Final report

1. Project details

Project title	BlueDolphin
File no.	64021-2065
Name of the funding scheme	The Energy Technology Development and Demonstration Programme (EUDP)
Project managing company / institution	Blue World Technologies
CVR number (central business register)	39931621
Project partners	Blue World Technologies, Aalborg University and TUCO
Submission date	02 January 2025

2. Summary

Project summary:

The purpose of the project

Currently the dominating commercialized green alternative for the offshore sector is batteries. However, the power consumption of offshore vessels are significant due to the high resistance of the water, from which other alternatives or hybridizations are called for. The BlueDolphin project has enabled a state of the art scalable fuel cell system for this application which was demonstrated onshore.

Results, conclusions and perspective

The project derived multiple results, being:

- A scalable fuel cell system designed for the rough environment which can be obtained offshore
- An innovative water neutrality system enabling only the need for methanol as fuel instead of split fuel or premixed
- Long testing of the BlueDolphin platform onshore with special focus on degradation mechanisms, reliability and durability
- A research and demonstration study investigating the robustness of the fuel cell stack simulating the vibrations observed for offshore vessels
- A comprehensive Life-Cycle-Analysis of the BlueDolphin platform
- Electrification of an offshore vessel

As the HT-PEMFC technology used in this project is nowhere near as commercialized known as the LT-PEMFC, the need for a demonstration unit was strongly needed. The BlueDolphin platform has therefore been used as a showcase unit which has enabled strong commercial partnerships which will be, and currently is, being exploited. The foundation of these new partnerships are based on the tremendous work conducted with respect to the reliability, durability, functionality and maturity of the platform. The key focus of the BlueDolphin platform has always been enabling a system with maturity somehow close to a real product throughout the entire supply chain.

Projektresumé:

Formålet med projektet

På nuværende tidspunkt er batterier den dominerende grønne kommercielle løsning til offshore sektoren. Energiforbruget for offshore fartøjer er dog signifikante pga. den høje friktion til vandet hvorfra andre alternativer eller hybride løsninger er nødvendig. BlueDolphin platformen har muliggjort en onshore demonstration af et brændselscellesystem til denne sektor.

Resultater, konklusioner og perspektiv

Projektet har afledt flere resultater som listet nedenfor

- Et skalerbart brændselscellesystem designet til at modstå de håre omgivelser som opnås til søs
- Et innovativt vand-neutral-system som muliggør behovet kun for metanol som brændstof og ikke både vand og metanol
- Langtids test af BlueDolphin platformen på land med specielt fokus på degraderings mekanismer, pålidelighed og holdbarhed
- Et forsknings- og demonstrationsstudie med fokus på robustheden af brændselscellestakken ved påvirkning af vibrationer som opnås til søs
- En omfattende Livs-Cyklus-Analyse af BlueDolphin platformen
- Elektrificering af et offshore fartøj

Da HT-PEMFC teknologien brugt i dette projekt ikke tilnærmelsesvis er lige så kommercielt kendt som LT-PEMFC, var behovet for en demonstrationsplatform nødvendigt. BlueDolphin platformen har derfor været brugt som en demonstrations enhed hvilke har sikret nye stærke kommercielle samarbejdspartner som vil blive, og allerede bliver, udnyttet. Fundamentet for disse nye samarbejdspartnere er bygget på det enorme arbejde der er lavet med henblik på pålidelighed, holdbarhed, funktionalitet og modenhed af platformen. Nøglemålet med BlueDolphin platformen har altid været at lave et system med en modenhed tæt på et reelt produkt gennem hele forsyningskæden.

3. Project objectives

The objective of the BlueDolphin project was to develop and demonstrate a scalable high-temperature proton-exchange membrane fuel cell (HT-PEMFC) range-extender platform for smaller electric marine vessels such as yachts, workboats, ferries etc. The platform would be powered by liquid renewable methanol and thereby enable indirect electrification of waterborne transport. The solution would eliminate all harmful emissions such as NOx and SOx and reduce CO2 emissions significantly. The proposed solution overcame critical challenges with alternative sustainable solutions (hydrogen fuel cells and battery electric) by offering core value propositions such as long travelling range, superior energy density, high efficiency and cost-competitive fuel economy compared to today's diesel engine alternative. Also, the distribution and refueling of liquid methanol can utilize the existing infrastructure used for fossil fuels and thereby strongly reduces the need for infrastructure investments. The platform was designed to operate in harsh marine environment and the impacts from vibrations, shocks and salt vapors were investigated and strategies for mitigating these were developed and implemented. Furthermore, concepts for smart use of waste heat from the fuel cell were investigated and analyzed to increase the system efficiency above 80%. Waste heat can be used for cabin heating and cooking. The BlueDolphin platform were supposed to be demonstrated on- and offshore with the purpose of validating functionality, performance and identify further optimizations. The project was strongly aligned with national and global strategies for efficient energy use, reduction of harmful- and greenhouse gas emission benefiting the health of aquatic ecosystems and urban air quality. The conceptual idea may be seen in Figure 1.

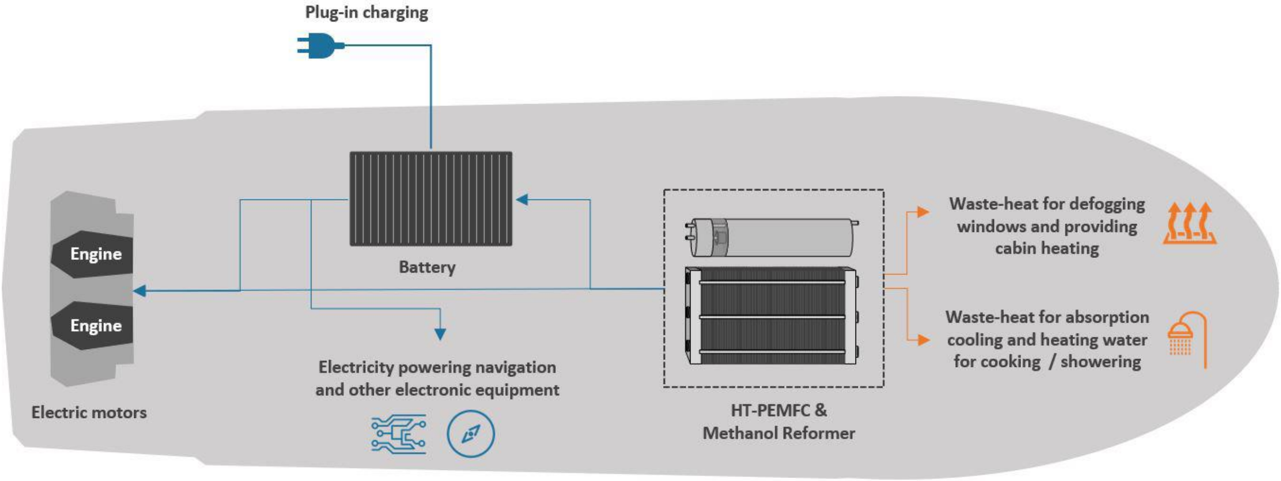


Figure 1 Conceptual idea of the BlueDolphin platform

The key objectives of the project may be seen in Table 1

Parameter	**Value**
Power output	15kW to 45kW
Electric efficiency / CHP efficiency	45% / >80%
Durability	7,500 hours lifetime on system-level
Cycle robustness	3,000 thermal cycles
Reliability	2,500 hours service interval
Sales price at 5,000 units annually*	1000€/kW
Temperature rating	-20degC to +50degC
Modularity	Serial connection of up to 3 platforms

Table 1 Key objectives of the BlueDolphin project
*Excluding battery and fuel tank

4. Project implementation

The BlueDolphin project utilized the maturity of the fuel cell stack and the reformer which is a result of other work caried out through research projects supported by EUDP and Energy Cluster Denmark among others. It was therefore of high importance for the project to immediately start designing the FC platform based on previous knowledge and new knowledge acquired from stakeholders to establish a dissemination plan for end-user demonstrations.

4.1 Project risk and mitigation

Before the start of the project, commercial and technical risks were identified, and preventive actions were planned. These are presented in the following with a reflection of the actions taken and potentially planned for further development.

Failing to meet lifetime targets in a marine environment with increased mechanical stress

Mechanical stress from continuous shock and vibrations were expected to have a negative impact on the lifetime. With this hypothesis, mitigation measures to reduce degradation caused by mechanical stress were introduced to the overall platform design. Concurrently with the design phase of the platform, AAU investigated this hypothesis and discussed specific design strategies to ensure meeting the lifetime targets. These results will be presented later.

These mitigations were done prior to the offshore testing as these tests would function as the definitive tests to determine whether or not the mitigations were successful. However, the consortium failed to conduct the offshore testing, which will be discussed later. However, as a result of this the hypothesis regarding the mitigations are still to be tested.

Increased degradation from accumulation of salt particles (from salt vapor) on the FC cathode

Strategies to mitigate and avoid salt vapors in the cathode intake air were investigated and further implemented. It was known that insufficient filtration of the air intake has a strong impact on the durability and efficiency of the system. Different OEM’s were therefore contacted in the design phase where multiple solutions were proposed. The one which showed the greatest potential was chosen, but once again as the offshore testing never happened, its functionality is still to be tested.

Missing technological alignment with end-user requirements

The consortium focused on a scalable platform to target multiple vessel segments. This, however, also creates the possibility that the solution neglect important requirements from individual segments. An in-depth analysis was conducted with a decision matrix to ensure that trade-offs were not hampering the commercial offering for different segments. Additional add-ons and product features for selected segments were investigated and evaluated.

The analysis included inputs from different potential customers, OEM’s and integrators. The analysis were made and concluded upon, however, the true acceptance of the platform was not disclosed before the platform was built and showcased. Even though the offshore testing and demonstration never occurred, the project also included onshore testing which was used as a demonstration platform. With minor feedback the platform seems to fulfill the requirements of the individual segments.

4.2 Project timeline

First half year period of 2022

Construction of the boat

Relatively soon after the kickoff of the project, the construction of the boat began as this was a significant amount of work. Initially the work consisted of the hull construction and afterwards the electrification of the boat.

Platform concept development

Throughout the first half year of 2022 work package 2 was of focus, being the platform concept development. This included identifying OEM and end-user needs and requirements, definition of product specifications and concept development for platform integration. This was all done according to the plan.

Second half year period 2022

FC system optimization and development

The priority of this period, besides the continuously built of the boat, was to define the functional and mechanical design of the fuel cell platform as this would have great influence on the design of the boat. Concurrently with this work the remaining tasks of work package 3 was initiated, being the system simulation, tests and mitigation of shock and vibrations on HT-PEMFC stack and methanol reformer, BoP component sizing, selection and validation, functional and safety analysis and lastly the benchtop system build and validation.

First half year period of 2023

Milestone 2

All of the tasks defined above from work package 3 culminated in the report of milestone 2. Milestone 2 was a Go / NoGo gate with 4 objectives, being:

- Prove the platform concept was technical complaint with general OEM and end-user requirements. Externally validated.
- Platform concept was complaint with marine operational and safety standards. Internally validated.
- A market entry platform price at <2250€/kW was proven on a BoM level excluding fuel tank and battery. A realistic and feasible roadmap for achieving a platform sales price at 1000€/kW in 2029 was developed.
- The end-game system lifetime must be documented during the benchtop validation testing.

This gate was passed, and the results will be discussed in later sections.

Field test of the boat

By the end of this period the electrification of the boat had been achieved from which offshore test of the boat was conducted.

Optimization of the system layout

Throughout more or less the entire 2023 continuous work was done toward the mathematical optimization of the platform based on the systems P&ID.

Second half year period 2023

Further fuel cell platform build

The gate from milestone 2 allowed the continuation of the BlueDolphin project, where the next step among others was to focus on the onshore- and offshore testing from which more fuel cell platforms were needed.

Integration of the fuel cell platform in the boat

Besides the built described above, the work enabling the integration of the fuel cell platform in the boat started. It was in this period discovered that not all the needed hardware for the integration in the boat was purchased. Work was conducted to solve the problem and by the end of 2024, the missing hardware was disclosed.

First half year period of 2024

Officially the last period of the project

Throughout this period the last tasks associated with work package 4 and 5 was finalized with the exception of the integration of the fuel cell system in the boat and the offshore demonstration. The finalized tasks with respect to work package 4 included the cabinet design and selection of support systems, the benchtop build into cabinet and validation and onshore testing and validation. The finalized task with respect to work package 5 was the life-cycle assessment study.

By the beginning of this period the consortium was made aware that TUCO had an outstanding with their subcontractor who provided the electrification of the boat with respect to the driveline. Due to this outstanding the integration-progression stalled as it was this subcontractor who had to provide the missing hardware. As the time approached the original deadline of the project, the consortium saw the need to apply for an extension of the project by 6 months. This was needed to enable the integration of the BlueDolphin platform into the boat and then further achieve the offshore testing and demonstration. By the end of this period the EUDP granted the consortium an extension of the project by 6 months as it had been verified by TUCO that the outstanding was concluded meaning the hardware could be purchased and the integration could once again continue.

Second half year period 2024

By the end of October a guy from Blue World Technologies traveled to TUCOs facility in Faaborg for the integration of the BlueDolphin platform into the boat. By the second day he was made aware by the before mentioned subcontractor that the outstanding was not resolved, meaning the missing hardware was still not implemented. By the next day the guy from Blue World Technologies travel back home with the BlueDolphin platform and EUDP was made aware of the situation. It was agreed that all parties desired to see the offshore demonstration occur, however, as the resources at this point was close to zero, a realistic approach had to be considered. On the 7th of November the consortium agreed upon the following plan.

Plan A) By the 15th of November the consortium had to have received written confirmation from the subcontractor that the outstanding had been resolved and they would make the installation of the missing hardware in the near future.

The second deadline was on the 29th of November and assumed that plan A failed. This second deadline included two other solutions, being B1 and B2.

Plan B1)

TUCO would find another way around the integration without the missing hardware. The consortium was on standby with support if needed, however, TUCO had the lead.

Plan B2)

TUCO would find another electric boat which could be used for the offshore demonstration. The consortium was on standby with support if needed, however, TUCO had the lead.

By the 5th of December the consortium had secured a solution with a new company who was willing to do the integration and offshore demonstration on one of their boats. Blue World Technologies, acting as project leader on the project, decided however to stop this effort due to the associated risks and the limited resources taken into consideration. As a result of this, the BlueDolphin project ended without any offshore demonstration.

5. Project results

5.1 Design of the fuel cell platform

In order to gain a better understanding of what was requested by the end-users, different relevant companies were contacted. From a lot of conversations the consortium gained a clear insight of what was requested, which turned out to follow a clear pattern. In general, it was desired to have a plug'n 'play solution independent of the power requirement. For minor power applications, such as sailboats, a rectangular-prism-shaped box was desired likewise a common genset. For larger applications, such as motorboats or auxiliary power, space is usually in surplus, from which the desired geometry was less specified compared to the latter application.

Plug'n 'play solution

The plug'n 'play solution should essentially be a closed cabinet with the required connections on its side, which would sever several benefits.

1. It allowed multiple applications, as no individual modifications were required depending on the individual boat.
2. As no individual modifications were required, the cabinet could easily be installed or replaced if needed.
3. The coupling between the cabinet and the boat would be fairly easy as the cabinet would have its connections placed on the side. These connections should be a type of quick connections. The required connections would be the fuel-inlet, cooling inlet/outlet, power cables to the battery and the exhaust.
4. The cabinet should be homologated as a standalone product from which the homologation between the cabinet and the boat should be minor.

“Nice to have” and “Need to have”

As stated in the project proposal, some features were classified as “nice to have” and others as “need to have”. A typical “nice to have” feature was real time monitoring of the system which could be enabled through Wi-Fi or similar. A more relevant “nice to have” feature was the incorporation of the heat generated from the system. The generated heat could be categorized as low- and high temperature heat sources. As the fuel cell technology was based on HT-PEM, it operated around 170degC which enabled high temperature heat. Different power electronics required also liquid cooling, which were however limited to approximately 60C. In many applications this heat was considered waste heat and removed without utilizing it. However, in this applications this heat could be utilized in multiple ways, such as space heating, cooking, showering etc.

One of the “need to have” features has already discussed, which is the quick connections. It was essential that the platform was a plug’n ‘play applications in order to minimize modifications to the boat. Another “need to have” feature was with respect to automation. Independent of the application, the platform would be a hybrid-system with batteries, from which an interface between the battery management system (BMS) and the fuel cell system was required. The BMS monitors and controls the battery in order to ensure its health. It was therefore required that the fuel cell system was able to communicate with the BMS in order to adjust the power output to what would be required.

The cabinet

As the objective of the project was to define a scalable platform, the term “scalable” had to be discussed and defined. A concept discussed was a cabinet with a fixed power output which could be scaled, simply by installing more of these cabinets on the boat, and thereby not changing the geometry of the cabinet. The concept may be seen below in Figure 2.

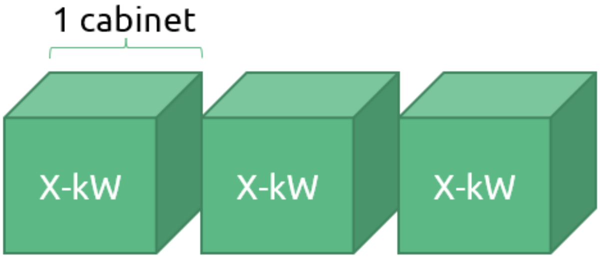


Figure 2 Cabinet with fixed power output

Another concept discussed was a cabinet which geometry would vary depending on the desired output. In this concept, a fuel-cell-box would be designed with a fixed output and fixed geometry, from which more of these boxes could be stacked within the cabinet in order to scale it. This would however require multiple cabinets depending on the desired output as the cabinets height would increase along with the power output. The concept may be seen below in Figure 3.

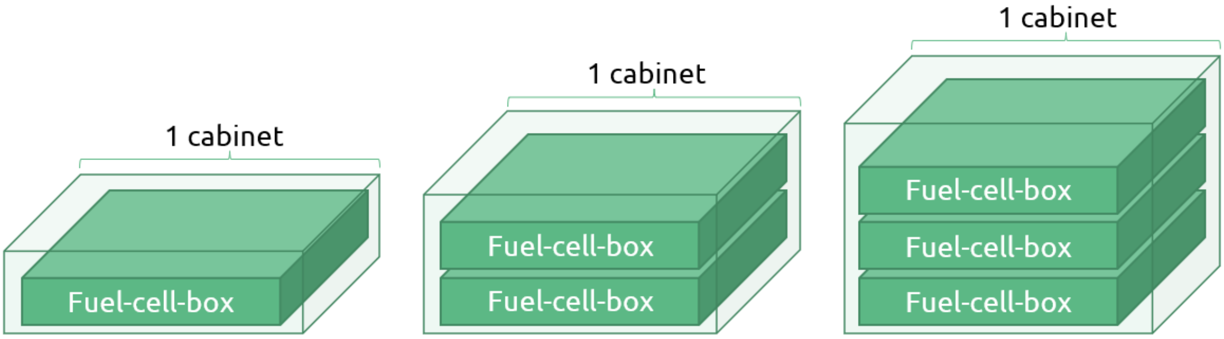


Figure 3 Cabinet with varying power output

Power output

When designing a scalable platform, the power output of each module had to be carefully defined. If it was too large, the smaller power requirements might be overdimensioned, but if it was too small it would require a significant number of modules to meet the largest power requirement. The maturity of the fuel cell and reformer had, however, also to be considered when defining the output.

The end-users had in general shown the greatest interest of the first concept, where they requested a power output of approximately 10-20kW. The median, being 15kW, was chosen as the ideal power output for this design, which was also chosen as the design platform for the BlueDolphin platform.

Conceptual illustration

The concept of the fixed cabinet design was to replace the gensets available on the market. Fischer-Panda is a worldwide acknowledged genset manufacturer which produced marine gensets from 3.5kW up to 12.7kW. The Fischer-Panda 15000x PMS was their largest marine genset producing 12.7kW. A geometric comparison of this model was conducted with a simple design of the BlueDolphin platform. The length, height and width of the Fischer-Panda model was known and thereby also the volume. The BlueDolphin platform had the same volume as this, however, the length, height and width was adjusted due to the length of the reformers. The comparison may be seen in the four pictures below, being Figure 4, Figure 5, Figure 6 and Figure 7, where the empty cabinet represent the Fischer-Panda model and the other cabinet represent the BlueDolphin platform.

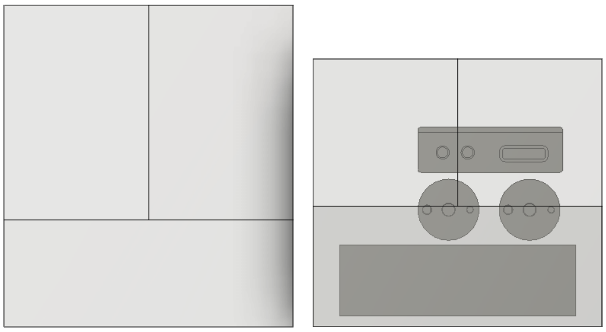


Figure 4 Front view, fixed cabinet concept

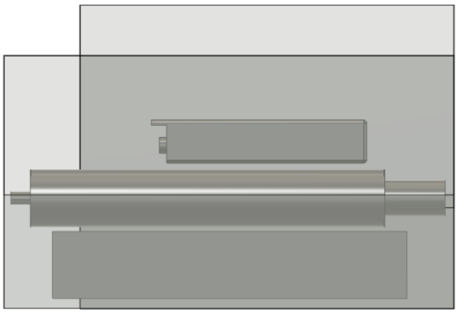


Figure 5 Side view, fixed cabinet concept

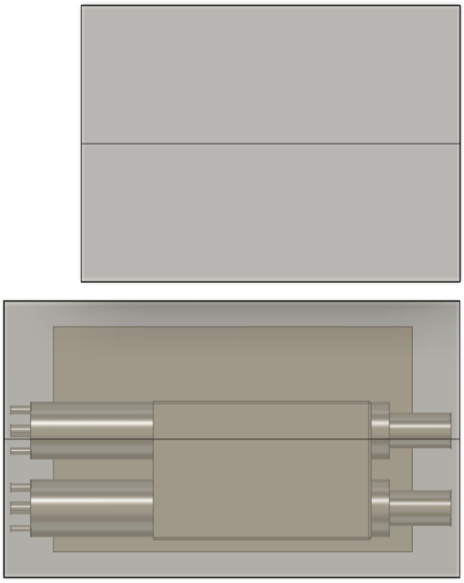


Figure 7 Top view, fixed cabinet concept

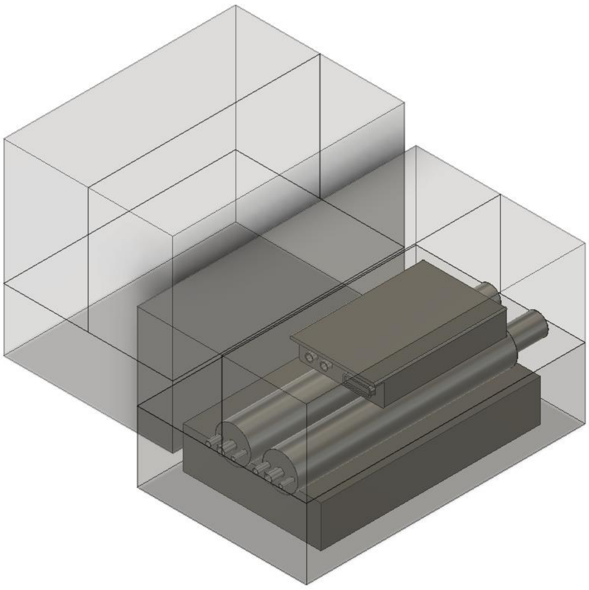


Figure 6 Cross view, fixed cabinet concept

The BlueDolphin platform was fitted with the 4 largest components, being the fuel cell stack, 2 reformers and the DC/DC converter as it was assumed all other BoP components could be fitted around these. A more detailed 3D model was though required in order to determine if a 15kW fuel cell genset could be made to fit within a cabinet with the same volume as the Fischer-Panda 15000x PMS. Even if this was not possible, the end-users had stated this would not be a problem as the market was undersaturated with respect to green alternatives to the fossil based gensets. With the overall design somehow defined, the P&ID was defined with a belonging 3D-drawing. The P&ID may be seen in App. A and the 3D-drawings may be seen on the following pictures, being Figure 9 and Figure 8.

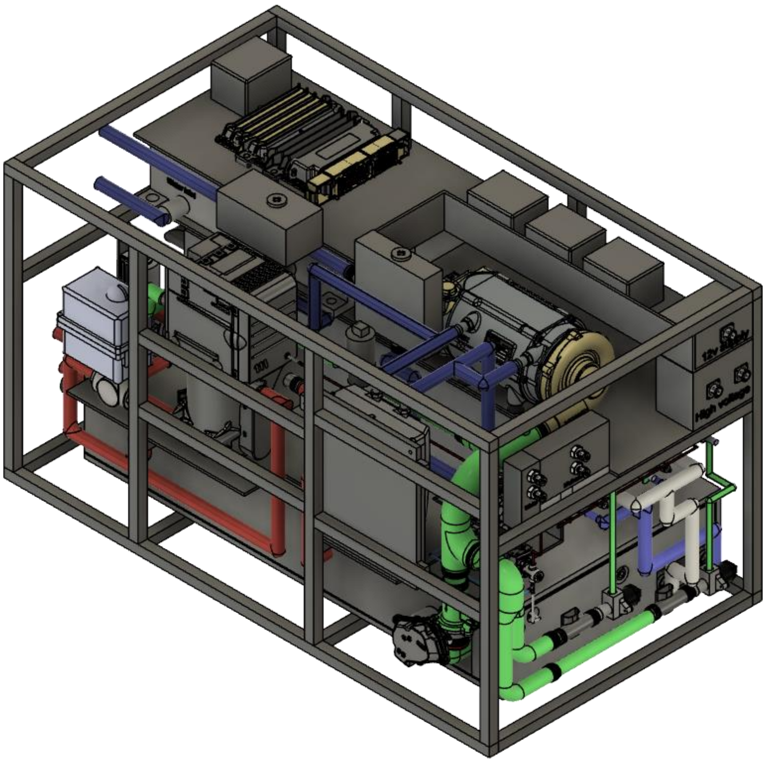


Figure 9 Front cross view of the BlueDolphin platform

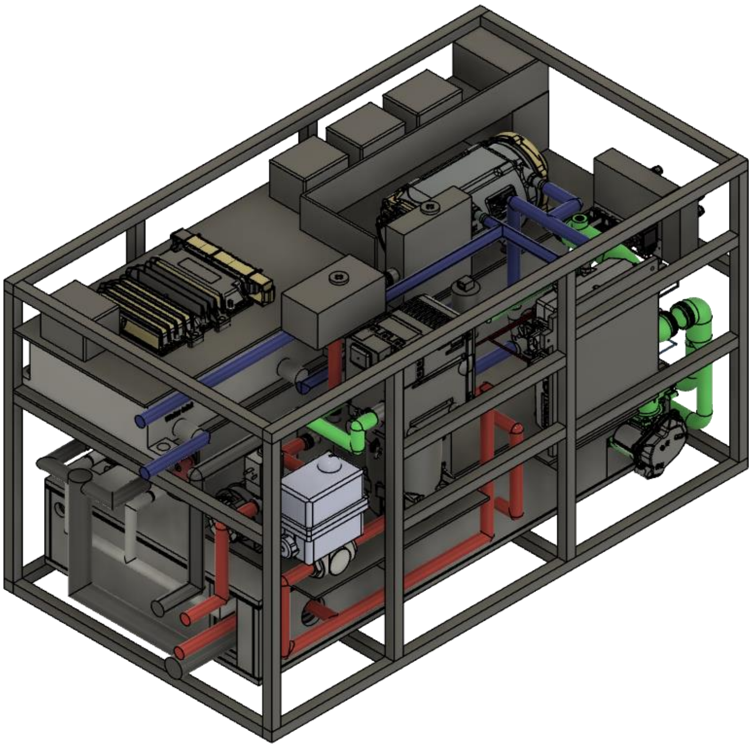


Figure 8 Back cross view of the BlueDolphin platform

5.2 Benchtop build and Go / NoGo gate

Figure 10 below showcase the benchtop build of the BlueDolphin platform.

Figure 10 Benchtop build of the BlueDolphin platform

This platform was used to complete milestone 2 which functioned as a Go / NoGo gate where 4 objectives had to be fulfilled, being:

1) Platform concept is technically compliant with general OEM and end-user requirements. Externally validated.
2) Platform concept is compliant with marine operational and safety standards. Internally validated.
3) A market entry platform price at <2250€/kW must be proven on a BoM level excluding fuel tank and battery. A realistic and feasible roadmap for achieving a platform sales price at 1000€/kW in 2029 must be developed.
4) The end-game system lifetime must be documented during the benchtop validation testing.

Platform concept is technically compliant with general OEM and end-user requirements. Externally validated

To verify whether or not this objective was fulfilled, the platform was showcased to multiple potential customers, OEMs and integrators at Blue World Technologies facility throughout the first half year of 2023. The responses were above and beyond, and the general takeoff was the desire for the platform to be a certified product able for purchasing right away.

Platform concept is compliant with marine operational and safety standards. Internally validated

The BlueDolphin platform was based on different IEC standards. These standards were, however, not made for fuel cell technologies for marine application as these were yet to be released. Instead, the used IEC standards referred to stationary fuel cell applications and truck fuel cell applications. Even though these standards were not made for marine applications, much information were incorporated into the safety design of the BlueDolphin platform based on these.

In order to state the safety of the BlueDolphin platform a FMEA was carried out. In general, the most potential hazards were associated with methanol and hydrogen as these could cause fire or explosions. Much effort was spent trying to design the system ensuring it could not leak methanol or hydrogen. In order to accommodate any potential leaks, forced ventilation was installed. Hydrogen is explosive if the concentration is above 4vol.%. Assuming a complete hydrogen pipe burst, the hydrogen concentration would be less than 0.5vol.% at full power, with the given volume flow of the installed blowers. Further, if a complete burst were to happen, the fuel cell stack would shut down within less than a second, from which the concentration of 0.5vol.% would only be present within less than one second.

A market entry platform price at <2250€/kW must be proven on a BoM level excluding fuel tank and battery. A realistic and feasible roadmap for achieving a platform sales price at 1000€/kW in 2029 must be developed

Based on the P&ID illustrated in App. A a BoM was made where the summation may be seen in Table 2 below.

Subsystem		**Single unit cost (2023) [€]**	**Bulk price (2029) [€]**
Fuel cell stack		8,300	6,800
Reformer		2,000	1,500
Air system		4,000	2,000
High voltage system		4,500	2,000
Fuel system		1,200	450
Cooling/Heating		1,800	500
Electric and control		3,000	950
Summation	**Total cost**	26,800	15,700
	€/kW	1,790	1,050

Table 2 Summation of the BoM

The relative savings between single unit price and bulk prices may be seen in the Figure 11 below.

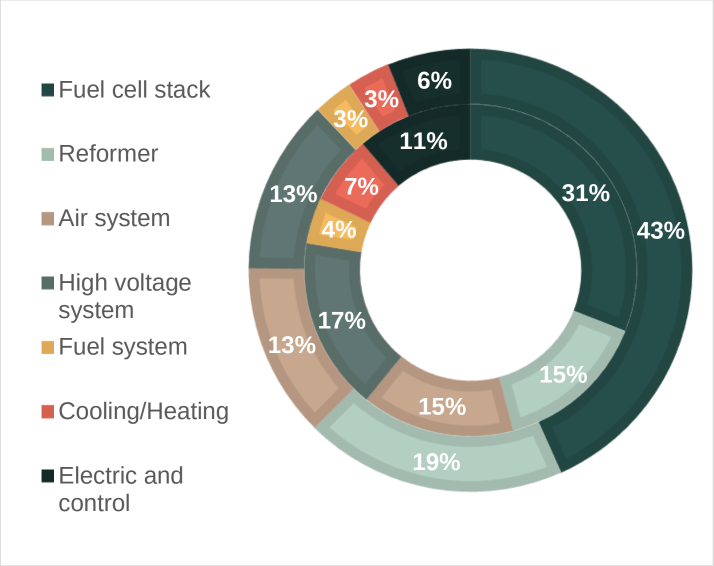


Figure 11 Relative savings between single unit price and bulk prices

The inner circle illustrates the current cost distribution where the outer circle illustrates the 2029 cost distribution. The major difference between the current status and the 2029 prediction is the Air system and the High voltage system. Currently the selection of air supply was limited due to working area of these. The pressure/flow ratio required for a fuel cell system differs significantly from traditional applications. As a result of this the only technology available at that time was compressor technology. However, as the fuel cell technologies are rapidly finding their way to the market, the demand for cheaper alternatives are needed. The cost of the used compressor dropped 25% by the beginning of 2023. It was therefore argued as a valid assumption that the cost of the compressor would additionally drop 25% by 2029, which was assumed in the analysis. A technology which was and is currently adapting to the fuel cell technology market is blowers. Compressors was approximately 10 times more expensive compared to blowers. Therefore, if the blower technology could be adapted to fuel cell technology, the Air supply cost contribution for the system could be reduced by more than a factor 10. Blue World Technologies was designing and testing different blowers at the time in order to replace the utilized compressor. As blowers were yet to be developed for such systems, compressors were still utilized. However, based on todays knowledge these blowers are now available.

The other critical contributor for the total cost was the High voltage system. The relatively high cost of this contributor was based on the fact that the DC/DC converter was a costum made component. In order to decrease the cost of this, bulk capacity was taken into consideration. Offers were made from the supplier to meet the desired targets if bulk capacity were to be ordered.

Based on these prices and assumptions, it was deemed realistic to meet a cost of 1000€/kW by 2029.

The end-game system lifetime must be documented during the benchtop validation testing.

The end-game system lifetime was defined as 7500h with 3000 thermal cycles. In order to validate the end-game system lifetime, an accelerated stress testing (AST) was conducted as stated in the project proposal. The run-time and thermal cycles was defined in the project proposal as “approach preferable during a period of 750h and 50 thermal cycles”. As stated in the headline, it was the “system lifetime” which had to be tested and validated. However, all components with the exception of the fuel cell stack and the reformers were external off-the-shelf products with a stated lifetimes of at least 10000 hours, meaning the critical components were the reformers and the fuel cell stack. The objective of the AST was therefore narrowed to test the durability of the fuel cell stack and the reformers. In order to define the AST, the critical degradation influences for both the fuel cell stack and the reformer were analyzed.

With respect to the fuel cell stack the critical influence was the thermal cycling. Once the fuel cell stack was in operation the degradation was close to negligible compared to the degradation contribution of cycling the stack between on and off. With respect to the reformer, it was not the thermal cycling which contributed to the biggest degradation but instead overheating. The catalyst degradation increased exponentially with increasing temperatures. Likewise the fuel cell stack, once the reformer was in operation the degradation was close to negligible.

Based on this it was concluded that the AST should initially focus on thermal cycling before focusing on the overall runtime. Within a day, 2 thermal cycles were conducted. Initially the reformers were preheated followed by a break, in order to obtain proper heat distribution. After the break the system was enabled following the standard procedure. Due to the preheating, the reformers were exposed to a higher temperature compared to standard procedure. 1 hour after the system entered the operation phase, it was shut down again until the reformers reached a temperature which yielded them being exposed to a higher temperature compared to standard procedure when enabling the system again. This sequence may be seen in Figure 12 on the following page.

A total of 75 AST cycling was conducted without any noticeable degradation in performance of either the fuel cell stack or the reformers.

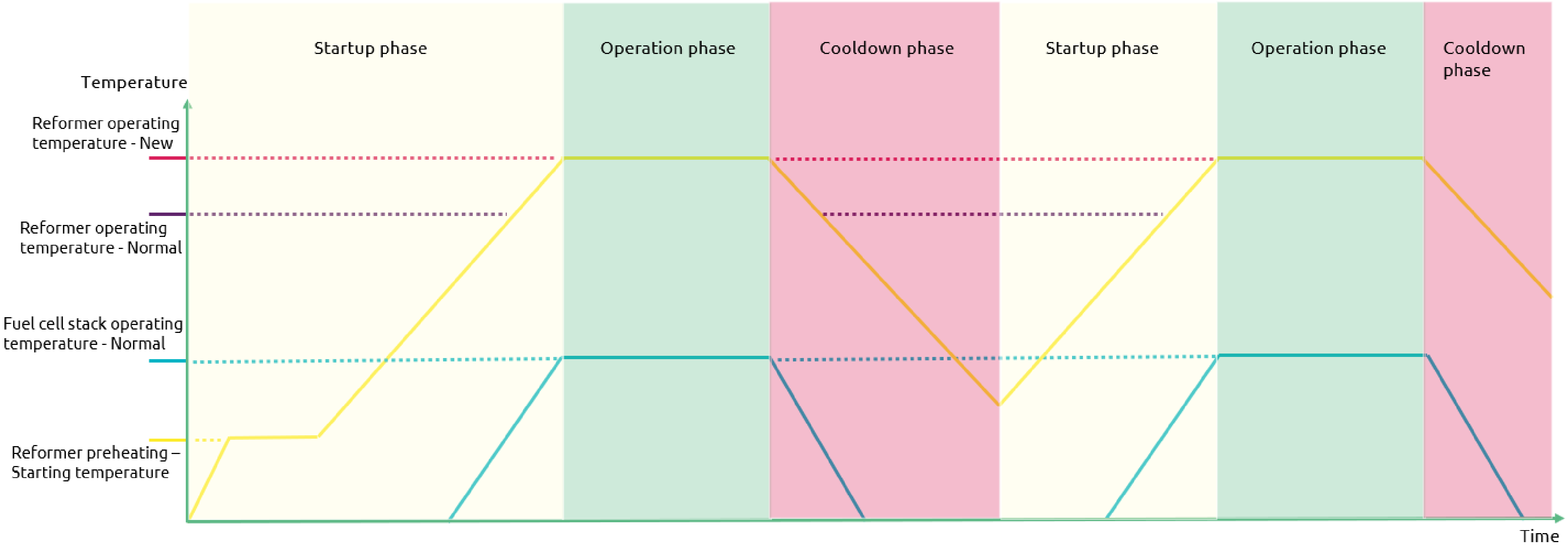


Figure 12 AST of the BlueDolphin benchtop

As all thermal cycling was conducted, the previously defined AST method was replaced with a long term test of the system. This long term test ended with a clock count of approximately 550 hours.

When this project proposal was defined it was assumed that one of the biggest degradation mechanisms with respect to the fuel cell stack was related to the total run time. However, 3 years later when these experiments were conducted this was proven not to be true. In Figure 13 belove the degradation of a single cell may be seen as function of time at a constant load point. Throughout 9000 hours the average degradation is 7µV/h which correspond to less than a 10% degradation.

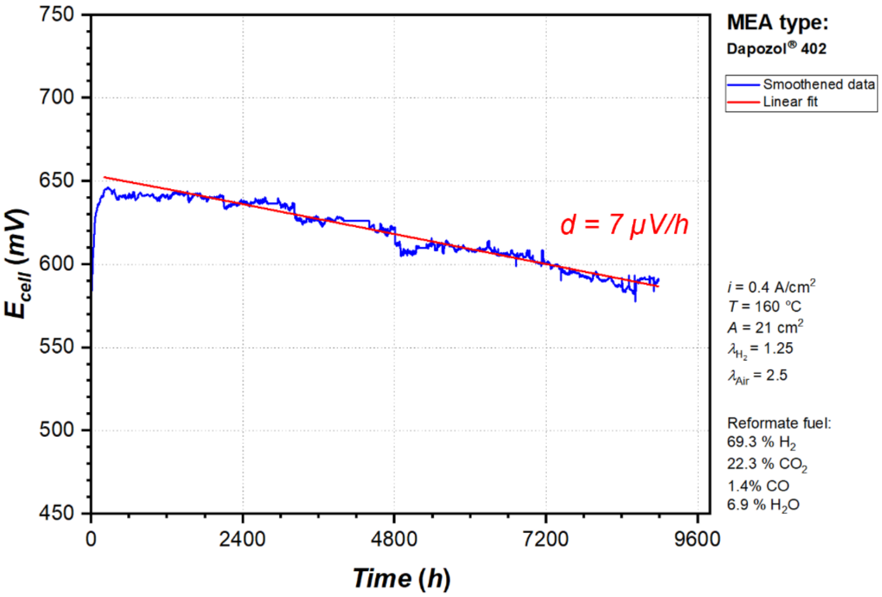


Figure 13 Cell degradation as function of time

To put this degradation into perspective, the following Figure 14 illustrates the cell voltage as function of time at a constant load point with a fuel starvation included. Between 19:00 and 20:00 a fuel starvation occurred. A fuel starvation is defined as a situation where the fuel cell is not provided with enough fuel. It may be seen in Figure 14 below that after the fuel starvation the cell was brought back to the same load point as before, whereas the cell voltage was now 565mV instead of 595 prior to the fuel starvation. This was an instantaneous cell voltage reduction of approximately 5%, in contrast to 10% over 9000 hours.

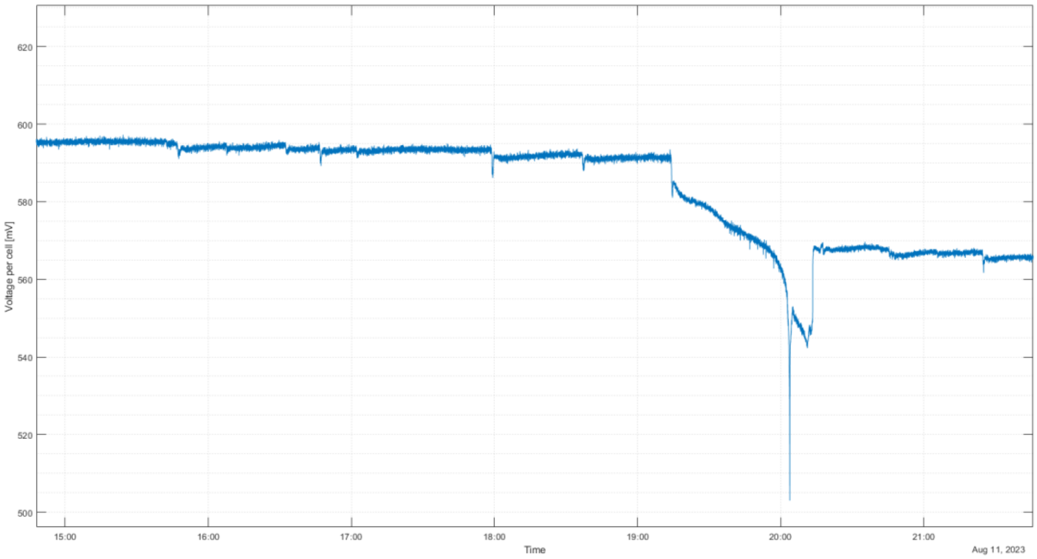


Figure 14 Cell degradation at constant load with a fuel starvation

As it was concluded that steady state operation did not contribute to the biggest cell degradation, it was decided to analyze another variable. An unknown variable was the ramping rate of the power output. Therefore, instead of working toward the 750 hours, the focus was shifted to analyze the influence of ramping the power output up and down. This was tested and further concluded that it did not degrade the fuel cell stack. The system had accumulated been ramped up and down approximately 400 times to investigate the influence. In order to include this in the AST, the ramping speed was also tested with an increment from the base line to a factor of 10 higher. This was also concluded not to have a negative influence toward the fuel cell stack lifetime which was a significant result making the system more dynamic.

5.3 System simulation

A comprehensive steady-state model of the 15-45 kW reformed methanol HT-PEM fuel cell system was developed. The model included a detailed representation of the HT-PEMFC, methanol steam reformer, burner, evaporator, battery, and all necessary BoP components, including the condenser for water regeneration from the fuel cell stack. The system contained components operating at different temperatures, where some components required heat and others produced heat. Therefore, simulating and optimizing the heat integration of the system was essential. The model helped the understanding of the system behavior under various operating conditions and improved the system design. Additionally, to meet the water neutrality, the system model incorporated an internal water regeneration model of the water produced in the fuel cell to study the feasibility of this scheme. The model consisted of the following subsystems

1. Primary components
    - HT-PEM fuel cell stack (15-45 kW)
    - Methanol steam reformer (multi-tubular packed-bed reformer)
    - Burner
2. Heat transfer components
    - Evaporator
    - Heat exchangers
    - Condenser
3. Storage components
    - Methanol tank
    - Water tank

4. Transport components
    - Pump
    - Compressor
5. Electrical components
    - Battery
    - Motor
    - Inverter
    - Controller

Among these, the HT-PEM fuel cell stack, methanol steam reformer, and burner were identified as the primary components of this system. Since methanol steam reforming (MSR) reactions are strongly endothermic, external heat was supplied by the heat flux from the burner. The CO, H_2, and CH_3OH that remained in the fuel cell exhaust gas were redirected to the burner. They were combusted with the incoming air in the burner to generate thermal energy. The methanol and water mixture were evaporated through an evaporator, and this methanol-steam mixture was reformed into a hydrogen-rich gas inside the reformer. The reformate gas was transferred to the anode side of the fuel cell stack. Through electrochemical reactions, the PEM fuel cell stack generated electricity by employing hydrogen from the anode side and oxygen from the cathode side. Furthermore, models of other components (evaporator, condenser, battery, heat exchangers, etc.) were specifically developed. Afterward, the modeled components were combined into a system model.

The models

Two numerical models of the reformed methanol HT-PEM fuel cell system were developed. The first was a comprehensive steady-state model that includes detailed subsystem models (HT-PEM fuel cell stack, reformer, and condenser) to study the effects of operating conditions on the performance of different modules and the thermal integration of the system. The second was a dynamic model, which was used to investigate the transient behavior of the system, enabling the study of water recycling, optimization of startup and shutdown procedures, design of control strategies under load changes of a boat, and the potential implementation of fault diagnosis and fault tolerance control.

The HT-PEM fuel cell model was further also used to study the effects of operating temperature, back pressure, and CO concentration on the anode side on the performance of the HT-PEM fuel cell. The simulation results have been validated against experimental data from the literature and experiments, demonstrating a fairly good agreement. Figure 15 illustrates the output voltage of a single high-temperature PEM fuel cell at different operating temperatures (423.15 K and 448.15 K) compared to experimental results from the referenced study.

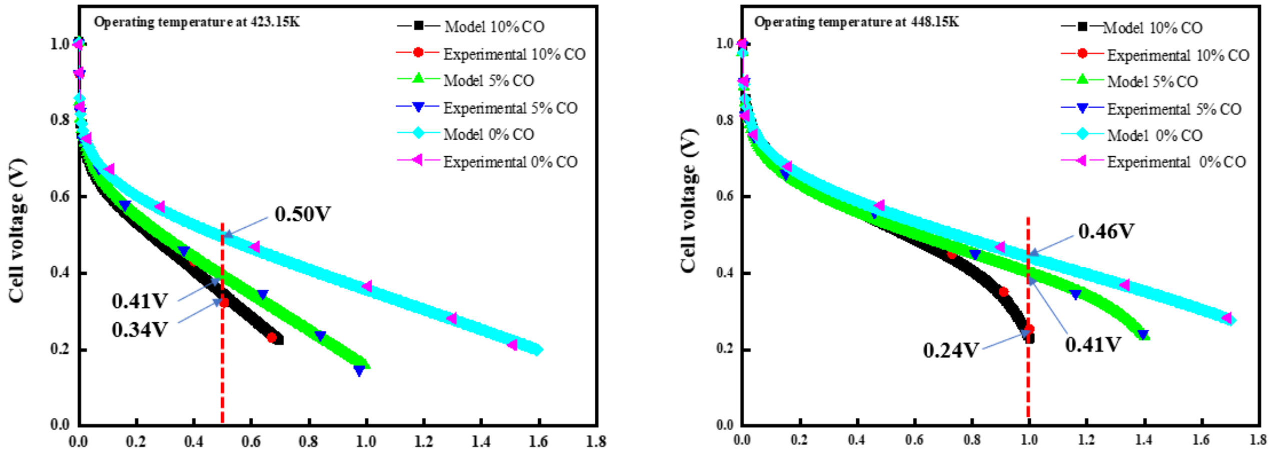


Figure 15 output voltage of a single high-temperature PEM fuel cell at different operating temperatures (423.15 K and 448.15 K) compared to experimental results from the referenced study

The steady-state model of the methanol steam reformer was utilized to validate the kinetics of the system by using our experimental data. This model was used to study the effects of operating conditions (inlet flow rates and temperatures in both tube and shell sides, pressure, tube diameter, and catalyst particles size) on the performance (outlet temperature, pressure and composition of reformate gas) of the reformer. The comparison between simulation results of the methanol steam reforming (MSR) process with experimental results is shown in Figure 16.

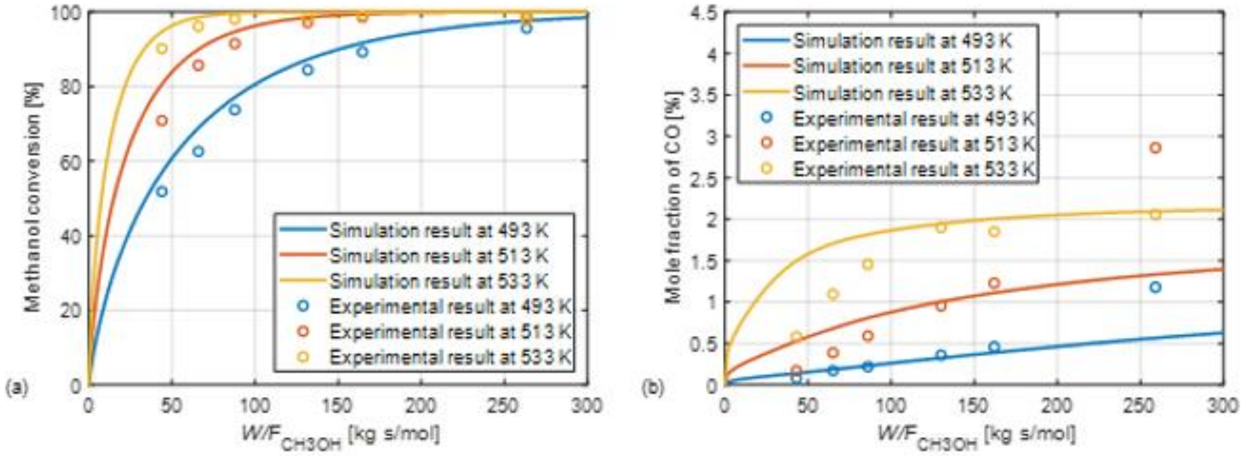


Figure 16 Comparison of the (a) methanol conversion and the (b) mole fraction of CO between simulation results and experimental results under different oerating temperatures [2]

5.4 Vibration tests

Firstly, a used 30-cell HT-PEMFC stack was subjected to vibration conditions using a robot arm. The purpose was to assess the stacks performance and behavior under vibration cycles. The test setup and parameters are detailed in Figure 17 and Table 3, respectively.

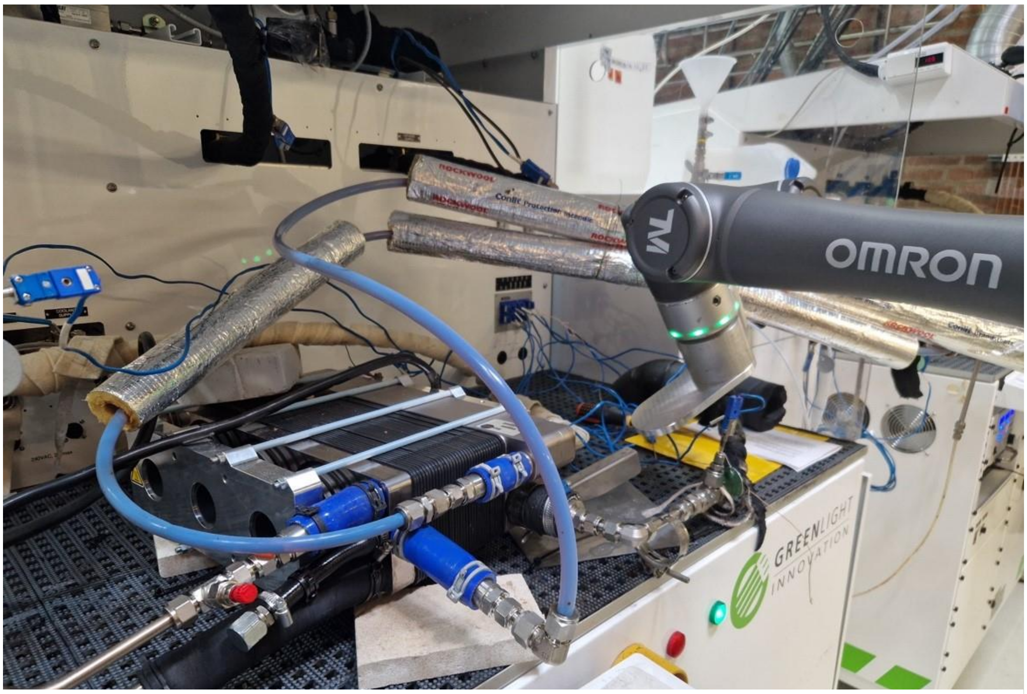


Figure 17 Vibration test setup, showing a 30 cell stack connected to a Greenlight Innovation test fuel cell test station and an Omron robot arm ready to apply the vibration

Parameter	Value	Unit
Load	0,2	A/cm^2
Anode feed	H2	%
Lambda_H2	1,25	-
Cathode feed	Air	%
Lambda_O2	2,5	-
Temperature	160	degC
Pressure	1	bar

Table 3 Test conditions

The vibration parameters for the first stack included a frequency of 0,17 Hz (6 seconds per vibration cycle) and an amplitude of 3,6 cm. The stack's performance was monitored before and after the vibration test. Before the vibration test, the stack's performance was recorded under the same operating conditions for reference. The break-in period for the stack was 72 hours and the stack has already been tested for load cycling and start/stop cycling. Therefore, the vibration tests on this stack were done to learn and define better the vibration test procedures and to gain experience on an old stack before a newer stack can be tested.

During the vibration tests, the stack was subjected to more than one day of continuous small shocks, totaling over 20000 vibration cycles. The fuel cell was then started up and once the stack stabilized at a current density of 0,2 A cm-2, the vibration was introduced again, but was unfortunately, soon interrupted due to stack leakage.

Figure 18 displays the stack's performance before and after the shock test. The black line represents the stack's performance before the vibration test, while the red line represents the stack's performance after 20000 vibration cycles. The stack voltage did not exhibit a significant change before and after the shock. However, the heating process was notably affected. The stack had an external oil cooling system to maintain an operating temperature of 160degC. As the stack outlet temperature exceeded 160degC, the inlet oil temperature decreased to balance the stack temperature, resulting in changes in stack performance.

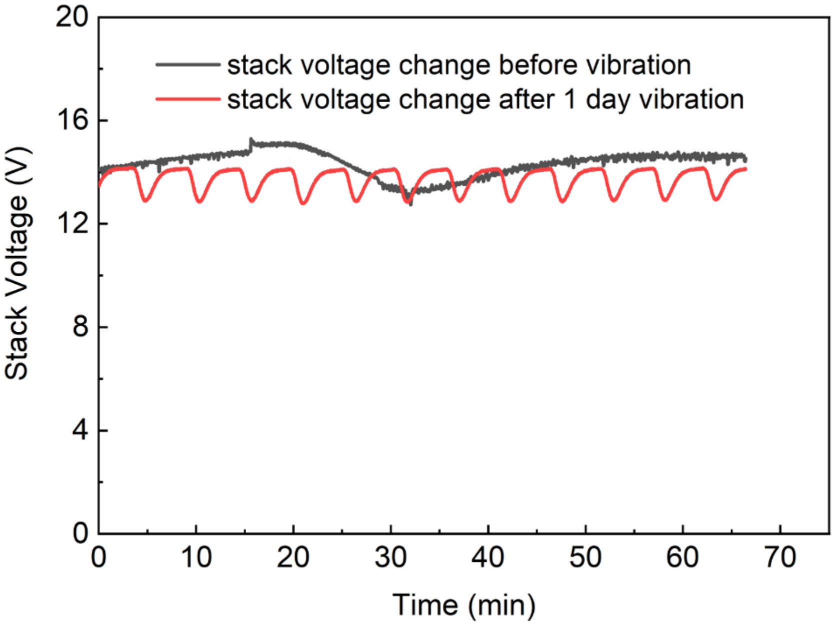


Figure 18 voltage profile before and after vibration tests

As can be seen in Figure 18 voltage profile before and after vibration tests, before the vibration, there was only one cycle of up and down changes in the stack voltage due to temperature fluctuations in the 65 minutes measured. However, after one day of vibration, more frequent changes in stack voltage were observed, indicating an increase in the thermal cycling during operation. It is known that frequent thermal cycling during operation can lead to performance decay in the stack. However, it cannot be concluded that this effect is the result of vibration, even though it is seen after vibration cycles. Several factors, including the old age of the stack and the unstable oil cooling loop could have been affected by the vibration cycles rather than the fuel cell stack's internal parts. Furthermore, the stack was operated with vibration at the very end period of the test Unfortunately the gas leakage detected on the cathode side, which led to the shutdown of the stack. The cathode leakage cannot be attributed to the vibration test, but rather to poor connection of the stack to the test station. In fact, this was fixed for the second stack and did not occur any further during or after shock tests. Moreover, the real fuel cell system for the BlueDolphin project has more robust connection for the fuel, oxidant and coolant flows and such vibration is not expected to cause leakage. In conclusion, the first vibration tests on the old stack revealed that the stack voltage did not change significantly due to vibration tests, but the heating process was affected. Frequent thermal cycling during operation after the vibration tests led to slight performance decrease. Successively, a new stack was tested for further vibration tests, where different frequency was used. The tests also included a rest time between vibrations and vibration tests on operating stack were also performed. The results of the vibration and shock/drop tests on the new stack are summarized below.

Vibration and shock tests on new stack

For the second stack, the vibration tests were conducted after allowing the fuel cell stack to break-in for the first 24 hours. The vibration test procedure involved dropping the stack from a height of approximately one centimeter, with approximately 20 vibrations per minute and a one-minute settling time after each set of 20 vibrations. A total of 1600 vibrations of the same amplitude as the first stack were performed during this second round of vibration tests. During the vibration tests, the voltage of the stack initially increased during break-in but then remained constant throughout the rest of the test period, as can be seen in Figure 19. Polarization curves were recorded during the vibration tests. Then following the tests, the stack was operated for an additional 20 hours, and another polarization curve was recorded. The performance comparison before and after the vibration test is shown in Figure 20.

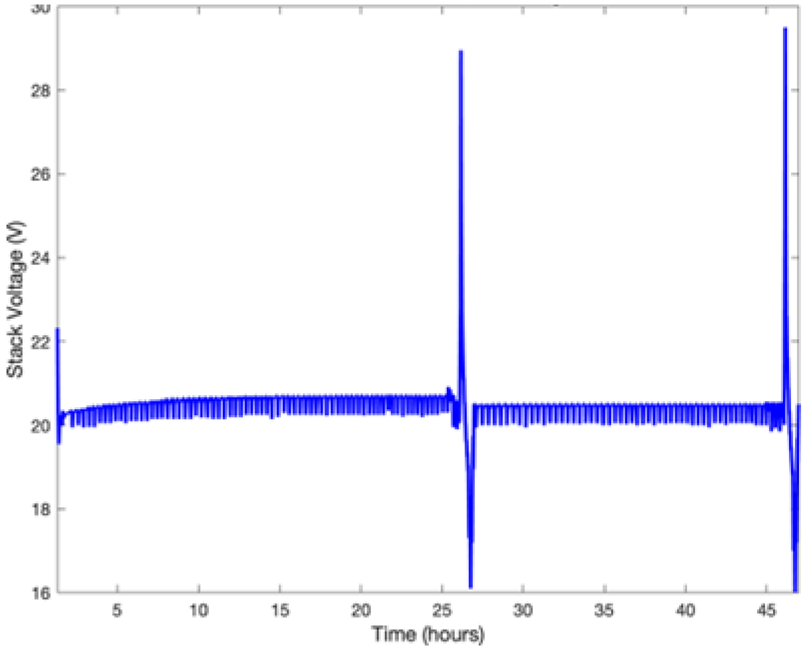


Figure 19 Voltage profile of new stack before, during and after vibration tests

Figure 19 shows the voltage profile for the second stack during and after the vibration tests. The during operation vibration tests were performed right after the 24 h break-in period. Right after the polarization curve mark was performed slight drop in the stack voltage was observed in the voltage profile, as shown in Figure 19. However, it cannot be concluded whether this drop is a result of the vibration tests or the polarization measurement itself, which includes operation at OCV for around a minute. The polarization curve in Figure 20 remains unaltered after vibration tests, showing that the vibration tests in the case of the new stack did not influence the fuel cell stack performance. The stack operating conditions during these tests are the same as those shown in Table 3.

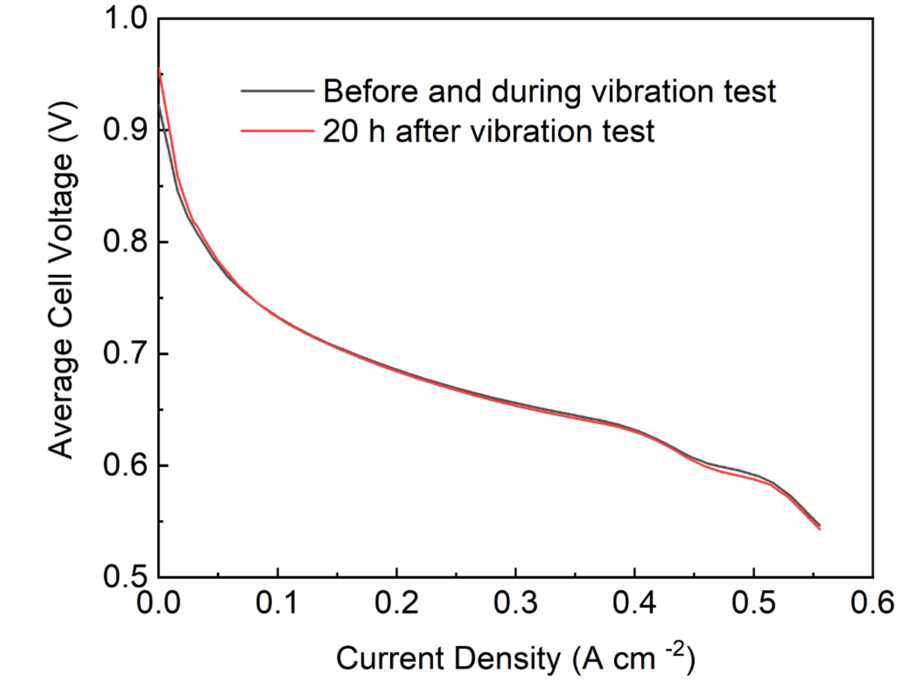


Figure 20 Performance of the fuel cell stack before and after vibration tests

5.5 Onshore tests

In order to enable a more in depth analysis of the BlueDolphin platform, onshore testing was required to determine the following:

- Efficiencies
- Power outputs
- Reliability
- Dynamic operation
- Start/Stops

In addition to these, an innovative water neutrality system was also designed and tested onshore. The inside of the test container may be seen in Figure 21 below.

Figure 21 Inside of the test container

System performance

Figure 22 below illustrates the power produced by the stack which is displayed by the dark green column whereas the light green column indicates the net power. The black line indicates the efficiency of the Blue-Dolphin platform, and the orange line indicates the fuel cell stack efficiency. The component with the highest influence toward the net efficiency is the air supply. The green line indicates the expected efficiency for the next iteration of the BlueDolphin platform where it has been adjusted with the power consumption of a blower made for this application replicating the same flow and pressure needed for the different operation points.

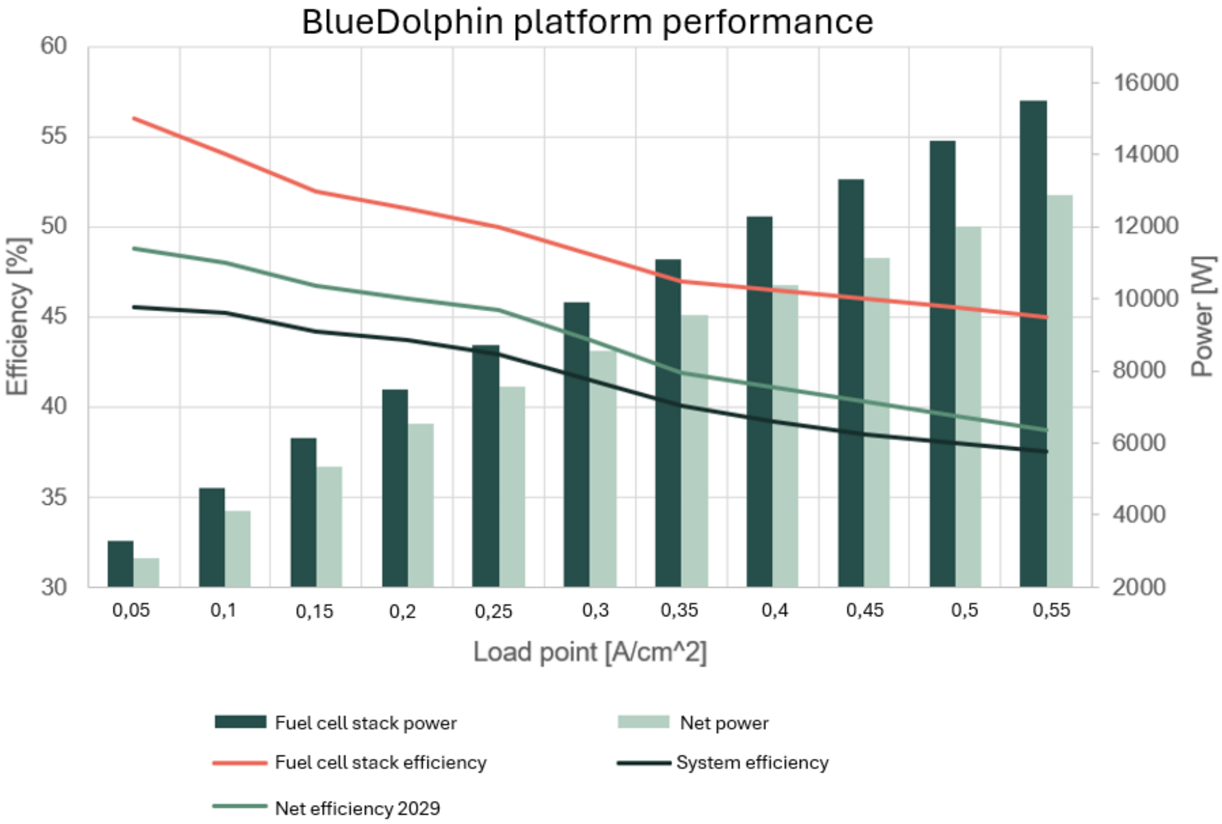


Figure 22 BlueDolphin platform performance

Power output

The target of the BlueDolphin platform with respect to the power output was 15-45kW. Figure 23 below display the power output for an arbitrary run, where the lower limit of 15kW was met. The peak power for this run was just shy of 16kW and obtained with a fuel cell stack temperature of approximately 160degC. The specified temperature range in the project proposal was 160-180degC, from which a 20degC increment in the temperature would approximately correspond to a peak power of just shy of 20kW. In order to obtain a longer lifetime the system was though maintained at 160degC.

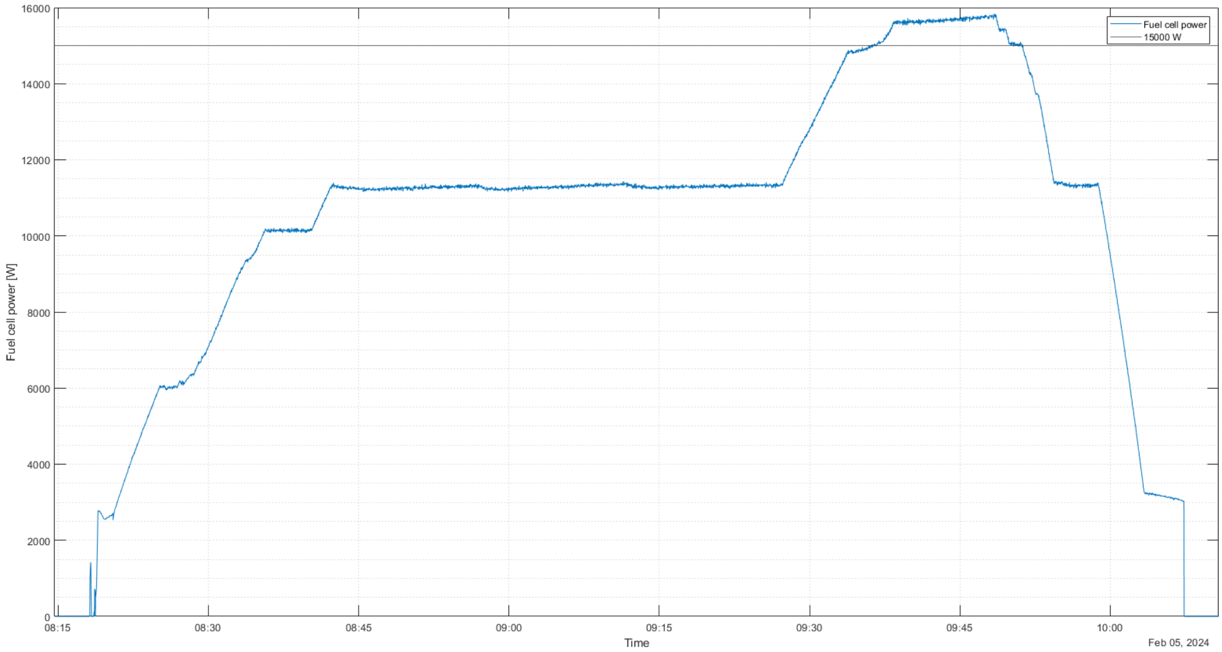


Figure 23 Net power for an arbitrary run

Reliability and start/stops

A part of the onshore test was to prove reliability. However, before it could be proven its meaning had to be defined. The end user would most likely define it as the measure of the success-rate of the startups, or the rate of unintended shutdowns. These definitions were, however, the result of the reliability of the software and how well it was able to control the system based on multiple inputs and impacts. As the BlueDolphin platform was intended to work along with a battery, its demand for dynamic response was limited. The software was therefore optimized with respect to steady state operation within its power range. Figure 24 below display the temperature gradients for the reformers for an arbitrary run at a current density at 0.4A/cm^2.

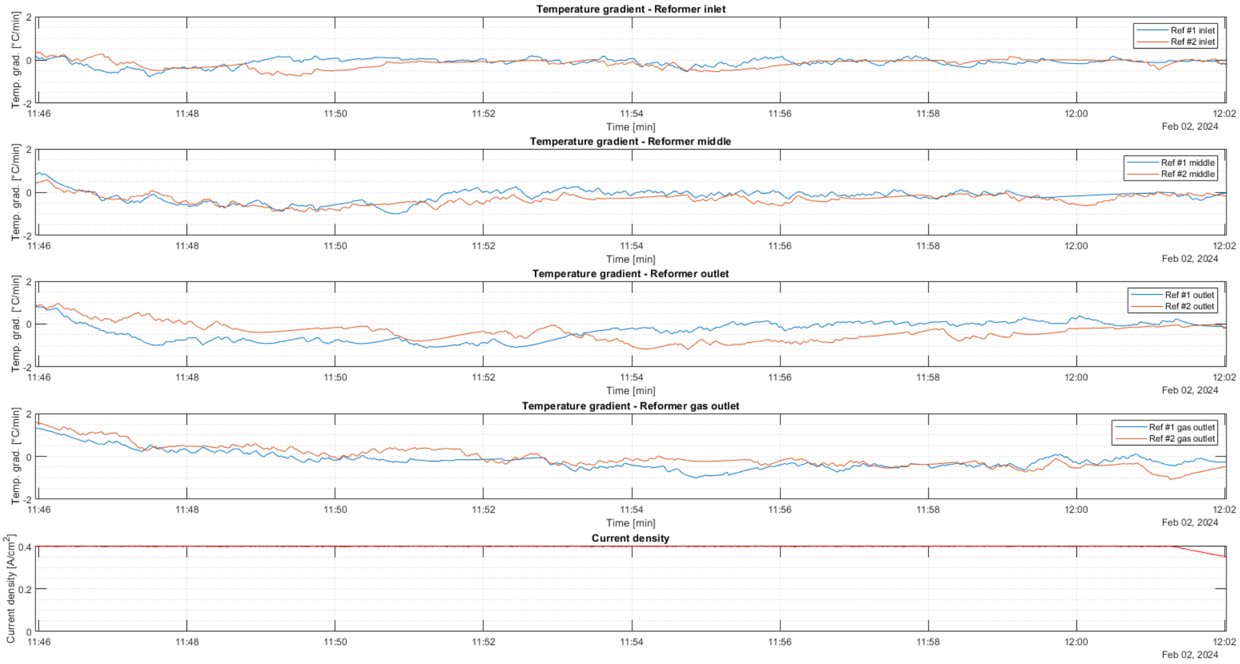


Figure 24 Temperature gradients for the reformers for an arbitrary run

It may be seen that none of the gradients exceed -+2degC/min over a timespan of 15min, from which it was concluded to be above and beyond acceptable with respect to steady state. It was stated above that a stable and reliable software indirectly yields a reliable system for the end user.

Returning to the two previously mentioned definition of reliability, as the measure of the success rate of the startups and the rate of unintended shutdowns. The benchtop was exposed to 75 start/stop cycles which was enabled from 88 attempts yielding a success rate of 85%. This was argued to be well acceptable for a benchtop. As always, the learnings from the benchtop build was significant and was implemented for the second iteration of the platform which was used for the onshore/offshore tests. The onshore system had a total startup count of 107 which was enabled from 116 attempts yielding a success rate of 92%, which was once again argued to be well acceptable as it was yet not a commercialized product. Of those 107 runs only 9 ended in an unintended shutdown. Of those 9 unintended shutdowns, 3 was not system related, but an error in the test container. Subtracting those 3 shutdowns, the fail rate was less than 6%, which was also argued to be well acceptable.

Long term test

Due to the design of the test container, the ambient temperature within the container could be adjusted to match the outside ambient temperature. This enabled long term test under different ambient temperatures. The system was operated for a week during the winter, spring and summer, where the ambient temperature in the container was kept somehow constant at -5degC, 20degC and 40degC, respectively.

During the winter test, the main concern was the influence of the negative temperature and how it would affect the water in the system. Essential 2 water sources was present in the system, the first being the water used for the reforming process. As the system mix water and methanol internally, it was known that the water tank and the water pipes needed a heat source. This was added and solved the problem. The second water source was, however, the biggest concern, being the water generated within the fuel cell stack. As water is the product of the electro-chemical reaction, water was present at the cathode of the fuel cell stack. However, as the steam to carbon ratio in the reformer was 1.5, water was also present at the anode of the fuel cell stack. Therefore, once the system was turned off, a small amount of water could potentially accumulate within the fuel cell stack. It was a great concern that if the system was kept below 0degC for a significant amount of time, any potential water within the fuel cell stack could break the MEA due to the freezing of the water. The system was therefore enabled for 6 hours a Thursday in February and left shut down during Friday, Saturday and Sunday. At this time period the average temperature was -5 and did not exceed 0degC. The system was enabled the following Monday, and after a week of operation the data was compared to that of the previous week. It was concluded that the negative temperature did not damage the fuel cell stack.

The spring test did not pose any significant concerns, from which this time was used mostly to test some of the other described tests.

The summertime enabled the system to be tested at the other end of the temperature spectrum. Even though the elevated temperatures did not pose any concerns with respect to damaging any equipment, overheating was the main concern forcing the system to shut down. Even though all of the equipment used in the BlueDolphin platform was rated for elevated temperatures, it still needed to be proven. During the summer the container was kept at 40degC for a week without any shutdowns.

The system was operated at approximately 1350 hours with 7 longer runs in the time range of 5-13 days.

Novel water neutrality system

Along with the test of the fuel cell system a novel water neutrality system had to be designed and built. A fuel cell system replica was designed instead of utilizing the BlueDolphin platform in order to enable simulations based on a more mature fuel cell system. Meaning, currently the BlueDolphin platform was limited to a cathode lambda value of 2.5 whereas a more mature system should be able to run with a value of 2 which would benefit the condensation process with respect to both the CAPEX and OPEX, and also the system efficiency.

Such a fuel cell system replica may be seen in Figure 25 below.

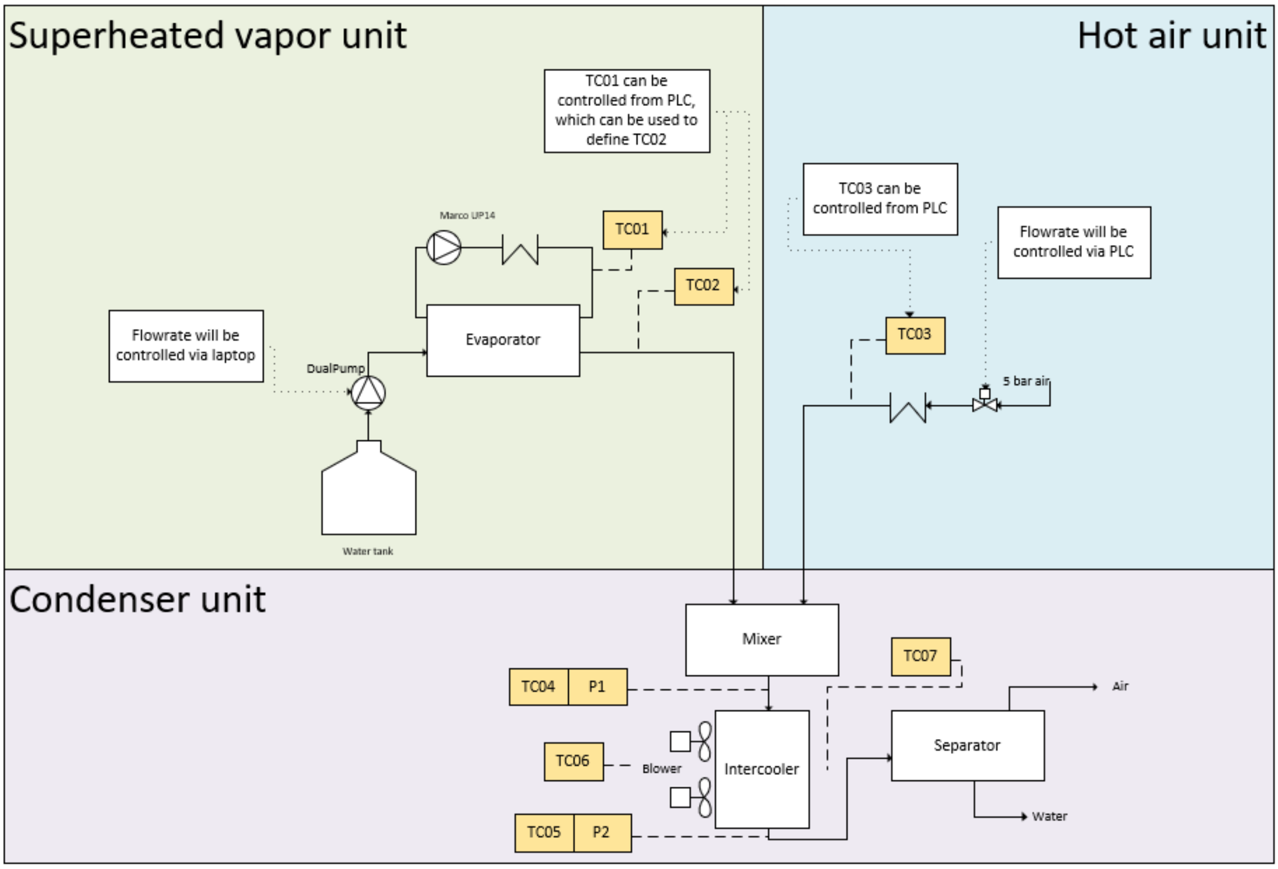


Figure 25 Fuel cell system replica

In order to replicate a fuel cell system, a source of heated air was required along with a source of vapor. The vapor was controlled from a setup which may be seen in the green square in the figure above. This setup was consisting of a controllable water pump and an evaporator which could evaporate and superheat the water. The heated air was controlled from a setup which may be seen in the blue square in the figure above. This setup was consisting of a valve with an internal mass flow sensor and a heat source to heat the air. The output of these two processes were mixed as may be seen in the purple square in the figure above. Such a replica enables the possibility of simulating:

- Different load points
- Different anode lambda values
- Different cathode lambda values
- Cathode exhaust alone
- Cathode exhaust combined with the reformer burner exhaust
- Different ambient temperatures
- Different condenser designs

After the mixer, the mixed gas entered an intercooler functioning as a condenser where the condensed water was separated from the exhaust gas in the separator. Two fans were mounted to the intercooler in order to provide the required cooling.

For the initial tests, two objectives were of interest. The first being whether or not the initial condenser was sufficient, and second, the required overall heat transfer coefficient such more system suitable condenser could be sourced. In order to determine whether or not the initial condenser had a sufficient cooling capacity, it was needed to take into consideration whether the exhaust should be the cathode only or if should be joined with the exhaust from the reformers. The disadvantage of joining the exhausts was the increment of the required cooling, whereas the benefit was the increment in the dew point. The dew point is the key variable which is defined as the minimum temperature of the exhaust after the condenser in order to reach water neutrality. By joining the two exhausts, the dew point increases about 10degC. A rule of thumb states that a great heat exchanger can reach a temperature difference of 5-10degC between the two medias. Therefore, if only the cathode exhaust was to be utilized, a water neutral system would in principle not be possible if the ambient temperature would exceed 30degC. This value would however be 40degC if both exhaust were joined. The results of both the condensation rate and overall heat transfer coefficient may be seen in Figure 26 below. The notation on the x-axis should be read as follow. The name consist of 3 statements xxx.yyy.zzz where xxx denotes whether or not the exhaust is a combination of both the cathode- and reformer exhaust or if it is just the cathode, if it just the cathode it is denoted “Cat” and “CatRef” if it is a combination. The yyy denotes the ambient temperature in degC. Lastly, zzz denotes the number of fans turned on during the experiment.

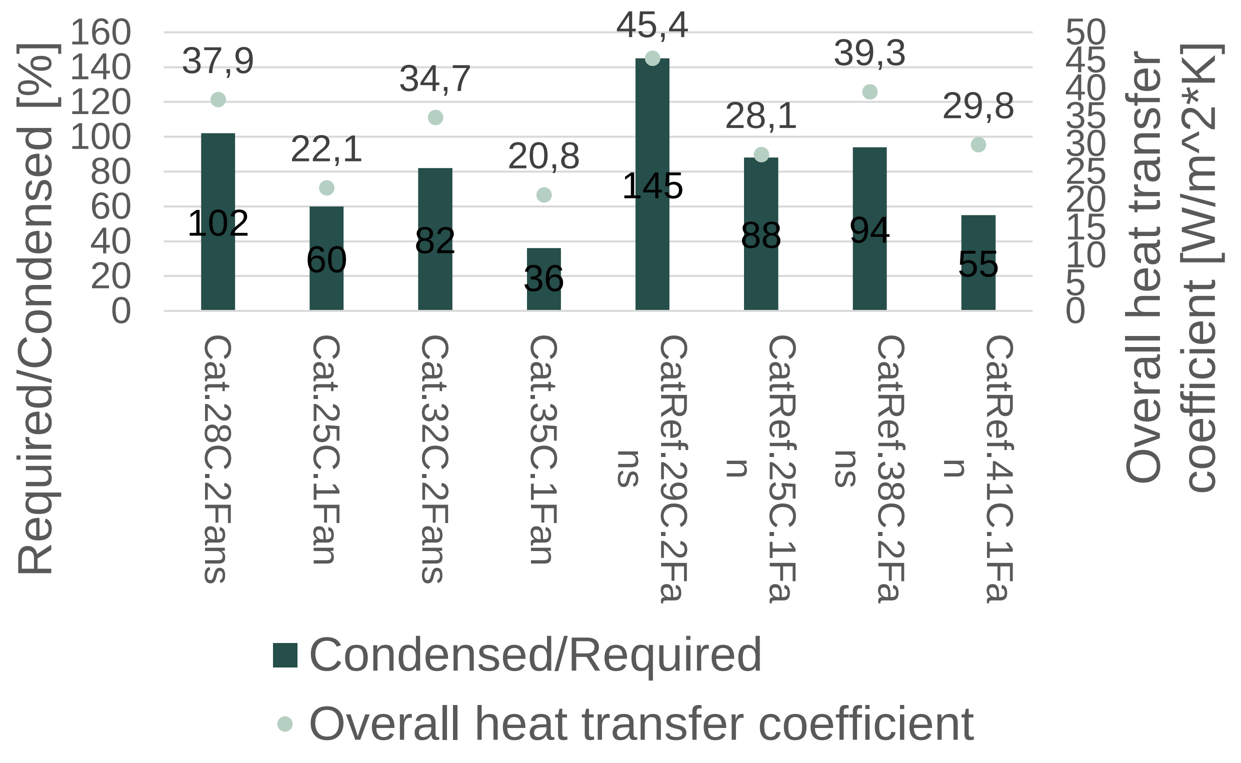
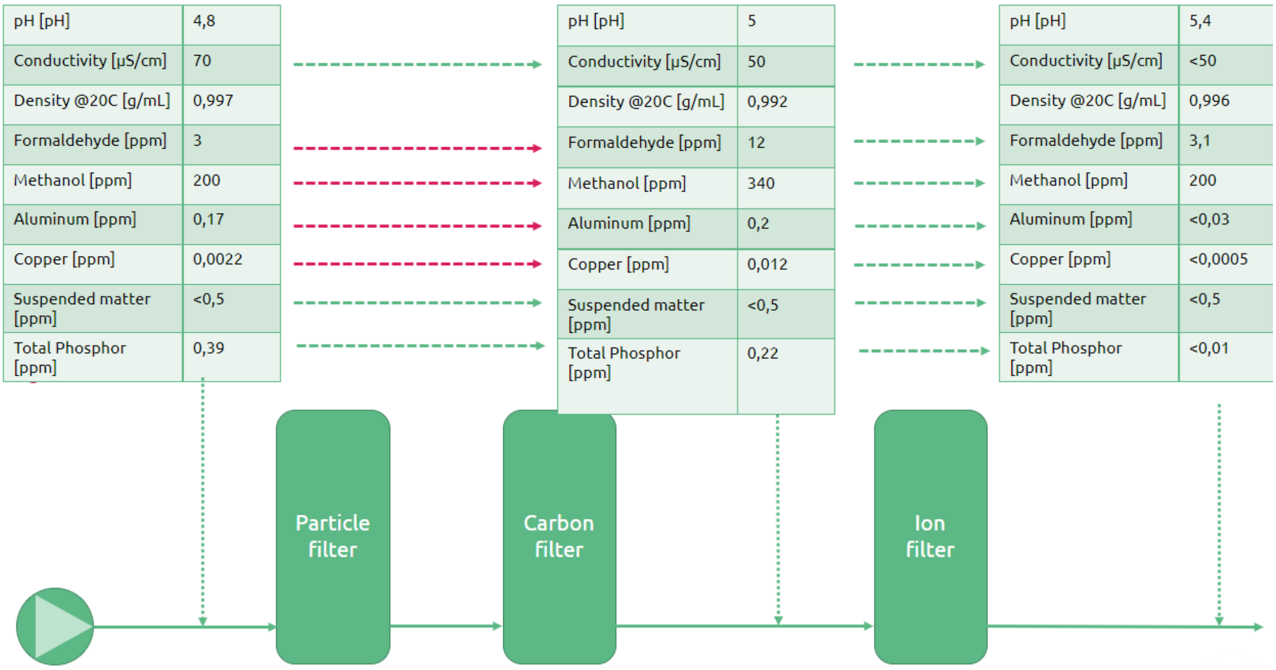


Figure 26 Condensation rate and overall heat transfer coefficient

The experiments are based on the following values: Anode_lambda=1.2, Cathode_lambda=2.5, current density=0.6A/cm^2, n_cells=160, area=297,5cm^2, SC_ratio=1.5. As expected, water neutrality was difficult to obtain with a reasonable sized condenser unit if the cathode exhaust was only used at elevated temperatures, from which a combination of both exhaust were used in the following tests. As previously mentioned, the cooling requirement was, however, greater with a joined exhaust, from which it would be of interest to only utilize the cathode exhaust. In order to realize this, the overall heat transfer coefficient is the most crucial variable when designing/sourcing a condenser for commercial utilization.

Implementation of the water neutrality system

Based on previous studies it was expected that a purification system would be needed. The initial purification system consisted of three filters. The first filter was a 5µm particle filter, in case of any residue. The second filter was a carbon filter, in case of phosphoric acid residue or similar. The last filter was an ion filter in case of ions. In order to check the influence of these, multiple water samples were collected and analyzed. The results may be seen in Figure 27 below, where a green arrow represent a reduction of the value, opposite to a red arrow.



pH [pH]	4,8
Conductivity [µS/cm]	70
Density @20C [g/mL]	0,997
Formaldehyde [ppm]	3
Methanol [ppm]	200
Aluminum [ppm]	0,17
Copper [ppm]	0,0022
Suspended matter [ppm]	<0,5
Total Phosphor [ppm]	0,39

pH [pH]	5
Conductivity [µS/cm]	50
Density @20C [g/mL]	0,992
Formaldehyde [ppm]	12
Methanol [ppm]	340
Aluminum [ppm]	0,2
Copper [ppm]	0,012
Suspended matter [ppm]	<0,5
Total Phosphor [ppm]	0,22

pH [pH]	5,4
Conductivity [µS/cm]	<50
Density @20C [g/mL]	0,996
Formaldehyde [ppm]	3,1
Methanol [ppm]	200
Aluminum [ppm]	<0,03
Copper [ppm]	<0,0005
Suspended matter [ppm]	<0,5
Total Phosphor [ppm]	<0,01

Figure 27 Water contamination

An increment of the formaldehyde, methanol, aluminum and copper from measuring point 1 and 2 may be seen. It was expected that multiple errors could result in such increments, however, as their values were of an unsignificant magnitude, it was accepted. The key variable was however the conductivity as this was a direct measurement of the water purity, which was reduced as expected.

Even though such results are of high value it was still unknow how pure the water had to be in order not to influence the functioning and efficiency of the system. A qualitative approach was therefore introduced, where a system was operated with the water condensed based on this setup. The system was continuously operated at steady state for approximately 450 hours. It was concluded that no deviation of the systems functioning, or efficiency could be measured after the 450 hours. In order to determine if this success was as a result of the filters, the same system was once again tested with the condensed water, however, this time the water bypassed the three filters. The system ran for approximately 50 hours before it was no longer functional. The stack was removed from the system and further disassembled in order to determine the error. It became clear the evaporator was blocked due to residues and further corrosion due to acid.

5.6 Boat build and the electrification

The boat being built for this project was a ProZero modular lightweight composite workboat built in carbon fiber. The boat was a zero-emission version where the propulsion is secured by 2 electrical outboard motors, with the following specifications

Length	11,5m
Width	4,0m
Draught	0,73m

The boat may be seen in Figure 28.

Figure 28 The boat build for the BlueDolphin project

Electrification of the boat

For the BlueDolphin project it was mandatory to equip the workboat with an electrical propulsion system in order to benefit from the electrical supply coming from the fuel cell system. Torqeedo electrical propulsion system was chosen as they were able to supply a complete power driveline ideal for this purpose. The driveline consisted of the following subcomponents

- Outboard engines
- Batteries
- System-Management-Unit (SMU)
- Charger and inverter
- DC system integration
- AC system integration
- OEM user interface
- Remote service module

Two outboard engines were installed, each producing 50kW. The motors were liquid-cooled permanent magnet synchronous motors yielding outstanding efficiencies up to 98%. Two batteries were installed powering the motors, each with a capacity of 42kWh with a voltage range of 250-400VDC witch were matched by the fuel cell system. In order to control the entire system a SMU was needed which controlled the intelligence and power distribution of the driveline. As the SMU functioned as the brain of the driveline redundancy was a crucial aspect. The driveline was therefore fitted with 3 SMU coupled such if one were to fail the remaining two would split into two parallel circuits once again enabling redundancy. As the driveline was designed for onshore charging it was fitted with a 22kW three-phase charger. As the batteries utilize dc voltage, inverters were also installed to enable an ac circuit on the boat for utilization. The majority of the components used in the boat were powered by 24VDC from which converters were also installed to buck the voltage from the voltage of the batteries to 24VDC. In order to control the driveline an interface was installed. Propulsion system parameters such as speed, power and battery charge status were displayed on the main screen. The software provided additional detailed system management information, such as system component status, energy flows etc. In order to continuously enable updates and optimize the driveline it was fitted with a remote service module. A schematic of the complete driveline may be seen in Figure 29

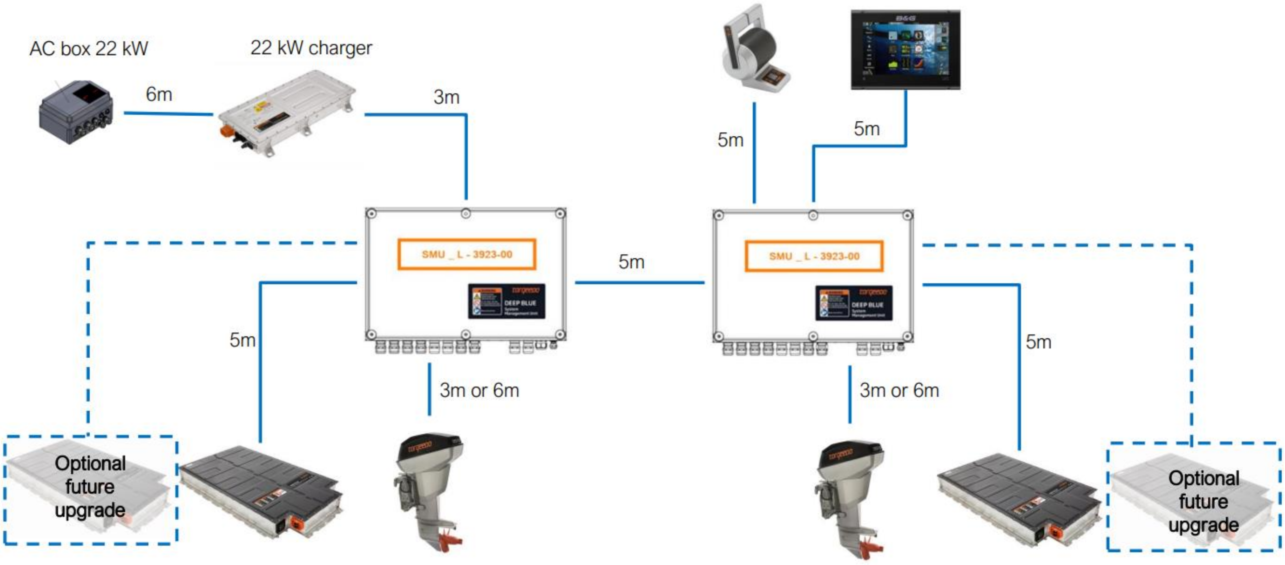


Figure 29 Schematic of the driveline

5.7 Life Cycle Analysis (LCA)

From an academic perspective, reducing Pt loading addresses two critical challenges simultaneously. First, it lowers costs, enhancing the commercial viability of fuel cell technologies. Second, it mitigates the environmental impacts associated with Pt production and usage, directly aligning with sustainability goals. The strong focus on Pt reduction in research reflects its disproportionate impact on both economic and environmental aspects of fuel cell systems. Life Cycle Assessment studies further reinforce this focus, consistently identifying Pt as the primary contributor to the environmental footprint of PEMFCs.

Platinum (Pt) serves as a cornerstone for Proton Exchange Membrane Fuel Cells (PEMFCs) due to its unmatched catalytic properties. It enables the key reactions required for high efficiency and low emissions in fuel cells, positioning PEMFCs as a leading clean energy technology. However, Pt is one of the rarest and most expensive materials on Earth, and its extraction and processing impose a significant environmental burden. These factors explain why Pt dominates the life cycle assessment (LCA) of PEMFCs and why academic research prioritizes its reduction or replacement.

Why Platinum Dominates PEMFC Life Cycle Assessments

Platinum’s role as a catalyst is indispensable due to its superior performance in electrochemical reactions. However, its environmental impact is substantial because of energy-intensive mining and processing activities. The emissions associated with Pt extraction, such as sulfur oxides, contribute significantly to global warming and acidification. Despite being a minor component in terms of weight constituting only 0,012% of the mass in a 1-kW PEMFC stack Pt accounts for up to 60% of the total environmental impact during the manufacturing phase. This outsized influence underscores the importance of Pt-focused LCA evaluations.

Key findings from LCA studies includes

- Manufacturing Impacts: The PEMFC stack contributes 60-90% of the total environmental impact, primarily due to Pt usage.
- Recycling Benefits: Recycling Pt during the end-of-life (EoL) phase can reduce the environmental burden by up to 95% for certain indicators, such as acidification and fossil energy demand. Without recycling, reductions in environmental impact during the EoL phase are negligible.
- Pt Loading Reduction: Studies show that halving the Pt content in PEMFC stacks can decrease the global warming potential (GWP) by 16%, while further reductions in Pt loading can lower GWP by an additional 10%.

Given these findings, LCA studies consistently point to Pt as the material with the highest potential for reducing the environmental footprint of PEMFCs. This explains the academic focus on minimizing Pt usage through various strategies, including material innovations and process optimization.

Academic Focus on Pt Reduction in HT-PEMFCs

While low-temperature PEMFCs (LT-PEMFCs) have lower Pt requirements, high-temperature PEMFCs (HT-PEMFCs) often demand higher Pt loading due to performance challenges such as slow oxygen reduction reaction (ORR) kinetics and phosphate anion poisoning. These systems, operating at temperatures above 120°C, have gained significant interest for their ability to tolerate CO impurities and offer enhanced durability under certain conditions. However, their reliance on Pt has created a bottleneck in advancing HT-PEMFC technology. Academic research has therefore concentrated on strategies to reduce Pt content without compromising performance.

Alloying Platinum

One of the most promising approaches involves alloying Pt with cheaper and more abundant metals such as cobalt (Co), iron (Fe), or palladium (Pd). Alloying enhances catalytic activity, improves resistance to impurities, and reduces overall Pt usage. For example:

- A 30 wt% Pt-Pd alloy catalyst demonstrated excellent performance in HT-PEMFCs, achieving a power density of 1,30 W/cm² with only 0,02 mg/cm² Pt loading.
- Pt-Co alloys supported on multi-walled carbon nanotubes have shown comparable performance to traditional Pt/C catalysts, but with significantly lower Pt content.

Alloying not only reduces costs but also improves the long-term stability of the catalyst, addressing one of the primary challenges in HT-PEMFCs.

Innovative Catalyst Supports

The choice of catalyst support material plays a critical role in reducing Pt loading. Carbon-based supports, such as graphene-doped carbon and multi-walled carbon nanotubes, enhance the dispersion of Pt particles, thereby increasing catalytic activity and reducing the amount of Pt required. Studies have also explored non-carbonaceous supports, such as silicon carbide (SiC), which offer improved stability and lower degradation rates compared to traditional carbon supports.

- Pt loaded on graphene nanoplatelets (GNPs) demonstrated superior performance in HT-PEMFCs, achieving power densities of 0,34-0,46 W/cm² at operating temperatures between 160°C and 190°C.
- SiC-based supports showed significantly lower electrochemical degradation compared to Pt/C, extending the lifespan of the catalyst.

These advancements highlight the potential of support-material innovation to address both cost and sustainability challenges.

Non-Platinum Catalysts

The development of non-platinum group metal (PGM)-based catalysts has gained traction as a long-term solution to Pt dependency. Iron-nitrogen-carbon (Fe-N-C) catalysts, for example, have shown promising results in HT-PEMFCs, achieving performance levels comparable to Pt-based systems under specific conditions. These catalysts are not only more affordable but also derived from abundant materials, making them a sustainable alternative.

- Fe-N-C catalysts demonstrated a peak power density of 0,325 W/cm², surpassing the performance of some Pt-based catalysts at equivalent operating conditions.
- Advanced doped carbon structures, such as SiO_2-doped phosphoric acid/polybenzimidazole membranes, have further enhanced the performance of non-PGM catalysts.

While non-Pt catalysts remain in the experimental stage, they represent a critical area of academic research with the potential to revolutionize PEMFC technology.

Recycling and Recovery of Pt

Recycling Pt at the EoL phase is another critical focus area. Recent advancements in Pt recovery methods have achieved efficiencies of up to 70%, allowing recycled Pt to be reused in new catalysts without significant performance loss. Studies have shown that recycled Pt catalysts can match the activity and stability of commercial Pt/C catalysts, demonstrating the feasibility of a circular economy approach.

- Advanced recovery processes have reduced primary energy demand by up to 20 times and sulfur oxide emissions by up to 100 times compared to virgin Pt production.
- Recovered Pt-based catalysts have shown excellent electrochemical stability, making them a viable alternative to newly mined Pt.

Recycling not only reduces the environmental footprint but also lowers dependency on mining, addressing concerns about resource depletion.

Implications for Fuel Cell Technology

The academic focus on Pt reduction and recycling stems from the need to address both environmental and economic challenges associated with fuel cell technology. By targeting the largest contributor to the LCA of PEMFCs—Pt—researchers are unlocking pathways to make fuel cells more sustainable, affordable, and scalable. Key strategies, including alloying, support material innovation, and non-PGM catalysts, are complemented by recycling efforts to create a holistic approach to Pt reduction.

Future work must continue to integrate these advancements into practical systems, ensuring that fuel cell technologies can meet the growing demand for clean and efficient energy solutions. By focusing on Pt reduction, academia is paving the way for a greener energy landscape while addressing the fundamental barriers to fuel cell adoption.

6. Utilisation of project results

6.1 Blue World Technologies

Throughout this project, the BlueDolphin platform has become of high interest for multiple markets and customers. The platform was showcased at Deutz Day back in November 2022 which may be seen in Figure 30 where it was of high interest with respect to multiple different range-extender applications. The BlueDolphin project has also resulted in a signed partnership-contract between Blue World Technologies and AGCO Power, see article https://www.blue.world/fuel-cell-manufacturer-blue-world-technologies-in-collaboration-with-agco-power-on-electric-fendt-tractor-to-run-on-methanol/. Back in 2023 Blue World Technologies entered a Swedish government funded project with the objective of integrating the BlueDolphin platform in an electric boat used for public transportation, see boat https://www.cstrider.com/. Blue World Technologies expect the outcome of this project to be another partnership.

One of the biggest challenges Blue World Technologies faces is the publics limiting knowledge of the HT-PEMFC technology from which demonstration of the technology is always required before new partnerships are formed. The BlueDolphin platform has proven to be the ideal showcase unit for this, which can easily be seen from the latter mentioned partnerships which could have been realized without this platform.

Figure 30 BlueDolphin platform showcased at Deutz Days 2022

6.2 Aalborg University

In the project, we established tests and methods to evaluate a HT-PEM system for use on a boat. Our tests and analysis showed that the methanol fuel cell technology is suitable for marine applications. Our focus was on the HTPEM and reformer setup, which performed well for installation on boats with its high efficiency, durability and low carbon footprint.

At the university, we focused on modeling the key components of the system. This work gave us valuable insights into how HT-PEM systems performed under typical marine conditions, such as changes in temperature, humidity, and power demand. This helped us implement inhouse strategies to test and optimize the operation and performance.

We performed vibration and shock tests in the lab to simulate the physical stresses the system experienced on a boat. These tests demonstrated that the fuel cell stack from Blue World Technologies is very durable and capable of handling the harsh conditions of marine use, including continuous motion and impacts. This result of this testing improved our understanding of how to design and test fuel cell stacks for these environments and supported both current and future projects in marine fuel cell technology.

6.3 TUCO

Electrical propulsion systems are already a known and recognized technology within the marine business, and have been incorporated into a number of TUCO ProZero boats. However, there are in general still a remarkable reluctance to use such systems, mainly due to the power density of the batteries. Therefore, a hybrid solution between a methanol powered fuel cell system and batteries is a viable solution to overcome this challenge. With such a hybrid solution, the applicable segment can be more or less all kinds of application within the marine vessel industry both pleasure and commercial.

The commercialization of the fuel cell technology can take place via a numerous actors within the marine business. It can be shipyards installing the system in new-built vessels, retrofit solution, propulsion suppliers who introduce the fuel cell technology in their product range or fleet operators who convert their fleet into low emission version.

For Tuco the commercialization of the fuel cell technology will follow as soon as the propulsion suppliers can offer a driveline solution at a developed mature level, which meets the demand of the market. Tuco do not foresee any obstacles introducing the technology and will welcome this as a vital competitive parameter in the future, which will both contribute to our turnover and at the same time strengthen our green profile.

7. Project conclusion and perspective

During the BlueDolphin project an innovative and efficient 15kW methanol powered fuel cell system based on HT-PEM technology was successfully developed and demonstrated. The BlueDolphin platform was developed as a range extender unit for the maritime market as their power demand calls for solutions like this in order to minimize the size of their batteries. A great interest was shown by potential customers in Denmark, Sweden, Germany and Finland. With this high interest the next step is to secure a partnership with an integrator which can take the BlueDolphin platform from what it is to a real product.

The project introduced several game-changing concepts. Among others, these included a novel water neutrality system enabling 100% methanol as fuel as wastewater from the HT-PEMFC stack was recovered and regenerated for internal fuel mixing. In addition to this an electric powered boat was designed and constructed with the spacing for the BlueDolphin platform in the engine room as if it was a final product. Studies was conducted to investigate and secure the survival of the fuel cell stack in harsh offshore environments.

Novel concepts for the thermal integration of system components and smart waste heat management ensured high electrical system efficiency above to 45%. With high fuel efficiency, the cost of ownership was highly cost-competitive compared with alternative solutions such as batteries and diesel generators.

8. Appendices

8.1 App. A