Innovative, non-nuclear Power Plant Concepts for modern Submarines with very low Indiscretion Ratio

a review of a number of design studies

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Synopsis

Disruptive technologies exponentially increase the number of conceptual designs to be considered for non-nuclear power plants on board submarines. Not only are there more options nowadays, like Li-ion battery technology, fuel cell technology and permanent magnet electric machines; furthermore, one must realise that the power / energy rating of these different power plant components may vary almost continuously, and significantly, during concept design. For long-range expeditionary submarines for instance, given the constraint of a non-nuclear submarine, it is interesting to combine these new disruptive technologies in an optimally balanced power plant that utilizes diesel engine-generator sets as range extender at or near the surface, fuel cells as submerged range extender and a battery as an energy storage and peak load shaver required for e.g. submerged sprints; a “trihybrid” system concept for submarines.

The optimal power split between these components will greatly depend on the operational requirements of a navy, such as required range and (submerged) mission profiles. Should a limited range be acceptable for instance, then an all-battery power plant concept may be considered for which the power rating of the diesel-generator sets or fuel cells on board of the submarine is zero. The impact of these very different power plant concepts on the overall submarine design is significant. Selecting the right components of the power plant at an early design stage is therefore key to a successful submarine design.

In recent years, Nevesbu and TU Delft have developed, through a number of MSc graduation studies (of 9 months), mean-value first-principle tools that determine the mass, volume, power rating and energy rating of different optimally balanced submarine power plants based on parameterized mission profiles (and vice versa). Together, these design studies provide an interesting non-nuclear submarine concept exploration effort that demonstrates the impact of integrating disruptive technologies on overall submarine design. Combined, the studies provide an excellent opportunity to reflect on the design methods used and the importance of the starting point of a design study. This paper presents and discusses the results of the different design studies that were performed, i.e. the above-described submarine power plant concepts and their impact on overall submarine design, and concludes which power plants concepts are best suited for different design requirements.

1 Introduction

Diesel-electric submarines, a.k.a. conventional submarines, have a non-nuclear power plant that consists of two or more Diesel engine–Generator sets (DG-sets) and a large battery system. When the submarine sails at or near the surface, the DG-sets are operating and supply electric power to the submarine’s on-board energy users (i.e. propulsion system, auxiliary systems and mission equipment) and to the battery for charging. When the submarine submerges, the DG-sets are turned off and the submarine draws power from the battery system.

Propulsion power is the mechanical power required by the propeller to sail at a specific speed at any moment in time, submerged or surfaced. This mechanical power is nowadays typically delivered by one or two electric motors. Before WWII, submarines were sailing more often at the water surface than submerged during their missions and then it was still customary to have a diesel engine connected to the propeller mechanically as well. When surfaced, the diesel engine, or rather internal combustion engine (as petrol or kerosene was sometimes also used as submarine fuel), would drive both the propeller and the electric machine, which would then operate in generator mode and charge the lead-acid batteries. When submerged the Internal Combustion Engine (ICE) would be clutched out and the electric machine would drive the propeller, drawing power from the charged lead-acid batteries. This traditional power plant configuration for diesel-electric submarines is now well known and widely applied, according to Wikipedia, as a ‘parallel-hybrid powertrain’ (Figure 1) in Hybrid Electric Vehicles (HEVs).

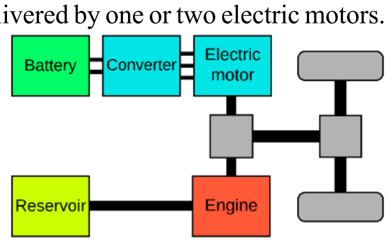

Figure 1: Powertrain of a parallel-hybrid vehicle (Wikimedia, 2020)

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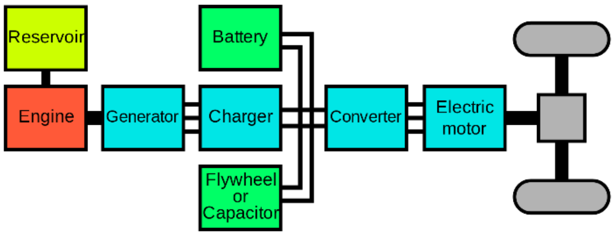

Figure 2: Powertrain of a series-hybrid vehicle (Oyster, 2020)

The typical diesel-electric power plant that is used on-board conventional submarines nowadays is known as a 'series-hybrid powertrain' (Figure 2) in HEVs. In series-hybrids there is no mechanical connection between the ICE(s) and the propeller. The propeller is always driven by Electric Motor(s) (EM), which draw power from the batteries when submerged and from the DG-sets when surfaced (or snorting). The type of fuel (reservoir in Figure 1 and Figure 2) is typically a MGO; F76 for NATO-countries. High-speed marine diesel engines are applied as ICE to drive an electric generator and the applied type of batteries is typically lead-acid. The EM(s) that drive the propeller are typically Direct Current-motors (DC).

The configuration described above is applied on board of many present-day, non-nuclear submarines indeed and is therefore considered a conventional diesel-electric submarine power plant in this paper. But other options for the power plant components exist of course. And especially nowadays these options have become more interesting with recent advances in alternative drivetrain technology. These options for powering non-nuclear submarines have been investigated in an on-going collaboration between Nevesbu and Delft University of Technology in the last couple of years. Students of the latter, in the graduation phase of their studies, have developed mean-value first-principle models of multiple submarine power plant components which are combined in different ways to realise time-domain models of different innovative submarine power plant concepts. Different approaches have been used during these studies, to determine the feasibility of innovative submarine concept designs on the one hand and to create designer support tools that help select an optimal power plant configuration based on a given mission profile on the other hand. This paper provides an overview of the developed (and/or updated) models and their results. The goal of this paper is therefore to present a number of innovative, non-nuclear power plant concepts for modern submarines and their impact on the overall submarine design.

2 Overview of investigated power plants

The following table shows the different options that have been investigated.

Table 1: Submarine power plant concepts and components discussed in this paper. Batt = Battery, ADPS = Air-Dependent Power System, AIPS = Air-Independent Power System, MGO = Marine Gas Oil, H2 = hydrogen, DG-set = Diesel engine – Generator set, PEMFC = Proton Exchange Membrane Fuel Cell, Li-ion = Lithium-ion, DC-compound = Direct Current compound electric motor, PMSM = Permanent Magnet Synchronous Machine.

Type of power plant component	Type of submarine power plant			
	Conventional (Batt + ADPS)	**Battery-electric (Batt)**	**Hybrid1 (Batt + AIPS)**	**Hybrid2 (Batt + AIPS + ADPS)**
Fuel (primary energy carrier)	MGO (F76)	-	H2	MGO & H2
E-power generation from fuel	DG-set	-	PEMFC	DG-set & PEMFC
Battery	lead-acid / Li-ion	Li-ion	Li-ion	lead-acid / Li-ion
Main Electric Motor (MEM)	DC-compound / PMSM	DC-compound	Permanent Magnet (PMSM)	DC-compound / PMSM

Many different types of components can be considered for different functions and the present study is not exhaustive. Stirling engines have also been applied as Air Dependent or Air Independent Power Systems (ADPS / AIPS). The same goes for closed-cycle diesel engines to make an ADPS an AIPS. All such technologies are not considered here. Rather a selection of power plant components has been made based on (subjective) reasons like technology maturity, (expected) availability, (expected) affordability based on commercial developments, etc. This leads to a number of innovative, non-nuclear power plant concepts for modern submarines that can best be distinguished by whether an ADPS and/or AIPS has been applied. For the Air Dependent Power System (ADPS), if present, conventional technology is applied; see the fifth column of Table 1. For the Air Independent Power System (AIPS) a Proton Exchange Membrane Fuel Cell (PEMFC) that uses hydrogen as a fuel is used; see the fourth column of Table 1. In all innovative power plant concepts Lithium-ion batteries are applied, as this battery technology is considered to be now sufficiently mature and far superior in terms of energy density over lead-acid battery technology (which will also be shown). This leads to the Energy Flow Diagram of Figure 3, which represents all innovative power plant concepts considered. The difference is whether the ADPS and AIPS are included in the concept and which type of batteries and electric machines are applied. Note that the ADPS may contain multiple DG-sets and the AIPS may contain multiple PEMFC modules.

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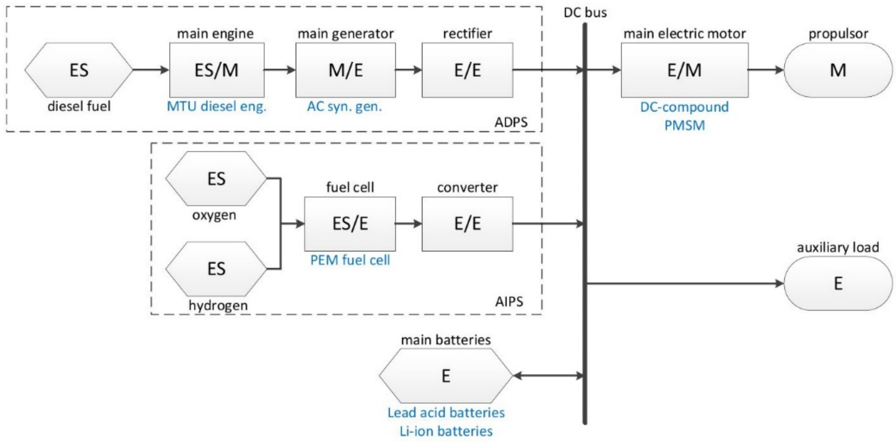

Figure 3: Energy Flow Diagram as representation of the three innovative power plant concepts considered in this paper; figure adopted from (ten Hacken, 2017). ES = Energy Source, M = Mechanical Power, E = Electrical Power.

3 Power plant model

3.1 Modelling approach

The marine engineering section of Delft University of Technology identified the "Mean-Value First-Principle" modelling approach a long time ago as an approach that fits well with the nature of the work of a ship designer with a focus towards the operation of systems on board of ships; see a.o. (Grimmelius & Stapersma, Analysis of the Impact of Control Strategy on Internal Component Loading for a Ship Propulsion Plant, 2003) and (Shi, Grimmelius, & Stapersma, 2010). The Mean-Value First-Principle modelling approach is also applicable for researchers in this area of expertise as such researchers are typically interested in a systems-level approach rather than in-depth component performance analysis (depending on who one might ask).

The MVFP approach is akin to what is more commonly known as a lumped system analysis or lumped-parameters approach. Generally speaking, the approach neglects location-dependency of physical variables and only tries to capture the time-dependency of relevant physical variables as well as possible. Take as an example the pressure and temperature distribution in an internal combustion engine cylinder. Especially during combustion it is quite clear that both pressure and temperature are variable within the enclosed cylinder volume with high temperatures and pressures occurring in flame fronts and relatively lower temperatures and pressures in the "corners" of the enclosed cylinder volume. However, in a lumped-parameters approach this location-dependency of pressure and temperature is neglected and one is only interested in how average pressure and temperature change over time. Depending on the type of (research) question, this approach may be acceptable and in fact preferred if e.g. a faster-than-real-time model in being strived for.

Especially in early stages of design such "simple" models are highly favoured as many details of the final product are still unknown. But even when the submarine has been built, such MVFP models can proof valuable as they can be used to quickly simulate different submarine operations, test different control strategies, etc. Thus, many marine engineering graduates and researchers from Delft University of Technology are familiar with this modelling approach and have applied it in many projects; see e.g. (Vrijdag, Boonen, & Lehne, 2018), (Grimmelius & de Vos, 2011), (Geertsma, Negenborn, Visser, Loonstijn, & Hopman, 2017) and (Stapersma, Grimmelius, Hopman, & Shi, 2008). There is always a discussion on whether the scope and level-of-detail of the applied Mean-Value First-Principle time-domain model is suitable for the (type of) question that one tries to answer with such a model. This discussion is valuable on its own accord as it offers insight into the scope, fidelity and accuracy of the developed and/or applied (component) model(s).

3.2 MVFP models of submarine power plants

An already existing Mean-Value First-Principle system-level model of a conventional submarine power plant, built in the Simulink® environment, was the starting point of the studies described in this paper. In qualitative terms this model could be described as relatively detailed for a lumped-parameters approach time-domain model; the fidelity of the initial model is therefore considered to be high. Although high fidelity does not necessarily mean that a model is highly accurate as well, the initial model is also considered to be relatively accurate with respect to dimension prediction (mass, volume, length, width, height of system components) and with respect to calculating efficiency of components and the overall system. The initial model is capable of simulating all relevant stages of a conventional submarine mission: sailing at the surface, snorting and submerged operations; it is however restricted to conventional power plants only and parameters of the model were outdated.

The first student therefore focussed on updating the Simulink model and demonstrating its capabilities for conventional submarine power plants based on either lead-acid or Li-ion battery technology (Rietveld, 2017). (ten Hacken, 2017) expanded the model with sub-models for the PEMFC and PMSM and compared eight different power plant concepts using a parameterised mission profile as input. The work flow of the research of (Rietveld, 2017) and (ten Hacken, 2017) and the integrated submarine power plant model development in their studies is schematically shown in Figure 4. A pre-defined time-domain mission profile provides information like maximum speed and therefore power required for propulsion, surveillance speed and endurance, attack speed and endurance and covert transit speed and endurance. The latter also leads to the required Indiscretion Ratio (IR) during covert transit. A discussion on the concept and (mathematical) definition of the IR is provided in the next section, as the typical definition of IR is less applicable to the considered power plant concepts and the here applied design strategy.

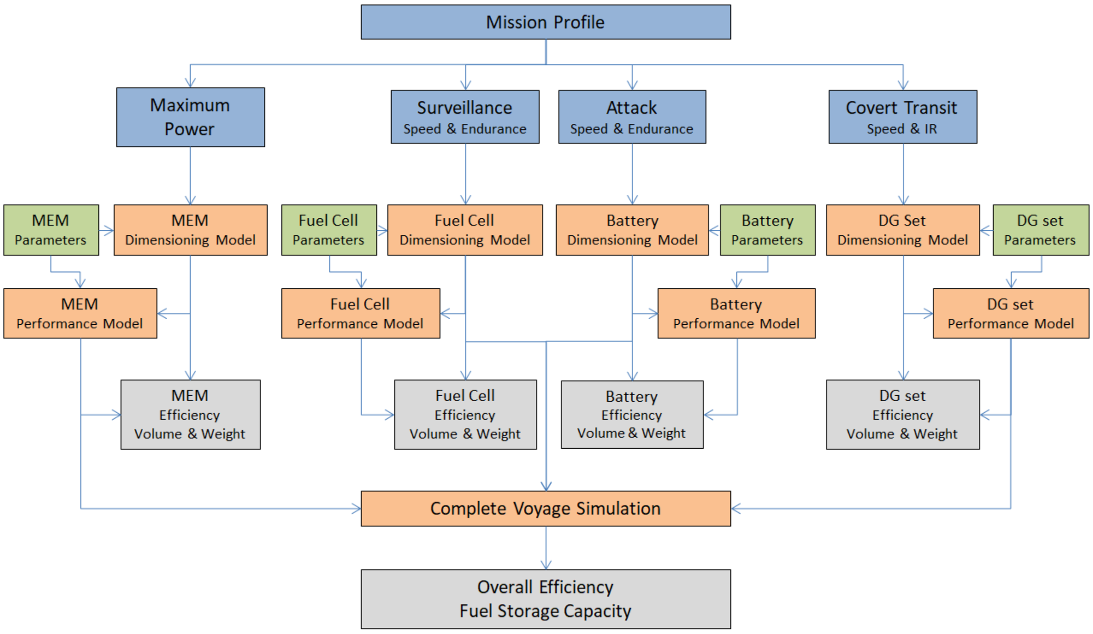

Figure 4: Power plant sizing tool for submarine designer support; figure adopted from (ten Hacken, 2017).

4 Power plant concepts comparison w.r.t. mass, volume and fuel consumption

Combining the studies of (Rietveld, 2017) and (ten Hacken, 2017) the conventional diesel electric power plant can be compared to the same power plant but with an AIPS system added. Furthermore, the impact of different battery types, lead-acid versus Li-ion, can be investigated, as well as the upgrade from a traditional DC propulsion motor, to the innovative Permanent Magnet Synchronous Motor (PMSM). (ten Hacken, 2017) ultimately compared eight different power plant concepts with respect to mass and volume of the different power plant components and total fuel consumption.

The resulting power plant variations are compared on the total required volume and mass to fulfil a predetermined mission. The mission profile that was first defined in (Rietveld, 2017), which is presented in Figure 5, is taken as baseline. This mission profile consists of several phases: the overt transit, the covert transit and the surveillance and attack phases, which occur in the "operational theatre". During the surveillance phase the power will be provided by either battery (in concepts without AIPS) or the AIPS when it does exist in the power plant concept. The latter can in that case be considered as a "submerged range extender". When AIP is present, the batteries provide the required power for the attack phase only and can then be considered as "power booster". The focus in this comparison is on the submerged endurance of the surveillance phase, because this will be the phase of interest for an AIPS. The original mission profile has a surveillance time of 10 hours. This is increased to a duration of three days, one week, two weeks and three weeks in a set of mission profile variations. The sailing speed during the surveillance phase in the presented mission profile is 5 knots, corresponding to 65-kW propulsion power for the benchmark (conventional) submarine. The power required for the hotel load and other auxiliary equipment during surveillance is assumed to be 130 kW (not shown in Figure 5). The mission profile variations for 5 knots surveillance speed are summarized in Table 2.

Table 2 Variations on baseline mission profile

surveillance length	**10 hours**	**3 days**	**1 week**	**2 weeks**	**3 weeks**
surveillance speed 5 knots	I-5	II-5	III-5	IV-5	V-5

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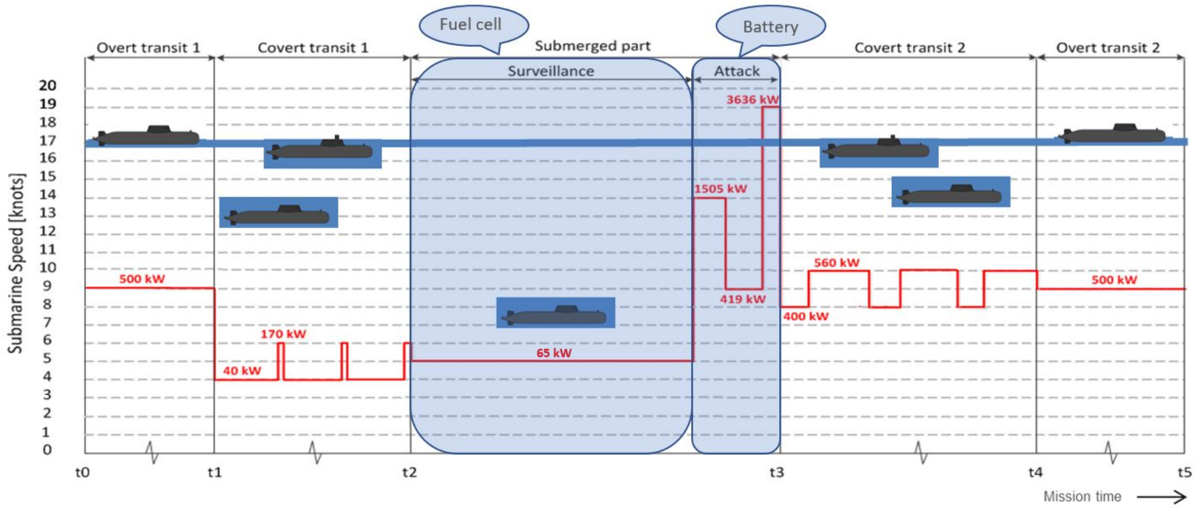

Figure 5: Parameterised mission profile of a submarine; the surveillance part is parameterised with different endurances for surveillance operations; figure adopted from (ten Hacken, 2017) after first appearance in (Rietveld, 2017).

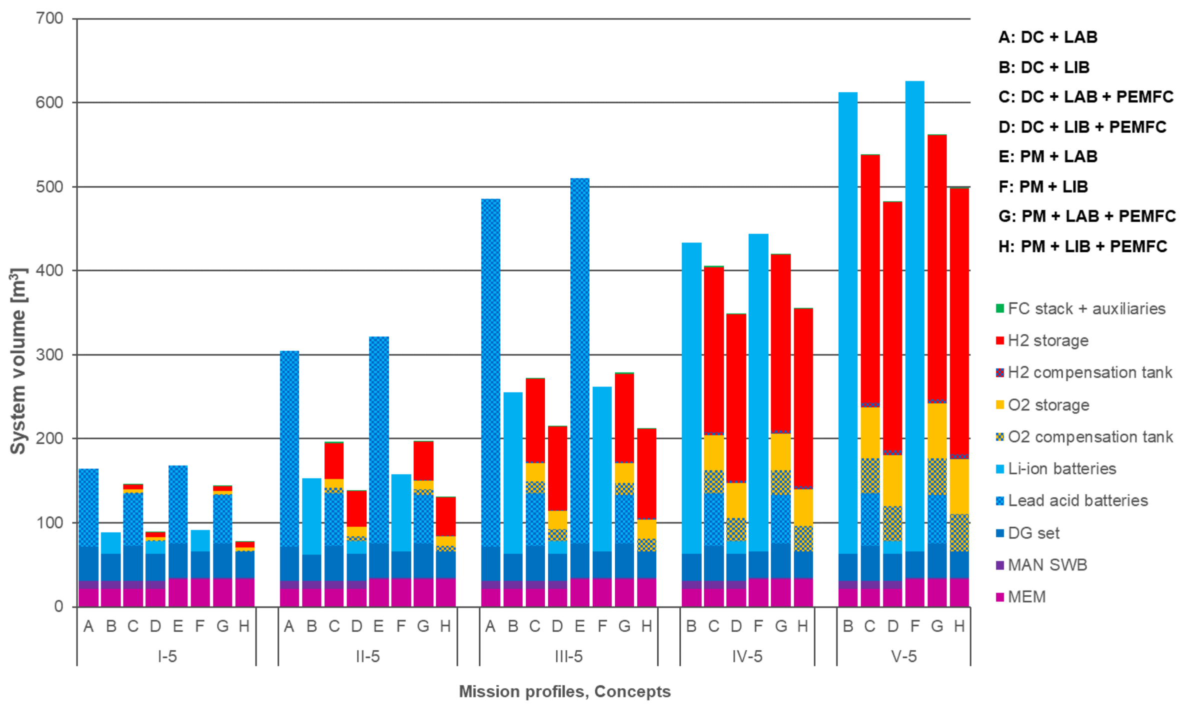

Figure 6: Required volume for eight different power plant concepts per main component including hydrogen and liquid oxygen storage (if applicable) for 5 knots surveillance speed; figure adopted from (ten Hacken, 2017).

The resulting system volume and mass are presented per concept and for each mission profile in Figure 6 and Figure 7. From these results it can be concluded that the change to Li-ion batteries and the addition of the AIPS pays off both in terms of volume and mass. For the original power plant concept (concepts A and E), without AIPS and with lead-acid batteries, the mission profiles with a surveillance time longer than one week are considered infeasible due to extreme volume and weight requirements. These concepts have therefore been omitted for mission profiles IV-5 and V-5 in Figure 6 and Figure 7.

Comparing the concepts with lead-acid batteries (A, C, E and G) with the concepts that apply Li-ion battery technology (B, D, F and H) clearly shows the effect of the increased energy density of Li-ion technology compared to lead-acid. Note that this effect is enhanced by the assumption that lead-acid batteries are charged and discharged between 20% to 80% DoD (Depth of Discharge) and Li-ion batteries between 10% to 90%. The much lower weight and volume requirements of Li-ion batteries will lead to the further investigation of all-electric submarines with

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only Li-ion batteries in the next section; i.e. no DG-sets (ADPS) or Fuel Cells (AIPS) on board (configurations B and F without DG-sets). Configurations D and H (without DG-sets) will also be further investigated in the next section as especially for the longer surveillance times it seems to pay off (in terms of mass and volume) to install an AIPS with Li-ion batteries; compare B and D or F and H. Finally it can be concluded, from comparing Figure 6 with Figure 7, that the hydrogen storage, and to a lesser extent, the liquid oxygen storage, will require much more volume compared to the other power plant components, especially for submarines with extremely long surveillance periods; i.e. mission profiles IV and V. This will cause submarine designs to be even more volume-driven (rather than weight-driven) than they already are. The latter also means that mission profiles IV and V may not be feasible as even the "smallest" concepts are much larger than the original power plant (concept A with mission I-5). A (number of) iteration(s) is required with respect to propulsion power requirement of larger submarines that can fit power plants capable of these mission profiles.

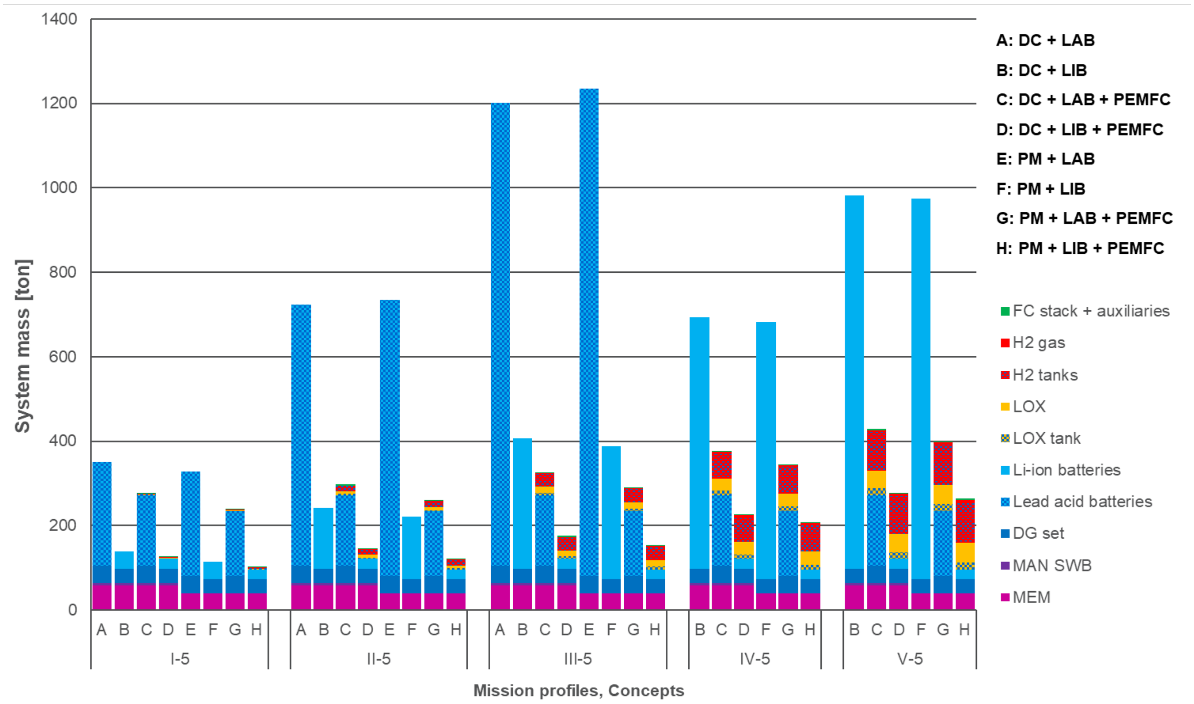

Figure 7: Required mass for eight different power plant concepts per main component including hydrogen and liquid oxygen storage (if applicable) for 5 knots surveillance speed; figure adopted from (ten Hacken, 2017).

Note that the typical mathematical definition of Indiscretion Ratio, which is the ratio of the time required for snorting and the "cycle time", i.e. IR = Δt_snorting / (Δt_snorting + Δt_submerged), cannot be applied to the eight concepts in Figure 6 and Figure 7. Or at least, not to the operations in the operational theatre, as the IR in these phases of the mission profile is for all concepts zero (snorting is not required/permitted during the surveillance and attack phases). This is a result of the applied design strategy in which the battery is sized to provide the energy required for both the surveillance and attack phases in the battery-only concepts and the attack phase only for the concepts with AIPS. In the latter concepts, the PEMFC together with the hydrogen and oxygen storages are sized to provide the energy for the surveillance phase. All concepts do still have DG-sets (ADPS) on board, but these are only required for overt and covert transit. Consequently, Indiscretion Ratio is only non-zero (and not equal to one) for the covert transit phase. This is why Figure 4 showed IR as an input to the model following from the Covert Transit phase definition in the pre-defined mission profile. In the model this leads to the size of the DG-sets. But at this point one may wonder whether DG-sets are still required, given the significant increase in submarine performance with Li-ion batteries and AIPS. This is the topic of the next section.

5 Submarines without Air-Dependent Power Systems

The results described in the previous section provide insight in the volume and weight requirements of different power plant components and their dependency on mission requirements. The promising results of both the lithium battery and fuel cell provide sufficient potential to look into innovative battery-electric (totally battery-powered) and hybrid-electric (battery- and fuel cell-powered) submarine concepts, i.e. concepts *without* DG-sets, so without Air-Dependent Power Systems. As described above, such concepts have an Indiscretion Ratio of zero (IR = 0) in the operational theatre, which equals the performance of nuclear-powered submarines without the difficulty and associated costs of on-board nuclear power plants. However, it must immediately be stated that battery-electric and hybrid-electric power plants for submarines are only interesting for short-range missions (from home port or

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mother ship), since the range and endurance is limited and high speeds can be attained for short periods only. Furthermore, liquid oxygen is required of course, not only for the AIPS (if present) but also for the crew's fresh air requirements. Still, the "nuclear performance" of such non-nuclear submarines is considered to be sufficiently interesting for further analysis and design, which is the objective of this section.

Removing both the conventional lead-acid batteries and diesel-generator sets (including all support systems and tanks) from a submarine design will significantly impact the submarine arrangement, systems and all design balances (mass, volume, energy, etc.) that are of great importance for feasibility studies into different submarine designs. Therefore, in-depth studies are required to investigate both the technical feasibility (with respect to safety, design balances and system integration) and operational feasibility of battery-electric and hybrid-electric submarines. The goal of the research performed by (Los S. , 2017) and (Venema, 2019) therefore was to determine the technical and operational feasibility of a submarine with respectively an all-electric and a hybrid-electric power plant configuration. These studies have taken the same design approach with an existing, detailed and well documented diesel-electric submarine design as starting point. This submarine, with a conventional diesel-electric propulsion plant, a submerged displacement of 1900 tons and a crew size of 34 crew members, has been redesigned into battery-electric and hybrid-electric submarine concepts. During this re-design process, the submarines submerged displacement, pressure hull diameter and design requirements (e.g. burst speed, payload, environmental conditions, amount of accommodation) are kept constant to enable a fair comparison between the operational capabilities of the three designs. During the re-design process the technical feasibility of the concepts is determined as well as possible in early-stage design. Operational capability studies are performed with the created time-domain models to determine the operational feasibility of the designs.

The battery-electric concept, shown in Figure 8, has a power plant concept consisting of Li-ion batteries and a DC-compound electric motor only (concept B in Figure 6 and Figure 7). Thus, the battery-electric submarine has no self-charging capacity. The batteries are applied in a string-based design, with short-circuit protection on string level, which is a common battery topology for large-scale Li-ion battery packs. The battery cell used as reference for this design is a lithium-ion battery cell of nickel manganese cobalt chemistry (Blomgren, 2017), which has a specific energy and an energy density of 261 Wh/kg and 505 Wh/l. A packing factor of 1.3 for weight and 1.6 for volume are used for the packing of the cells into modules (Los S. , 2017). In total almost 1500 battery strings are applied, providing a combined energy storage capacity of more than 80 MWh.

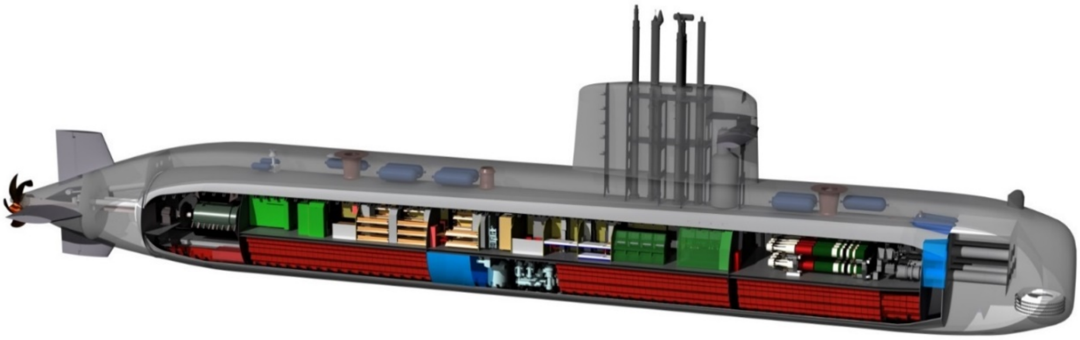

Figure 8: Battery-electric (totally battery powered) submarine concept design; figure adopted from (Los & Schiks, 2018). Li-ion batteries are shown in red in the bottom compartments.

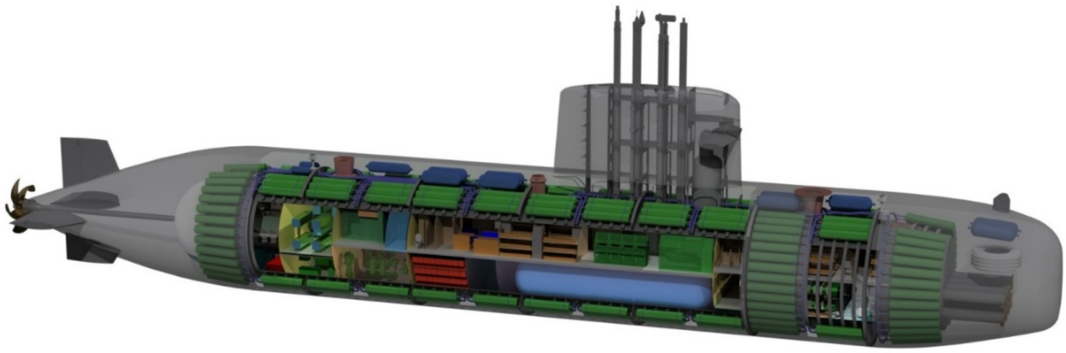

Figure 9: Hybrid-electric (fuel cell and battery powered) submarine concept design; figure adopted from (Los S. , 2019). Hydrogen tanks are shown in green; LOx tank in light-blue and Li-ion batteries in red are shown in bottom compartments.

The hybrid-electric concept, shown in Figure 9, has a power plant consisting of Proton Exchange Membrane Fuel Cells, Li-ion batteries and a DC-compound electric motor (concept D in Figure 6 and Figure 7). In total 800 kW of fuel cell power is installed, which is sized to be able to power the submarine up to its transit speed. In the higher

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speed regions (above transit speed), the battery cells provide the additional required propulsion power. The battery pack is sized to be able to meet the one-hour sprint requirement and consists of the same battery design as the battery-electric concept of Figure 8. After a high-speed burst, the PEMFCs can be used to recharge the batteries while sailing at a low speed.

In the hybrid-electric concept, the choice is made to use hydrogen storage in high pressure (700 bar) carbon reinforced plastic bottles, which is the technology of choice in the automotive industry. The hydrogen bottles are arranged in an outside pressure hull arrangement, which increases the volume efficiency of the design and brings the risk of the hydrogen bottles outside the pressure hull. Almost 400 high pressure hydrogen bottles are installed outside the pressure hull, having a volumetric storage capacity of 35 gram per litre, which results in a combined storage capacity of almost 8 tons of pure hydrogen. All these bottles add displacement to the design, the submarine is shortened to keep the submerged displacement equal and allow a fair comparison with the other designs. For oxygen storage, large LOx tanks are used which is a proven concept in submarines.

After the redesign process of both designs it is concluded that it should be technically feasible to design, build and operate battery-electric and hybrid-electric submarines. Both designs are well balanced, without an excess need of lead ballast. Furthermore, there are sufficient technical solutions found in both literature and industry examples to have confidence in the possibility of safely integrating both fuel cell technology and Li-ion batteries in a submarine design (e.g. Type 212 submarine of German Navy and Sōryū-class submarine of Japanese Navy). At the same time, it must be stated that detailed design solutions of safety systems for both battery and fuel-cell technology was outside the scope of the described research. Estimated space and weight reservations are included in the design to cover the safety systems though.

During the operational capability study, the maximum range and endurance of both concepts are determined and compared with the diesel-electric submarine design. The MVFP models of (Rietveld, 2017) and (ten Hacken, 2017) are used as verification tool for this purpose, based on the power plant design and energy storage capacity of the presented concepts. The submerged range and endurance of both the reference design and concept designs are shown for different speeds in Figure 10. The submerged range and endurance of both concepts is significant compared to the reference design. The battery-electric concept has a maximum submerged range of 1950 nm and submerged endurance of 24 days. The hybrid-electric design has even a higher submerged range and endurance; 2900 nm and 42 days. However, this is at the cost of a more complex design compared to the battery-electric design. In Figure 10, the fuel cell power limit is clearly visible by the drop in range and endurance of the hybrid-electric design.

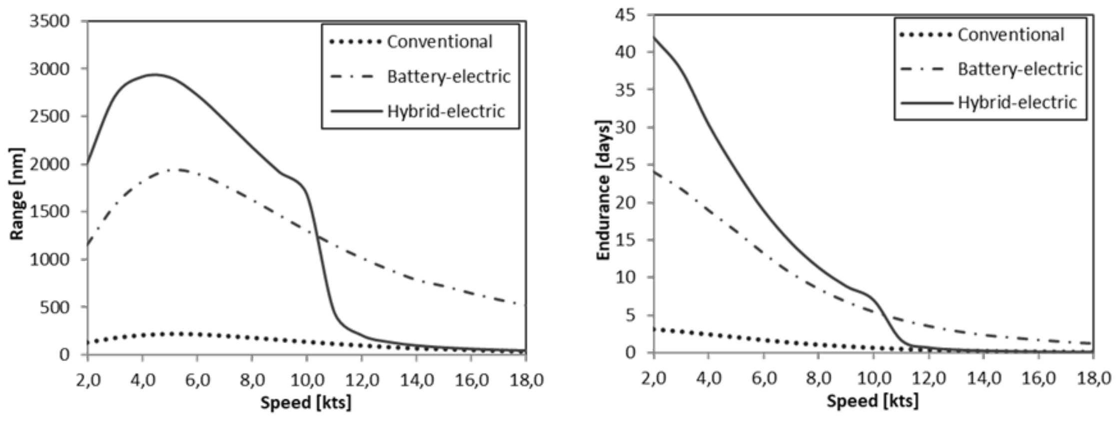

*Figure 10: **Submerged** range and endurance of the diesel-electric reference design, the battery-electric concept and the hybrid-electric concept; figure adopted from (Los S. , 2019).*

Although the submerged range and endurance of the conventional diesel-electric submarine is significantly less, it still has its re-charging capacity of the diesel-generators and the high energy storage capacity of MGO. Therefore, the total range of the conventional diesel-electric submarine is still significantly higher than the all-electric and hybrid-electric concepts. This is shown in Figure 11 and confirms the earlier statement that battery-electric and hybrid-electric concepts are only interesting for short-range missions. The total range of the conventional submarine is still more than four times as high as the hybrid-electric and battery-electric concepts. This does not mean that the two concepts are not feasible from an operational perspective. A range of more than 2000 nm and endurance of more than 24 days is expecting to make local to medium range missions feasible, for which long transits to the mission area are not required. To verify this, again the time-domain models are used as designer support tool for verification. Multiple missions are simulated to verify that sufficient battery capacity and/or

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hydrogen is left after performing a certain mission. An example of such a simulation is given in Figure 12, in which a mission with a duration of two weeks and travelled distance of 1850 nm is simulated for the battery-electric concept. During such a mission, a theoretical round trip around the Baltic sea can be sailed without surfacing once. After this mission, the battery-electric concept still has 5 MWh battery capacity left (within the preferable operational discharge limits of the batteries) which is considered sufficient margin for such a mission. This clearly shows the feasibility of short- to medium-range missions and the potential of such designs for homeland defence missions.

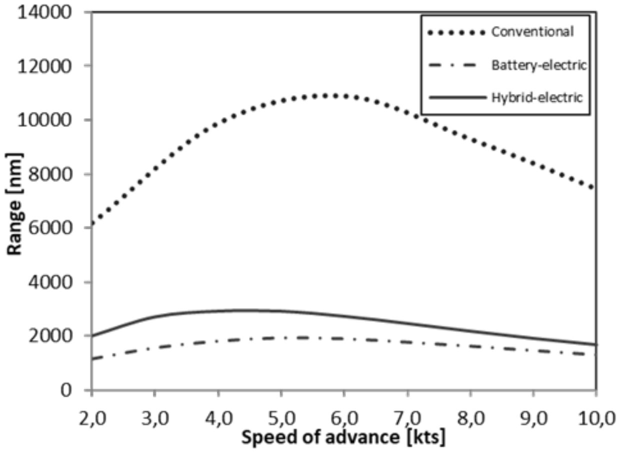

*Figure 11: **Total** range and endurance of the conventional diesel-electric reference design, the battery-electric concept and the hybrid-electric concept; figure adopted from (Los S. , 2019).*

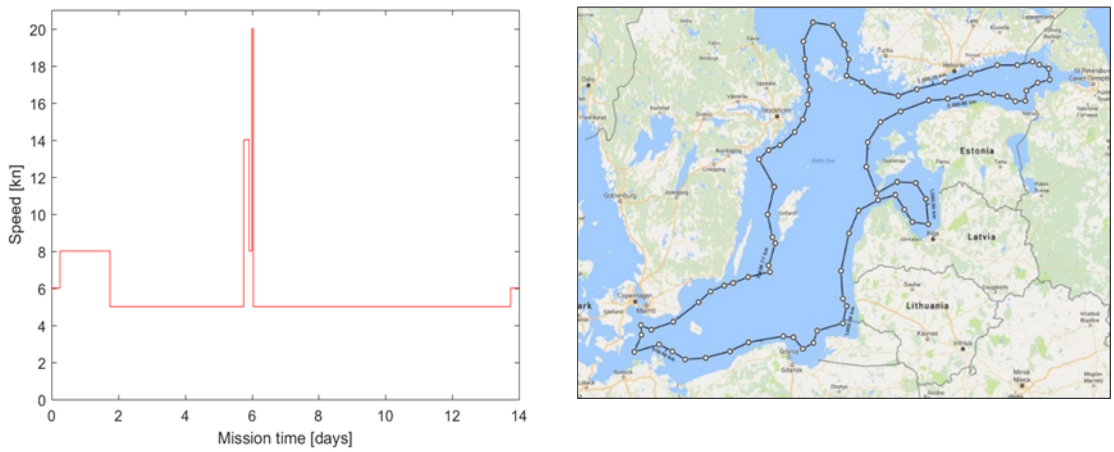

Figure 12: Example of a mission profile of the all-electric concept; figure adopted from (Los S. , 2017).

Both the battery-electric concepts and the hybrid-electric concepts are considered to have several advantages compared to the conventional diesel-electric submarine design. Firstly, a significant reduction in systems can be achieved when omitting diesel-generators from the design, since also all diesel-generator support systems can be omitted (e.g. cooling systems, fuel oil and fuel oil compensation systems, air intake system, exhaust gas system, etc.). The reduction in systems will reduce the design complexity and maintenance requirements and will improve the reliability and availability of the submarines. The underlying assumption is that the solid-state technology of fuel cells and Li-ion batteries will require (significantly) less maintenance than the heavily loaded rotating components of an internal combustion engine in conventional submarines.

Furthermore, the crew will have less systems to operate, monitor and maintain during operation. This may lead to a crew size reduction as well. A performed manning analysis showed that the crew size of the presented concepts can be reduced from 34 to 23 persons, which will have a positive effect on the range and endurance of the presented concepts (Venema, 2019). Taking this positive effect of the crew reduction into account results in a hybrid-electric design capable of achieving a range of 3850 nm. This is an improvement of approx. 30% compared to the operational capabilities of the hybrid-electric design presented in Figure 9 (which, as described earlier, did not take crew size reduction into account). A similar effect is expected for battery-electric submarines.

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One of the biggest advantages of both the battery-electric concept and the hybrid-electric concept is their covertness. Both designs have air independent power plant designs, meaning that they have an indiscretion ratio of zero in the operational theatre. This advantage is visualized in Figure 13, where a round trip of the hybrid-electric concept of (Venema, 2019) is compared to a round trip with the reference conventional submarine design, which has an indiscretion ratio of 13%. Each red block in the voyage is where the reference design needs to sail at snorting depth to charge the batteries. During this period the submarine is vulnerable, since it can be spotted visually and with radars. Furthermore, it experiences a significant increase in noise- and heat signatures.

Figure 13: Example of a fully submerged mission with a hybrid-electric submarine design (maximum range of 3850 nm is attained at a speed of 5.2 knots). Snorting moments of the reference design are indicated in red. Figure adopted from (Venema, 2019).

6 Discussion of results

The results clearly show how range, endurance, size and other important performance aspects of submarines are determined by the different technology options and mission requirements. Additionally, it should be understood that the elimination of the internal combustion engine system in the battery-electric and hybrid-electric configurations raise new challenges for the life support systems on board. Especially the consolidation of healthy air conditions, when no air refresh by snorting takes place, needs further research. Obviously, the choice of power plant concept heavily depends on the type of missions a navy wants to be able to undertake with a submarine. If a submarine is to be used for homeland defence missions only (limited range and endurance) an entirely battery powered submarine may nowadays be a very interesting option, mainly due to the increased energy density of Li-ion batteries in comparison to lead-acid batteries. However, if missions of an expeditionary type are to be undertaken (larger range and endurance) a battery-electric submarine is not feasible and an ADPS and/or AIPS needs to added. The choice between the two or even the combination of the two depends heavily on the required indiscretion ratio and/or the required independence of the submarine; is it acceptable for instance to charge a submarine at sea from a surface vessel that to a certain extent accompanies the submarine? Furthermore, such a submarine support vessel may even be necessary for submarines with AIPS depending on the availability of hydrogen and oxygen at the right conditions. Obviously, all options have their own consequences for the CAPEX and OPEX of a submarine; these considerations were however left outside the scope of the described studies.

7 Reflection on design and research approaches

Where (Rietveld, 2017) and (ten Hacken, 2017) started their studies with a (number of) operational profiles that a submarine needs to be able to sail and from there worked their way towards a power plant design, (Los S. , 2017) and (Venema, 2019) took the opposite direction: design a submarine in order to find the operational capabilities. Note that the first approach did not yet lead to actual submarine concept designs, i.e. with an initial general arrangement, mass and volume balances, trim polygons, etc., and in fact iterations might be needed with respect to the assumed propulsion power for the larger systems. This approach rather gave a deeper understanding of how different power + energy ratings for the different power plant components effect the required mass and volume for

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power plant components. The other approach did lead to submarine concept designs, but were of course limited in the variability of operational capabilities as the size of the submarine was fixed at the start of the study.

A general statement on the suitability of each approach cannot be specified as both approaches are valid and lead to interesting results and 'lessons learned'. Rather, it depends on the type of research question and the requirements on results of the study, which approach should be preferred. In any case, the underlying time-domain models that are used for simulating operations of different power plant concepts have proven to be indispensable in these studies. Obviously, the results are only as good as the quality of the input to the models and the fidelity of the sub-models used. The energy density of Li-ion batteries for instance is higher than that of lead-acid batteries, but how much higher depends very much on the actual battery system design, including its cooling and safety systems to prevent e.g. thermal runaway. Such details are not yet sufficiently addressed in the presented feasibility studies.

8 Conclusions and recommendations

This paper presented and discussed the results of a number of different submarine (power plant) design feasibility studies. Different, innovative submarine power plant concepts were introduced and their impact on overall submarine design was analysed. Disruptive technologies like Li-ion batteries and PEM Fuel Cells were integrated into the power plant and submarine conceptual designs. Mean-Value First-Principle tools were updated and developed; these proved to be indispensable in all feasibility studies. Results with respect to the impact on overall submarine design and operational capabilities for different, innovative power plant concepts were shown in different ways and at different levels of detail. Conclusions were drawn which power plants concepts are best suited for which different design requirements: battery-electric or hybrid PEMFC/battery-electric concepts are typically best suited for short- to medium-range missions while conventional diesel-electric concepts, with or without AIPS for submerged range extension, are typically best suited for long-range, expeditionary submarine missions.

A number of recommendations for future research are identified as well. First of all, the impact of changes in and to auxiliary systems, due to new mission profiles and/or changed power plant configurations, on overall submarine design and operation should be investigated further. Designer support tools are needed for the different auxiliary systems on-board the submarines with innovative power plant concepts to analyse and visualise such impacts. Furthermore, the paper showed conceptual submarine designs for battery-electric and hybrid-electric submarines without Air-Dependent Power Systems. Submarine concept designs for larger, expeditionary submarines with ADPS, still need to be developed. Finally, further verification and validation of the developed Mean-Value First Principle models of power plants and power plant components is needed to assess the fidelity and accuracy of (sub-)models.

9 Bibliography

Blomgren, G. (2017). The development and future of lithium ion batteries. *Journal of The Electrochemical Society, 164(1)*, 5019-5025.

Geertsma, R., Negenborn, R., Visser, K., Loonstijn, M., & Hopman, J. (2017). Pitch control for ships with diesel mechanical and hybrid propulsion. *Applied Energy, 206*, 1609-1631. doi:https://doi.org/10.1016/j.apenergy.2017.09.103

Grimmelius, H., & de Vos, P. (2011). Towards environment-friendly inland shipping - Propulsion systems for inland ships using different fuels and fuel cells. In C. Sys, & T. Vanelslander, *Future challenges for inland navigation* (pp. 134-155). Brussel: UPA.

Grimmelius, H., & Stapersma, D. (2003). Analysis of the Impact of Control Strategy on Internal Component Loading for a Ship Propulsion Plant. *13th ISCSS Symposium Proceedings.* IMarEST.

Los, S. (2017). *Concept design and feasibility study of an entirely battery powered naval submarine.* Master Thesis, Delft University of Technology. Retrieved from http://resolver.tudelft.nl/uuid:e51fa470-8742-4d90-9c41-fb2f8781cf79

Los, S. (2019). Fully Electric (Battery/Fuel Cell) powered Submarine. *Undersea Defence Technology.* Stockholm.

Los, S., & Schiks, W. (2018). Total battery powered submarine design, a new way of thinking. *Undersea Defence Technology.* Glasgow.

Oyster, F. t. (2020). Retrieved May 2020, from Wikipedia: https://commons.wikimedia.org/w/index.php?curid=36225265

Rietveld, L. (2017). *Optimization of a propulsion plant for a submarine based on first principles.* Master Thesis, Delft University of Technology. Retrieved from http://resolver.tudelft.nl/uuid:f449e975-7afa-4c68-aa78-dae02e279da2

Shi, W., Grimmelius, H., & Stapersma, D. (2010). Analysis of Ship Propulsion System Behaviour and the Impact on Fuel Consumption. *International Shipbuilding Progress*(Volume 57), 35-64.

Stapersma, D., Grimmelius, H., Hopman, J., & Shi, W. (2008). Simulation of the influence of ship voyage profiles on exhaust emissions. *International Mechanical Engineering Congress and Exposition (IMECE2008).* Boston: ASME.

ten Hacken, M. (2017). *Optimization of a submarine propulsion system by implementing a PEM fuel cell and a PMSM in a first principle model.* Master Thesis, Delft University of Technology. Retrieved from http://resolver.tudelft.nl/uuid:dc9fc6a8-142a-4d24-b65d-c9aca14e73fb

Venema, M. (2019). *Design of a Fully Electric (Battery/Fuel Cell) Submarine.* Master Thesis, Delft University of Technology. Retrieved from http://resolver.tudelft.nl/uuid:7a6c86f0-37a9-46a4-b75d-253dfe62fe3a

Vrijdag, A., Boonen, E., & Lehne, M. (2018). Effect of uncertainty on techno-economic trade-off studies. *Journal of Marine Engineering and Technology*(18 (2019) (3)), 122-133. doi:https://doi.org/10.1080/20464177.2018.1507430

Wikimedia. (2020). *Wikipedia*. Retrieved May 2020, from https://commons.wikimedia.org/w/index.php?curid=1527624

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Sven Los MSc is a naval architect at Nevesbu B.V. During his graduation research for his Master’s degree in Marine Technology, he performed a concept and feasibility study of totally battery powered submarines. After his graduation in 2017, he worked as a Naval Architect at Nevesbu on several submarine related projects and two amphibious navy vessels.

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