Ref. Ares(2025)6821688 - 25/08/2025

marpower

D1.4

System/cycle design and modelling report

2025

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

	Work Package No.	WP1	Task/s No.	Task 1.3
Deliverable title	System/cycle design and modelling report			
Linked Task/s Title	T1.3: System design and modelling			
Status	First version for review			
Dissemination level	PU			
Due date deliverable	2025-08-31	Submission date	2025-08-25	
Deliverable version	1.1			

Document contributors

DELIVERABLE RESPONSIBLE: Aurelia Turbines

Contributors	Organization	Reviewers	Organization
Teemu Turunen-Saaresti	LUT	Jussi Sopanen	LUT
Jacobo Porteiro	Uvigo	Ilmas Santos	DTU
Toni Hartikainen	Aurelia Turbines		

Document history

Version	Date	Comment
1.0	2025-08-01	First version for review
1.1	2025-08-15	Updated based on feedback and ready for submit

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Index

List of figures

List of Tables

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

List of abbreviations

ABBREVIATION	DESCRIPTION
GT	Gas Turbine
WHR	Waste Heat Recovery
WHRS	Waste Heat Recovery System
DT	Digital Twin
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
V&V	Validation and verification
LoD	Levels of Detail
WP	Work package
TIT	Turbine Inlet Temperature
ESI	Engineering System International

1. Introduction

This deliverable, prepared within the framework of the MARPOWER project, introduces the tools and systems applied to the design and simulation of the MARPOWER Energy Conversion System (MECS) cycles. It provides the foundation for understanding the methodologies and processes developed under the project. Task 1.3 focuses on the detailed specification of the gas turbine (GT) and waste heat recovery system (WHRS) cycles, together with the associated simulation tools. In alignment with the digital twin (DT) development in WP3, the project team decided to adopt the DT for cycle simulations, as it provides an effective platform for analysing stand-by conditions and transient operations.

2. Cycle design

2.1. GT & WHR cycle design tool selection

MARPOWER cycle design was done using in-house tools developed by LUT (project coordinator) with Excel. The cycle design tool consists of a recuperated GT simulation tool and a WHRS tool, including the boiler and steam turbine. The GT simulation tool included a preliminary estimation of WHR performance based on exhaust gas temperature. Working fluid properties were calculated using the Refprop library [1] in all simulation tools. Excel-based tools were used because they were readily

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

available and required only minor changes to apply to the MARPOWER cycle. In addition, tools were validated in previous projects [2,3].

2.2. Gas turbine

The GT simulation is based on modelling continuity and energy balances. To achieve the highest possible accuracy of the cycle's simulated results, the simulations were updated whenever more accurate estimates of pressure losses and component performance became available. The pressure losses in various components, including heat exchangers, the combustion chamber, and the boiler, were derived from the detailed designs provided by project partners Alfa Laval and DLR. The performance data for compressors and turbines were based on detailed designs developed by project partner Polimi. These factors significantly influenced the overall cycle performance and operational parameters. As a result, multiple simulations – up to 19 different cases – were conducted. Most of these simulations (up to Case 12) were documented in deliverable D1.3: *Thermodynamic System Design*.

The main challenges encountered were related to hydrogen combustion emissions and the cooling of turbine blades. To meet emission targets, the maximum turbine inlet temperature (TIT) had to be reduced. Additionally, different turbine blade temperatures (900 °C and 1000 °C), as well as various cooling methods, including convective and film cooling, were evaluated. The simulated cases are summarized in Table 1 .

Cycle option	Max pressure	Cooling	TIT
Case 13	12 bar	convective cooling, blade temperature 1000°C	TIT 1250°C
Case 14	12 bar	convective cooling, blade temperature 1000°C	TIT 1350°C
Case 15	12 bar	convective cooling, blade temperature 900°C	TIT 1250°C
Case 16	12 bar	film cooling, blade temperature 1000°C	TIT 1250°C
Case 17	12 bar	film cooling, blade temperature 1000°C	TIT 1350°C
Case 18	12 bar	convective cooling, blade temperature 1000°C	TIT 1200°C
Case 19	12 bar	no cooling	TIT 1200°C

Table 1. Simulated cycles.

Net electric efficiencies of GT and GT + WHR are shown in **Error! Reference source not found.**. Reducing TIT decreased the efficiency of the cycle, which was expected (case 13 vs 14 for convective cooling and case 16 vs 17 for film cooling). Interestingly, GT cycle efficiency was decreased by a higher TIT because higher cooling flow was needed. On the other hand, with the higher turbine inlet

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

temperatures (1350 °C and 1250 °C), NO_x emissions would be higher than targeted, even though efficiency would be better. TIT of 1200°C would result in NO_x emissions lower than the targeted one. The results show better efficiency when film cooling was chosen. However, the detailed study of cooling showed that film cooling was not suitable when a lower TIT was utilized. Case 18 was chosen for the detailed design of the components. This was a compromise between the targets of the project. Still, sufficiently good electric efficiency is achievable, and targeted emissions are met.

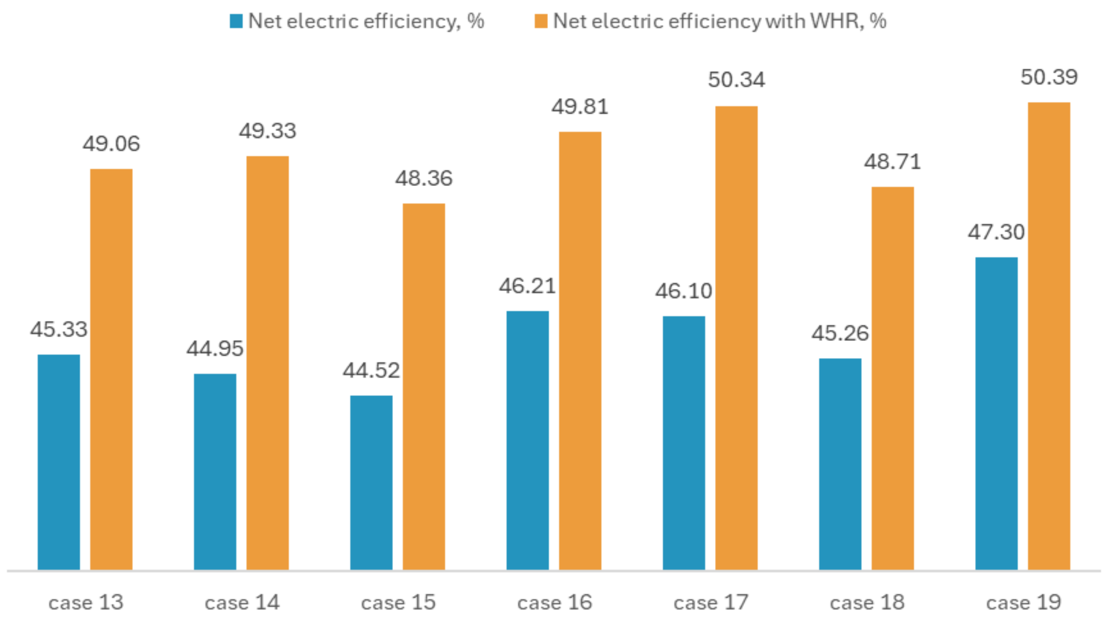

Figure 1. Simulated net electric efficiency.

2.3. Waste heat recovery system

The designs of the waste heat recovery (WHR) system key components, the boiler and the turbine, were conducted with in-house design tools. In the boiler design, preliminary modelling was made with LUT's design tool, and the final designs were made by Alfa Laval with their in-house tools. The results from both tools were also compared to check the accuracy of LUT's tool, indicating comparable designs. The turbine design was made with LUT's in-house tool, which has been verified in previous studies. The use of in-house tools made it fast and flexible to run simulations, but also the possibility to modify the tools due to access to all models/calculations was found important. This access would not be possible with external software. Alfa Laval's in-house tools can predict the off-design performance of the boiler, while LUT will use its in-house approach to model the turbine's off-design characteristics for the digital twin once the final turbine design is completed.

The LUT's radial outflow turbine design tool provides turbine performance values, turbine vane/blade heights, and other information that is needed to draw the aerodynamic shape of the machine. The turbine design was made based on the boiler outlet conditions, while the boiler was designed based on the recuperator outlet conditions. During the modelling, different boiler pressures and turbine condensing temperatures were simulated to find possible challenges. The LUT's boiler design tool provides, for example, the preliminary design of heat transfer surfaces and predicts the performance of the boiler.

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

During the modelling of WHR system, the key challenge was related to the effect of low condensing temperature, which led to higher powers but simultaneously made the design of the turbine more challenging. It was also found that the lower boiler outlet pressure led to higher turbine performance. Both findings were further utilized in the more detailed component designs.

3. DT Simulation tool

3.1. DT simulation tool selection criteria

A primary objective of the MARPOWER project is the development of a detailed digital twin (DT) of the ship's energy system, alongside a more compact version of the DT for its integration into the global simulation environment of existing vessels at the shipyard of project partner Chantiers de l'Atlantique.

The software selection process was based on a rigorous evaluation of key technical criteria: fidelity in modelling physical and multi-domain systems, interoperability with other simulation platforms, efficiency in developing complex models, availability of industrial support, and applicability to validation environments in the maritime sector.

3.2. Software Selection

A comparison of the main Modelica-based solutions (Table 2) led to the selection of Simcenter Amesim for the detailed digital twin and SimulationX for the integrated fast-running model. The technical justifications for this dual-software approach are explained hereafter.

Tool	Physical Modeling	Integration	Ease of Use	Industrial Support	Multidomain Simulation
Open Modelica	Partial support for the Modelica language; suitable for research purposes.	Compatible with FMI; limited integration.	Basic interface; steep learning curve.	Community project without dedicated support.	Basic multidomain capabilities through standard Modelica.
Dymola	High performance and full Modelica support.	FMI, co-simulation, integration with MATLAB/Simulink.	Technical interface; requires prior experience.	Professional support from Dassault Systèmes.	Multidomain with commercial and standard Modelica libraries.
Simcenter Amesim	Validated physical libraries, ideal for energy systems.	FMI, integration with MATLAB and control tools.	Very intuitive; block-diagram-based interface.	Backed by Siemens with strong technical support.	Ready-to-use multidomain libraries.
Simulation X	A causal modelling with	Export as S-Function, C code, FMI.	Modern interface with	Support from Keysight/ESI;	Multidomain libraries written in Modelica.

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

	control over the level of detail.		integrated tools.	widely used in industry.	

Table 2. Summary of the Technical Comparison of Modelica-Based Tools

Simcenter Amesim was selected for the detailed digital twin of the energy system due to its outstanding capabilities for high-fidelity physical systems modelling. This tool offers a wide range of predefined and validated components that accurately represent the subsystems typically found in a naval energy system (electrical generation, distribution, rotating machines, converters, hybrid propulsion systems, etc.). The use of validated libraries ensures confidence that the simulated behaviour aligns with real-world performance—an essential aspect for a detailed digital twin aimed at design validation. Unlike a generic Modelica environment, where the engineering team would need to develop or adjust many component models from scratch, Amesim provides ready-to-use blocks that encapsulate complex physical phenomena (e.g., fluid dynamics in fuel pipelines, characteristic curves of generators and motors, thermal exchanges in intercoolers) with simple parameterization. This significantly accelerates model development and reduces the risk of errors, allowing efforts to focus on analysis rather than on deriving every equation manually.

Another key factor was Amesim's ease of implementation and use. Its intuitive graphical interface, based on component diagrams connected through ports, facilitates the construction of the energy system model without the need to manually code equations. Engineers can "drag and drop" components into the diagram and connect them to represent, for instance, a fuel hydraulic circuit coupled with an electric generator and its control system. Comparative studies have highlighted Amesim as the most user-friendly tool in its category, offering a streamlined workflow and clear documentation. This high usability results in a short learning curve, even for users without expertise in Modelica, which was a decisive factor given the project timeline. In a validation environment where multiple model iterations may be required (e.g., to calibrate a controller or evaluate different configurations of batteries and generators), the speed with which changes can be implemented in Amesim provided a tangible advantage.

A critical aspect of the software evaluation was the platform's capacity for system integration and its degree of architectural openness. While Simcenter Amesim is a proprietary platform, its robust support for open standards ensures a high degree of interoperability, which was a decisive factor in its selection. Amesim provides comprehensive support for the Functional Mock-up Interface (FMI), the industry standard for model exchange and co-simulation. This allows for the import and export of models as Functional Mock-up Units (FMUs), enabling seamless integration with a wide array of simulation tools prevalent in the maritime sector. For the MARPOWER project, this capability is essential for validation and verification (V&V) activities. Furthermore, the platform's extensibility is significantly enhanced by its native support for the Modelica language. This feature permits the direct integration of external Modelica models, whether they are custom-developed code or specialized third-party libraries. This is particularly advantageous for MARPOWER, as it allows for the incorporation of highly specialized component models, such as advanced turbine models developed by project partners, directly into the Amesim simulation environment.

Ultimately, this architectural flexibility guarantees that the digital twin can achieve a comprehensive and high-fidelity representation of the complete energy system. It mitigates any potential limitations of the native component libraries and ensures that the specialized expertise of all project stakeholders can be fully leveraged. This guarantees that no subsystem remains unrepresented or oversimplified due to a lack of standard components.

For the development of the compact energy system model, intended for integration within the ship's global digital twin, ESI SimulationX was selected based on several complementary technical advantages. While SimulationX is also a multi-domain simulation platform based on Modelica, it is particularly distinguished by its advanced capabilities for model abstraction and reduction. The platform excels at generating computationally efficient and simplified models that preserve essential physical

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

phenomena and core dynamic behaviours. A key feature is its support for managing multiple Levels of Detail (LoD), allowing users to modulate model fidelity by easily switching between submodels of varying complexity. This functionality was a critical requirement for the MARPOWER project. The global digital twin, which simulates the entire vessel, mandates a computationally lean representation of the energy subsystem to ensure manageable simulation times, particularly for long-duration or real-time analyses. SimulationX directly addresses this need by enabling the creation of an aggregated or "equivalent" model. For instance, a compact model can represent the electrical grid and generation plant in a way that accurately reproduces the macroscopic system dynamics, such as power demands, fuel consumption, and transient responses to load changes, without the granular detail of every internal subcomponent. The resulting model achieves the necessary computational parsimony for integration into the global twin while maintaining the phenomenological accuracy required for comprehensive ship-level simulations.

A decisive factor in the selection of SimulationX was its strategic alignment with the existing simulation infrastructure at the Chantiers de l'Atlantique shipyard. The shipyard maintains a mature and operational simulation architecture for its vessel-level digital twins, an environment with which SimulationX demonstrates proven interoperability. A primary objective of the MARPOWER project is to validate the energy system's performance under representative operational scenarios. This requires integrating the energy model into the shipyard's global digital twin. Therefore, developing the compact energy model directly in SimulationX ensures seamless integration and functional compatibility with the shipyard's established toolchain, mitigating significant integration risks and development overhead.

This two-software strategy, using Simcenter Amesim for high-fidelity development and SimulationX for integrated deployment, provides a robust workflow. It allows the project to benefit from the detailed insights from the Amesim model while delivering a compact representation that is fit-for-purpose. This ensures that the final model is not only functionally compatible with the existing simulation architecture but also retains the necessary phenomenological fidelity for meaningful, full-ship simulations.

3.3. Digital twin model creation

The DT creation has been started as part of work package 3. The work of model creation will be reported in deliverables related to WP3.

4. Conclusion

The cycle design was performed using in-house tools developed in Excel, which were readily available, previously validated, and provided the flexibility to incorporate different cooling options, boundary conditions, and working fluids. In total, 19 cases were simulated, from which the configuration that satisfied emission targets while offering a balanced compromise in overall performance was selected for detailed component design. This selected case establishes the foundation for the subsequent development within the MARPOWER project, ensuring that the detailed design phase is aligned with energy-efficiency, performance and life-cycle objectives.

The capabilities of various Digital Twin platforms were evaluated to identify the one most suited to the project's requirements. The main selection criteria included:

- fidelity in modelling physical and multi-domain systems
- interoperability with other simulation platforms
- efficiency in developing complex models
- availability of industrial support

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

- applicability to validation environments in the maritime sector

As a result, two different platforms were selected: one for the high-fidelity digital twin and another for the integrated, fast-running model. Simcenter Amesim was chosen for the detailed digital twin due to its strengths in high-fidelity physical system modeling and its extensive library of validated model components. ESI SimulationX was selected for the integrated fast-running model, which is also a multi-domain simulation platform based on Modelica. SimulationX excels at creating computationally efficient and simplified models, and it supports the management of multiple levels of model detail, which is a critical requirement for the MARPOWER project.

The portability between AMESIM and SimulationX is straightforward, as both tools support standardized model exchange formats such as FMI (Functional Mock-up Interface). This allows models to be transferred and reused with minimal adaptation, ensuring consistency in simulations while enabling flexibility across platforms.

This dual-platform strategy – using Simcenter Amesim for detailed model development and SimulationX for integrated deployment – provides a robust and efficient workflow. It enables the project to leverage detailed insights from the Amesim model while maintaining a compact, fit-for-purpose model suitable for integration. This ensures that the digital twin remains functionally compatible with the existing simulation architecture and retains the necessary phenomenological fidelity for meaningful, full-ship simulations.

References

[1] Lemmon, E., Bell, I., Huber, M. & McLinden, M., 2018. NIST standard reference database 23: reference fluid theremodynamic and transport properties - REFPROP, Version 10.0,, Gaithersburg: s.n.

[2] Jaatinen-Varri A., Nerg J., Uusitalo A., Ghalamchi B., Uzhegov N., Smirnov A., Sikanen E., Grönman A., Backman J., Malkamäki M. Design of a 400 KW Gas Turbine Prototype. Proceedings of the ASME Turbo Expo, 2016, DOI: 10.1115/GT2016-56444

[3] Grönman, A., Nerg, J., Sikanen, E., …, Sopanen, J and Turunen-Saaresti T. Design and verification of a hermetic high-speed turbogenerator concept for biomass and waste heat recovery applications. Energy Conversion and Management, vol. 225, 2020. https://doi.org/10.1016/j.enconman.2020.113427

Funded by the European Union

Funded by the European Union under grant agreement No 101138341. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.