by behavioral changes, e.g., changed comfort settings or better route planning. Adopting more eco-friendly behavior can have substantial impact, but requires backing in policy for efficient implementation, as exemplified by the banning of CFCs (Haas, 1992) (Skinner, 1987).

While regulatory changes to the operation of cruise ships could potentially change environmental impacts from said ships, this paper focuses on the difference in impact from two different technologies to provide the same service on the basis that novel alternatives to established technologies should provide superior environmental performance to be included in the curriculum.

Thus, in this paper an LCA comparing two technologies for the provision of cooling for HVAC and evaluate their environmental performance is presented. Specifically, a conventional compressor driven chiller to an absorption chiller.

Absorption chillers, or heat pumps, utilize waste heat from main and auxiliary engines to produce cooling. While the absorption cooling process was invented in 1858, few such plants presently exist onboard ships due to various technical matters (Hafner et al., 2019). Recent innovations, however, are likely to increase the applicability in the coming years (Lundsgaard, 2016). From an environmental and sustainability viewpoint, absorption chillers offer lower electricity consumption and do not contain ozone depleting refrigerants with high global warming potential, but the plants are larger and heavier and thus consume more materials (total mass) in the construction phase (Nikbakhti et al., 2020).

The present study serves two purposes; 1) assessing the potential environmental impact of the compared technological solutions; 2) presenting a novel approach to qualifying subject matter included in an educational program. As such, the LCA carried out in this study serves as a pilot study to illustrate the validity and relevance of the methodology while offering concrete decision support to determine the best environmentally performing cooling solution in a concrete use case.

2. Materials and Methods

Goal and scope definition

This study compares two technologies for air conditioning onboard cruise ships using a consequential LCA covering cradle (extraction of raw materials) to grave (disposal or recycling of used materials).

By assessing the potential impacts across a range of impact categories, the compared systems may be evaluated against each other on their environmental performance during their life cycle stages. Unless otherwise explicitly mentioned, all inputs and emissions above a 1% threshold (cutaway) are included. Usage scenarios may vary across specific ship technology and sail routes, this is not considered in the present study.

The result of the study may be used to a) determine the environmentally best performing technology b) evaluate the importance of including learning objectives specific to absorption cooling plants. The latter based on a principle, that environmentally superior technologies should be included in the education program. The target audience of the study is professors at maritime and technical universities and maritime engineering professionals as well as other engineering professionals working with processes where both waste heat and cooling demand is present.

The functional unit (FU) towards which all flows are normalized is defined as the provision of 1 MWh of cooling for air conditioning purposes, specifically in the form of chilled water at a temperature of 12-19˚C. The lifetime of either plant is set to 25 years with an average daily cooling production of 5 MWh. The reference flows are thus defined as a) one absorption cooling plant using waste heat from ship engines and b) one traditional compressor cooling plant using R134a as refrigerant. Plant size is set to 300kW cooling capacity in both cases.

Validity of results is evaluated using scenario analysis with two types of fuel: marine diesel oil (MDO) and bio-methanol (MeOH). Emissions to air from burning of MeOH are not included.

Technology process overview

In a traditional cooling plant, an electrically driven compressor increases the pressure in an evaporated refrigerant which is then condensed, thereby releasing thermal energy, and subsequently expanded and evaporated, thereby absorbing thermal energy.

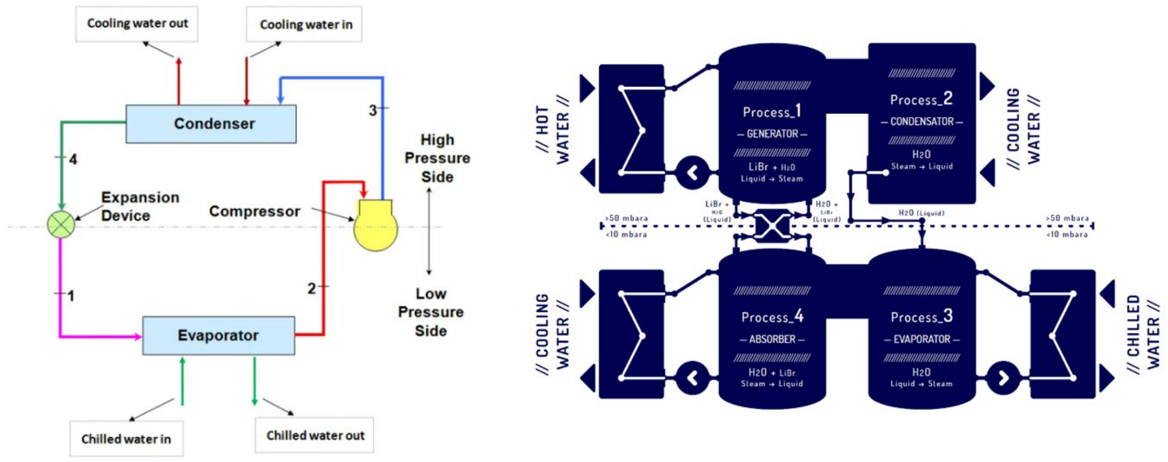

Figure 1 – Conventional compressor driven cooling plant (left) and absorption cooling plant (right)

Conversely, an absorption cooling plant utilizes waste heat, e.g., from engine cooling water, to concentrate and boil a refrigerant, which is then condensed using cooling water. The condensed refrigerant is evaporated, absorbing energy. There is no compressor in the plant, only pumps to transport the refrigerant between the process steps. Various pairs of absorbent and absorbate may be considered in an absorption cooling plant, e.g., H_2O-NH_3 or LiBr-H_2O, however, for industrial use cases where intermediate temperatures are needed, LiBr-H_2O is the preferred fluid pair due to superior performance (Nikbakhti et al., 2020). From an energy balance perspective during operation, the difference between the technologies is the needed electrical energy input and the utilization of waste heat. Figure 1 illustrates the two principles.

Inventory analysis and modelling

Table 1 lists main material and energy flows used in the modelling. A maintenance factor of 5% is included in all material input. Material recovery from recycling at EOL is set to 90%. Emissions related to transport and installation of plants are not included in the modelling. For the reference plant, no loss of refrigerant during the use stage is considered, apart from the maintenance factor.

Table 1 – Inventory of materials and energy for the compared systems

Material / energy input	Reference Plant	Absorption Plant
Steel, low alloyed [kg/FU]*	13,81e-3	20,38e-3
Steel, stainless [kg/FU]	n/a	123,3e-3
Copper [kg/FU]	15,19e-3	0,489e-3
Plastics [kg/FU]	690,4e-6	25,32e-3
LiBr [kg/FU]	n/a	18,41e-3
R134a [kg/FU]	2,133e-3	n/a
Electricity consumption during operation [MWh/FU]	0,2[1]	0,04[2]
Electric efficiency of generating set[3]	40%	40%

*FU is defined as 1MWh of cooling as per goal and scope definition

[1] An electrical COP of 5 is estimated for the reference plant

[2] A conservative estimate of electrical COP is set to 25 for the absorption plant

[3] As very limited research is available relating to MeOH as fuel, the same electrical efficiency is assumed for the generating set for both diesel and MeOH.

The consequential approach chosen for this study requires the identification of marginal suppliers to avoid burden shifting, which occurs when alternative fates or uses of materials or energies are not considered (Finnveden et al., 2009).

For the absorption cooling plant, primary data have been used to determine material composition and masses as well as energy flows during operation (Hansen, 2023). Reference plant data and background data used in the study stem from the consequential Life Cycle Inventory (LCI) database ecoinvent 3.8 (Wernet et al., 2016). As a consequential database it includes secondary services in individual processes. Modelling is carried out in SimaPro v.9.5.

In the scenario with MeOH as alternative fuel, a motor/generator set is used for electricity production. Bio-MeOH is considered, meaning that GWP for combustion is set to 0kg CO2eqv/kg.

The Life Cycle Impact Assessment (LCIA) method chosen is ReCiPe 2016, including 18 midpoint impact categories (Huijbregts et al., 2016). Results presented in this study do not include category endpoints or weighting of scores. Results are internally normalized by comparing impacts from the absorption chiller to the reference system.

3. Results and discussion

LCIA results are presented in Table 2. Environmental impact is shown for reference plant using MDO as source of energy for electricity production, with percentages in remaining columns stating impacts relative to this. In nine impact categories, use of MeOH as fuel results in considerably higher impacts (a factor two in freshwater and marine ecotoxicity to a factor 25 in marine eutrophication and water consumption and a factor 36 in land usage). Though not a focus point of the present study, these findings point to the general challenge when replacing fossil fuels with bio-fuels, that although the GWP of bio-fuels may be lower, there may be considerable environmental downsides in other impact areas if performing a 1:1 replacement (Osman et al., 2021).

Table 2 - LCIA results

Impact Category	Unit	MDO			MeOH	
		Ref. Plant		**Abs. Plant**	**Ref. Plant**	**Abs. Plant**
Global warming	kg CO2 eq	157,5	100%	20%	37%	8%
Stratospheric ozone depletion	kg CFC11 eq	2e-04	100%	20%	3%	1%
Ionizing radiation	kBq Co-60 eq	1,194	100%	21%	-361%	-71%
Ozone formation, Human health	kg NOx eq	2,608	100%	20%	3%	1%
Fine particulate matter formation	kg PM2.5 eq	0,669	100%	20%	45%	9%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,632	100%	20%	3%	1%
Terrestrial acidification	kg SO2 eq	1,159	100%	20%	27%	6%
Freshwater eutrophication	kg P eq	0,022	100%	23%	475%	99%
Marine eutrophication	kg N eq	2e-04	100%	41%	2.648%	550%
Terrestrial ecotoxicity	kg 1,4-DCB	310,7	100%	20%	53%	11%
Freshwater ecotoxicity	kg 1,4-DCB	2,33	100%	16%	212%	38%
Marine ecotoxicity	kg 1,4-DCB	3,053	100%	17%	213%	40%
Human carcinogenic toxicity	kg 1,4-DCB	0,297	100%	101%	1.639%	409%
Human non-carcinogenic toxicity	kg 1,4-DCB	21,82	100%	29%	711%	151%
Land use	m2a crop eq	2,332	100%	22%	3.656%	733%
Mineral resource scarcity	kg Cu eq	0,065	100%	79%	175%	94%
Fossil resource scarcity	kg oil eq	49,53	100%	20%	26%	6%
Water consumption	m3	0,072	100%	28%	2.426%	493%

The negative impacts calculated for ionizing radiation where MeOH is used as fuel should be disregarded, as the direct emissions from burning MeOH are set to nil in the modelling. A graphical representation of the internally normalized results is shown in Figure 3. The reference plant has higher scores in all but one impact category. Human carcinogenic toxicity is impacted by the chromium used in the large quantity of stainless steel for the absorption plant. Assuming a higher recycling efficiency for stainless steel would negate this impact.

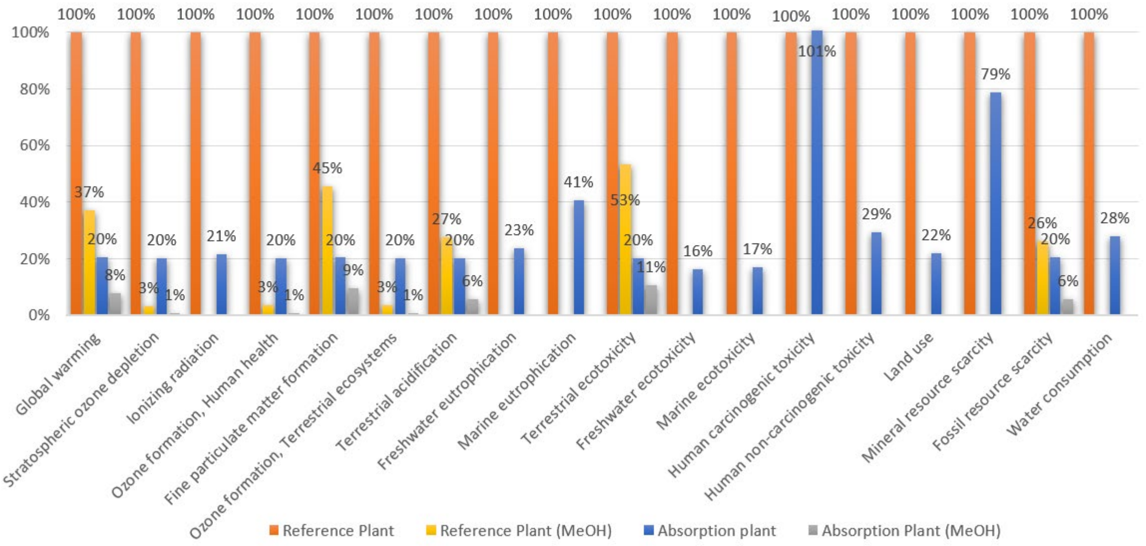

Figure 2 – Internally normalized LCIA results (impacts from reference plant is set to 100%) – the nine impact categories where MeOH performs worse than MDO are excluded from the graph to improve readability

With impact categories affected very differently when using MeOH as alternative fuel, the absorption plant has superior environmental performance with both types of fuel as illustrated in Figure 2 and Table 2.

Cooling is an energy intensive application, with Figure 3 illustrating that the energy consumption from the use stage is dominating across most impact categories. An increase of the conservatively estimated electrical COP of 25 for the absorption plant would be reflected in further improved environmental performance compared to the conventional plant.

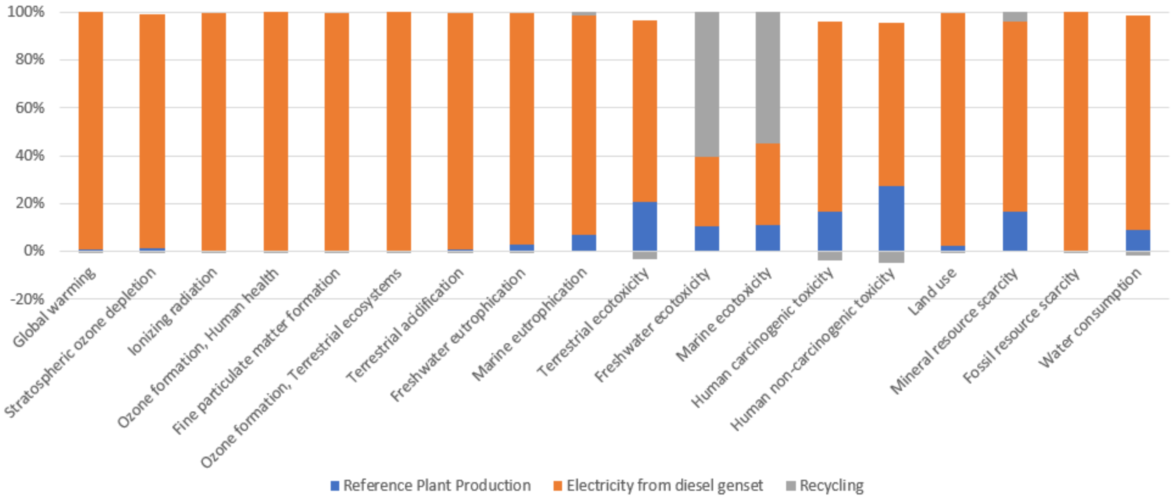

Figure 3 - Impact distribution for reference plant

While no LCA research on specific to the use case of cooling for HVAC onboard hotel ships have been identified during the literature review, other LCA studies comparing absorption plants to conventional cooling have found similar results (Nitkiewicz & Sekret, 2014).

Conclusions and further research

On the premise that technologies with superior environmental performance should be included in the curriculum, the results presented in this study clearly indicate that absorption chillers using LiBr should be included. It is also clear that the electricity consumption during the use stage of cooling plants have the largest environmental impact, indicating that improvements to COP or lowered cooling requirements would have significant effect. The consequential LCA methodology is well suited for decision support, and while time-consuming to conduct, provides a quantitative alternative or supplement to industry interviews. While the use of LCI databases facilitate the creation of LCA's, some experience and prerequisite knowledge is required in constructing the necessary inventory, assessing data quality, and performing the impact assessment and assessment of results. As such, we see a future application of the methodology would entail having a one or more expert LCA practitioners at the professional colleges to facilitate the studies.

In this study, an internal combustion engine is considered for electricity production from bio-MeOH. Further research should be carried out to determine implications of using fuel cells as an alternative. Other pathways for MeOH production or other non-fossil fuels, should be investigated as well.

References

[1] Barone, G., Buonomano, A., Forzano, C., Palombo, A., & Vicidomini, M. (2020). Sustainable energy design of cruise ships through dynamic simulations: Multi-objective optimization for waste heat recovery. *Energy Conversion and Management*, *221*, 113166. https://doi.org/https://doi.org/10.1016/j.enconman.2020.113166

[2] Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. Z. (2018). LCA History. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 17-30). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_3

[3] Cassard, A., & Hamel, J. (2018). Exponential Growth of Technology and the Impact on Economic Jobs and Teachings: Change by Assimilation. *Journal of Applied Business & Economics*, *20*(2).

[4] Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of environmental management*, *91*(1), 1-21.

[5] Hafner, I., Gabrielii, C., & Norne Widell, K. (2019). *Refrigeration units in marine vessels*. https://doi.org/10.6027/TN2019-527

[6] Hansen, D. B. (2023). Mail correspondance regarding primary data for absorption plants. In M. Rønn, J. Kolind (Ed.).

[7] Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Hollander, A., Zijp, M., & van Zelm, R. (2016). ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report I: characterization.

[8] Haas, P. M. (1992). Banning chlorofluorocarbons: epistemic community efforts to protect stratospheric ozone. *International Organization*, *46*(1), 187-224. https://doi.org/10.1017/S002081830000148X

[9] IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

[11] Lundsgaard, H. N. S. H., Daniel Buhl; Viese, Mark Hollaender; Jensen, Christian Fonnesbaek (2016). *Absorption refrigeration and air conditioning devices* https://worldwide.espacenet.com/patent/search?q=pn%3DWO2017129464A2

[11] MEPC, R. (2011). Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution From Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto. *Amendments to MARPOL Annex VI. MEPC*, *70*, 18.

[12] Nikbakhti, R., Wang, X., Hussein, A. K., & Iranmanesh, A. (2020). Absorption cooling systems – Review of various techniques for energy performance enhancement. *Alexandria Engineering Journal*, *59*(2), 707-738. https://doi.org/https://doi.org/10.1016/j.aej.2020.01.036

[13] Nitkiewicz, A., & Sekret, R. (2014). Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. *Energy Conversion and Management*, *87*, 647-652. https://doi.org/https://doi.org/10.1016/j.enconman.2014.07.032

[14] Osman, A. I., Mehta, N., Elgarahy, A. M., Al-Hinai, A., Al-Muhtaseb, A. a. H., & Rooney, D. W. (2021). Conversion of biomass to biofuels and life cycle assessment: a review. *Environmental Chemistry Letters*, *19*(6), 4075-4118. https://doi.org/10.1007/s10311-021-01273-0

[15] Skinner, B. (1987). Why we are not acting to save the world. *Upon further reflection*, 1-14.

[16] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*, 1218-1230.